R&D Technology Roadmap

A contribution to the identification of key technologies for a sustainable development of European road transport
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FUIRORE CONSORTIUM
FURORE - Background and Objectives

The Thematic Network FURORE establishes a platform of stakeholders to discuss breakthrough technologies and the corresponding research demand for vehicles of the year 2020 and beyond. The network focuses predominantly on road vehicles powered by internal combustion engines, but is also analysing potential breakthrough technologies in alternative fuels and systems such as hybrids and fuel cells. FURORE serves as an umbrella to co-ordinate dissemination efforts and to initiate basic research activities for the development of these technologies by universities and R&D organisations, enabling product development by the automotive industry and providing input for future research programmes through more transparency in automotive research and development.

The scope of the present FURORE document was to consolidate the opinions of the participating organisations, the results of dedicated workshops and literature analysis to a comprehensive Automotive R&D Technology Roadmap. The technology expectations outlined by organisations, which are not linked to any vehicle or engine producer, shall serve as an independent decision support for the EU Commission for future research policy regarding land transport in the ongoing and future Framework Programmes for RTD. Furthermore the roadmap is intended to aid the co-operation between industry, research institutions and universities. The output will be disseminated via international symposiums, a public web-site and a CD-ROM plus database of information and material generated within all activities.

For the execution of this project several organisations, among them usually competing companies, have formed a task force, each one contributing in its special field of competence. All FURORE partner companies are organised in EARPA, the European Automotive Research Partners Association. Additional input came from EUCAR/SG Powertrain, CONCAWE and other leading European organisations in automotive research. The description of technologies, the findings and conclusions are predominately based upon specialist knowledge and opinion, the workshops performed to specialised topics and literature search.

Key Findings and Messages

It is anticipated that a smooth transition from the conventional to the new technologies will happen, no radical change is foreseen in the time period envisaged. The consortium believes in evolution rather than in revolution. Furthermore it can be foreseen that driven by various fuel scenarios, the diversification in powertrain technologies is increasing, many technologies may run in parallel in the future.

Political & economical boundaries and technical feasibility will determine the speed gradient of the smooth transition to new technologies.

Big improvement potential is still seen in the further development of state of the art technologies. The immediate impact of these improvements on environment and economics is considered to be much bigger than the effect achievable by the introduction of completely new technologies which suffer from shortcomings in production, infrastructure and public acceptance.
Nevertheless the introduction of completely new technologies must be encouraged too in a sensitive manner also taking into account the international situation. Any solo activity in the European community might have negative impact for European automotive industry on competitiveness on the world markets.

A comprehensive, system-oriented view on potential new technologies is required, not only tank-to-wheel considerations but also well-to-wheel or fuel-production-to-wheel analysis. For a complete understanding an approach which covers the whole life-cycle of a technology is essential.

By this “Revolution by Evolution” approach, research demand is found in many areas - "state of the art" and alternative powertrain systems.

The present study assessed various fuel and energy scenarios, analysed the most important powertrain technologies and judged them in terms of emission, \( \text{CO}_2 \) and efficiency gains and potential risks, and was looking into future complete vehicle technologies such as new vehicle structures, safety and NVH aspects. For all these topics the future research demand has been listed and reasoned.

In the following the most important findings are mentioned and research topics are highlighted and emphasised.

**Vision for 2020 and beyond**

The breakthrough technologies and the derived research demand are based on a comprehensive analysis of future road transport scenarios, voting exercises, workshops and individual discussions. In general, technological targets can be split up into research targets, engineering targets and commercial targets. It is essential to mention that FURORE focuses primarily on research targets. This means that the potential of a technology to realise intended technological objectives is examined but the aspects of feasibility and large-scale production are not investigated in detail.

**View on future European traffic scenarios:**

Due to its enlargement to include Central and Eastern European Countries, the European Union is expected to be the world’s strongest economic area in 2020 with an estimated population of 450 million (in 27 member states). More than 70\% will live in urban and suburban agglomerations and more than 25\% of the population will be older than 60 years. These are selected criteria which have to be considered when discussing future technologies. Future mobility will be focused predominantly on the citizens and their needs, which are basically individual mobility and the availability of goods. By 2020 there will already be positive results of today’s efforts in optimising intermodality and interoperability among the different transportation systems. Nevertheless, the road will still be the dominant mode of travel and transportation and person-kilometers will further increase. It is possible that there will be subscription systems with the possibility to use several means of individual and collective transportation depending on safety, effectiveness, cost, time and comfort. Citizens will expect the freedom to choose among the several means of transportation with seamless transfer from one to the other and with a minimum of concern for the vehicle used. Goods transport will increase as well due to EU enlargement and integration, just-in-time production and distribution (both world-wide) and freight and fleet deregulation to drive costs down and increase competition. Infrastructure (including physical network and traffic management systems) will be required to keep travel time to a minimum, reduce congestion and realise efficient
intermodality. As the establishment of trans-European transport networks is a prerequisite for future mobility, much improvement will have to be realised by 2020.

View on future European energy scenarios:
Traffic forecasts for the next 10-20 years show that the increase of traffic volume and congestion will counteract the significant improvement of the vehicle technologies and the negative consequences of energy consumption, emissions, noise and safety will further increase. To enhance the quality of air, future legislation will impose even lower the quality of air, future legislation will impose even lower pollutant emission targets, approaching zero-impact level, but recognising the diminishing return as this zero-impact is approached. Exhaust emission is expected to be at levels where new measurement techniques will be needed, with light duty Diesel nearly performing at or below the next level of gasoline engine limits.

The EC plans the substitution of parts of the oil-based fuel market by alternatives (in particular natural gas, bio-fuels and hydrogen) by 2020. A further objective is the reduction of the European Union’s energy dependency which will also improve the security of energy supply. Today, transport is 98% dependent on crude oil, representing 67% of final oil demand. There is consensus that, if the use of alternatives grows until 2020 in line with EU targets, the majority will be supplements to existing liquid fuel types. Hydrogen - often seen as the ultimate goal - is another option. H2-penetration until and also beyond 2020 depends greatly on progress in solving the challenges of production and storage. Apart from that, it requires political decisions on prime energy sources which have not yet been made.

For certain alternative fuels there are still major hurdles - technological as well as cost-related - which need to be solved before a major increase in market share can be expected. There is a continuing downward pressure on CO2 and voluntary agreements are likely to spread to all sectors. In order to meet EU greenhouse gas emission targets, as well as to decrease energy dependency, overall energy consumption in transportation must be reduced significantly. Together with considerable efficiency gains it is believed that this is the only measure which will lead to success.

The following Research Targets have been identified by the consortium:

<table>
<thead>
<tr>
<th>Car</th>
<th>Truck</th>
<th>Bus</th>
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<tbody>
<tr>
<td><strong>Fuels</strong></td>
<td>2020: Achieve EU target 20 % substitute fuel, fuel / combustion optimised together, significant depot-fuelled fleets (e.g. bus) using CNG and H2</td>
<td>2030: Routemap to sustainable transport identified and enacted</td>
</tr>
<tr>
<td><strong>CO₂ / GHG</strong></td>
<td>2020: 95 g/km</td>
<td>2020: -10 % on today</td>
</tr>
<tr>
<td><strong>Emissions</strong></td>
<td>2020: 50 % EU IV + PM O.1 control</td>
<td>2020: NOx &lt;25 % EU IV, PM &lt;50% EU IV, inclusion of unregulated compounds, local control</td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>2020: Road deaths -75 %</td>
<td>2030-2050: Introduction of autonomous driving</td>
</tr>
<tr>
<td><strong>Traffic</strong></td>
<td>2020: Telematics and traffic management enable congestion and stress free highway driving</td>
<td></td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>2020: Adequate noise level to the ambient. Holistic approach for real world noise reduction.</td>
<td>2030-2050: Further reduction in urban noise towards WHO targets</td>
</tr>
<tr>
<td><strong>Recycling</strong></td>
<td>2020: 85 %, introduction of useable cradle-to-grave analysis standard</td>
<td>2040: 95 % by weight, low environmental impact of disposal of the last 5 %</td>
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Energy and Fuels: Objectives and identified breakthrough technologies

Encouraged by the European Commission’s above-mentioned target for alternative fuels, the portfolio of available fuels will become more heterogeneous by 2020. The introduction of several new fuels is a challenge due to the costly proliferation of many different engine and emission control technologies, and a parallel proliferation of supporting fuel infrastructures. In some cases these new fuels or blends may be synergistic with new combustion modes, but this remains to be verified.

Conventional Fuels: The main fuels for transportation, i.e. gasoline and Diesel fuel, will not change dramatically but fuel specifications could further evolve. Both will become practically sulphur-free (10 ppm sulphur achieved in 2009), and other property improvements should be evaluated strictly with regards to well-to-wheels efficiency and CO2 impacts.

Advanced conventional fuels: These are mainly mineral-oil-based, such as syn-fuels and blended fuels. They are directly linked to future combustion requirements and/or optimisation constraints. Pure or blended fuels must be considered. For liquids from natural gas or coal, cost and CO2 have to be tracked.

Alternative fuels: Natural gas, biomass to liquid fuels, bio-fuels and hydrogen are the main candidates of the very ambitious alternative fuel proposal. Large-scale production facilities are still missing and it can be estimated that there also is still an optimisation potential in the production processes when building up those production facilities. Nevertheless the major issue with these fuels is how to produce, store and distribute them at a competitive price. It is assumed that pure hydrogen could only attain a non-negligible market share beyond the considered time period, by 2030 and later, for example also as a valuable ‘add-in’ for biomass-based renewable fuels. Production of hydrogen from hydrocarbons either in the plant or in the vehicle is not efficient with regard to CO2 and the security of supply objectives, and does not seem to be a feasible long-term solution. The production of hydrogen from electricity via electrolysis is needed in large scale quantities and not only for niche applications. This seems not feasible from renewable sources only. Therefore the use of nuclear power is one option but would definitely lead to a general political discussion on energy supply. The other alternative liquid fuels are in a slightly better cost situation even if there are concerns about massive biomass production in relation with food target land use.

Hydrogen could serve as an intermediate vector for the possible use of electricity in road transportation. As the electricity distribution grid is largely existing and competitive, research on efficient and cost-effective on-board electricity storage development should not be overlooked as an interesting solution, especially when combined with CO2 control of power generation (CO2 centralised sequestration process potential). Focussed basic research is needed to solve the problems of energy storage, especially batteries.

Major concerns with all these alternative solutions are production costs, and for gaseous fuels the distribution and improvement of storage solutions; if there is no breakthrough improvement in this area, alternative fuels will remain marginal and will serve niche markets only. All future research initiatives must consider fuels, engines and aftertreatment as interactive systems.

- Higher variety of fuels is expected on the market
- Designed fuels for new combustion processes will be needed
- Hydrogen will first come in niche markets
- Electricity as prime energy will only penetrate the market with cost-effective advanced batteries / energy storage systems
Powertrain Technologies incl. emission and aftertreatment:

Objectives and identified breakthrough technologies
Vehicle propulsion system technology development is an evolutionary process, influenced by the requirements of customers, the legislative boundary conditions like emission and safety standards, the energy resources and prices influenced by production/distribution costs and taxes. The general targets for technology trends and visions are energy consumption reduction, near zero emissions and alternative fuel-compatible power systems.

Spark ignition engines - state-of-the-art technology until 2007
In the near future, the importance of down-sized spark ignition engines will increase considerably. Boosting (supercharging and turbocharging) will be combined with displacement reduction, sometimes with new, redesigned engines. The feasible reduction in cylinder displacement is up to 40 percent, with a corresponding benefit in fuel consumption and carbon dioxide emissions of up to 20 percent. The adoption of direct injection will be another means of improving engine efficiency, but in terms of costs, these engines with stratified combustion are more expensive than conventional spark ignition engines due to the need for advanced injection technology and additional nitrogen oxide aftertreatment. As an interim step, direct injection with homogeneous combustion (enabling conventional emission control) in combination with supercharging, will take a growing market share. Variable valve trains enable a significant fuel economy increase and CO2 reduction up to 20%.

Another option are concepts with a variable compression ratio (VCR) in combination with downsizing, which offer (for supercharged engines) a potential up to 25% CO2 reduction.
And finally, first low cost belt-driven starter generators operating at 14V will reduce fuel consumption by enabling automatic stop/start, but without re-generative braking and torque support which require 42V systems. Naturally, many of these technologies can be effective in combination but research work must be carried out to find a cost-effective solution for high fuel economy for each vehicle type.

Spark ignition engines - technology trends until 2020
For the time span to 2020 it is most likely that above-mentioned technologies will further evolve and will feature advanced, adaptive control of these flexible sub-systems, using new sensor technologies. New combustion systems such as controlled auto-ignition with very low engine-out emissions of NOx and particulates will be realised to be effective in a wide engine map area and without full-load penalties. Some evolution of fuel properties may support this new combustion philosophy. Spark ignition engine technology is fully compatible with both natural gas and hydrogen, and when logistical problems are solved and if energy policy promotes these fuels into the marketplace, combustion systems tailored to these fuels will emerge. Extreme-charged lean burn spark ignited combustion processes are promising in this respect too. This combustion technology has extremely low NOx emissions and may only need oxidation or three way-catalytic converters.

Light-duty Diesel engines - state-of-the-art technology until 2007
The significance of down-sized Diesel engines will also grow in the next decade, because of increased supercharging rates, intercooling as well as the possibility of electrically assisted turbochargers and variable valve train concepts, which enable an optimised torque and transient characteristic. A specific power output up to 70 kilowatt per litre seems to be reachable. Compared with current Diesel engine technology, a fuel consumption benefit of up to 25 percent is predicted as a result of down-sizing measures and further reduction of friction losses.
Advanced fuel injection systems, which allow an adapted injection characteristic such as pilot, split and post injection as well as rate shaping, will reduce the local emissions substantially, perhaps avoiding the need for additional particulate and NOX control devices in small to medium vehicles. Also injection nozzles with variable injection-hole size will be a part of these advanced Diesel engine concepts.

**Heavy duty Diesel engines - state-of-the-art technology until 2007**

The challenges for the heavy duty engine are similar, with greater emphasis on emission control but a stronger market desire for efficiency in order to reduce operating cost. Fuel consumption and NOX/PM emission will be addressed by combustion process improvements, including application of flexible high-pressure fuel injection, four valves per cylinder, improved boosting, electronic control and low oil consumption. There are a variety of combustion process philosophies with corresponding emission control needs. Exhaust gas recirculation (EGR), particulate traps, lean NOX traps and selective catalytic reduction (SCR) based on urea in combination with oxidation catalyst will be used.

**Diesel engines: technology trends until 2020**

To obtain further reductions in emissions and fuel consumption, sub-system variabilities will increase for both heavy duty and light duty Diesel engines, enabled by advanced control systems. To increase the degree of down-sizing, in-cylinder peak pressure will increase, calling for new engine design concepts including supercharging and improved materials. With single cycle control strategies, emissions will decrease further. A greater step in NOX emission reduction in a wide mapping area will be expected for homogeneous charge compression ignition (HCCI) in the part-load range without full-load fuel consumption penalties.

**Aftertreatment - state-of-the-art technology until 2007**

Aftertreatment systems for 2007 are mostly visible today. Existing aftertreatment technologies - three-way catalyst, DeNOX catalyst, oxidation catalyst and Diesel particle filter - will be continuously improved regarding cost, sizes and efficiency. The first SCR systems based on urea will soon be implemented for truck engines.

**Aftertreatment - technology trends until 2020:**

In this timeframe, advanced aftertreatment systems for Diesel engines will be the greatest challenge. Key technologies for the most stringent NOX and PM control are cooled EGR, high-pressure fuel injection, Diesel oxidation catalyst, Diesel particulate filter, catalytic reduction of NOX by SCR or NOX-adsorber, and combinations of these, depending on needs of market and exhaust emission regulation for world-wide emission development strategies. System integration including electronic on-board diagnostics (EOBD) is an absolute must, i.e. combustion systems, mechanical systems, control systems, aftertreatment systems, and measurement systems have to be optimised as a whole to meet market demands and legislation requirements. Durability and reliability of the various systems still need to be proven before production release. The time for this is very short. This applies particularly to aftertreatment systems for NOX and PM, since NOX-adsorbers and Diesel particulate filters for heavy-duty Diesel engines are still in the laboratory development phase. The combination of NOX trap and particle trap in one system offers cost and fuel consumption advantages. Improved SCR technology with improved reduction agents can reduce the cost of NOX aftertreatment systems. Non-precious metal aftertreatment systems are the hope for future cost and resources savings. However, the pollutant transformation efficiency still needs intensive research work.
Transmission and driveline

The desire for CO₂ reduction, combined with market demand for best driveability, will cause a significant change in the European transmission market. It is unlikely that the conventional automatic transmission will gain a much larger market share, due to its fuel economy penalty, although the adoption of torque converter locks and six or more ratios will mitigate this effect. Continuously or infinitely variable types (CVT, IVT) offer improved efficiency especially for bigger displacement engines. Robotised transmissions (automated-manual, AMT) offer significant fuel economy benefits (typically 5%), but the driving experience will remain compromised by the interruption of torque during shifting, developments are ongoing to avoid this disadvantage. Market penetration will be significant but limited to smaller vehicles. The dual clutch transmission (DCT) offers almost as much benefit but with seamless shift quality under most conditions. This technology could achieve very significant penetration of the market if manufacturing costs prove competitive in high volumes. The popularity of four wheel drive will continue to increase in this time frame, particularly in lifestyle-orientated vehicles based on front-wheel-drive platforms. Premium vehicles will adopt increasingly sophisticated technologies for distributing drive torque between the wheels in a safe manner.

Hybrid and auxiliary power units

Increasing on-board electric power requirements, together with a desire for powertrain efficiency improvement, creates a need for hybrid-electric technology and auxiliary power units. Hybrids with an Integrated Starter Generator and “42 Volt boardnet”, in combination with a down-sized engine, are set to become a widespread measure for reducing fuel consumption and emissions, especially in city traffic. This “mild hybrid” technology provides good fuel saving potential by applying engine-shut-off-and-brake energy recovery, and by using the electric motor to assist for improved launch of vehicles with down-sized engines. Costs, weight, reliability and increased complexity were identified as the hurdles and barriers for this technology. Research has to be done on the electric machines, the integration of the starter generator, the control system and the reduction of weight. Nevertheless hybrid technology with a high share of electrical power calls for a greater change to the powertrain of a conventional vehicle. New transmissions, clutches and big electric machines are needed, together with high-power batteries, which remain very expensive and not sufficiently developed. Research is needed on the components in a hybrid powertrain, like new transmissions, electric motors and batteries. Also the integration and control of all the components is an important issue. Considering the additional complexity and components compared with the conventional powertrains, full hybrids will only slowly penetrate the market. Particularly the cost/fuel & emission saving ratio have to be considered. A different approach, which avoids the many issues related to batteries and electrical energy storage in general, is the use of small, efficient auxiliary power units (APUs) to supply base power needs, supplemented by a main internal combustion engine providing high power.

Fuel cells or combustion engines (perhaps innovative linear, or rotary types) are suitable as an auxiliary power unit. Fuel cell systems as APUs require significant reduction in cost, weight and size, both of the stack itself and also for the fuel and air supply systems and the thermal management. Reforming of liquid fuels, or feasible hydrogen storage will be required. The reformer adds complexity and costs to the fuel cell system. Reformers for gasoline and Diesel are in a very early technological stage and a lot of research is needed to guarantee the hydrogen generation in the transient operation in a vehicle.

Technology visions beyond 2020

It is likely that the “variable” combustion engine, with highly variable subsystems under the control of a sophisticated powertrain management system, will continue to evolve in combination with improved, partly renewably-sourced, fuels.
The Diesel homogeneous charge compression ignition (HCCI) and gasoline controlled auto ignition (CAI) combustion processes, which have many similarities, may merge along with fuel properties into a "combined combustion system". In combination with the improved aftertreatment technologies, "zero impact" emission levels will be reached. 

In combination with advanced transmissions (probably dual-clutch or infinitely variable type) with high efficiency and flexibility, the energy consumption of vehicle power trains will be reduced further. Together with new materials and new design rules, a specific engine power of 150 kW/litre for gasoline and 75 kW/litre for Diesel engines can be expected. Electric hybridisation may be commonplace beyond 2020, both as an efficiency improvement enabler and provider of extra power needed for x-by-wire systems. Significant improvements and possibly a breakthrough in energy storage technology are required to overcome the major hurdle, provided that the research effort has been supported in the intervening years. Thus, if there is more CO₂-free electrical energy available from renewable or nuclear sources, battery-electric vehicles have to be discussed again. Pure battery vehicles already exist in niche applications and have been under research for decades. The main research field is consequently the battery, which has to be improved regarding energy and power density, reliability as well as with regard to cost reduction. For the electric powertrain itself new, more cost-effective and material-saving production methods for electric motors are an issue.

Fuel cell vehicles running on hydrogen have the advantage of being real zero-emission vehicles. Technologically, they can be considered as electric vehicles in which the battery has been replaced or supplemented by a fuel cell. In many applications a secondary, conventional battery will be needed for start-up and for conditioning of the fuel cell. Fuel cell stacks show best efficiency at part load, which is favourable for inner city driving. The stack is only one part of the fuel cell power train efficiency - it is necessary to take into account the air system, the heat management, the cabin heating/cooling, the cooled climate start (freezing of combustion water in the cell), the electric machine and the power converter, which decrease the overall powertrain efficiency. On top of this, the efficiency of the reformer (if used) and well-to-tank efficiency of fuel production have to be considered. Combining these factors, today's fuel cell vehicles using non-renewable hydrogen do not offer an improvement in well-to-wheels efficiency over the best IC-engine hybrid technologies. As the fuel cell technology is relatively new, high basic and applied research efforts are necessary to reduce production cost, increase overall energy efficiency and to reduce size and weight. To overcome these problems, real breakthroughs in the stack and fuel storage technology are necessary. The market chances of fuel cell vehicles are generally assessed more pessimistically than a few years ago expecting it mainly in niche applications also for the period after 2020.

To summarise the findings about powertrain technologies:

- IC-engines will be the powertrain backbone for the time beyond 2020
- IC-engines with one combined combustion system will come to the market
- Fully-variable engine concepts and their control will be state-of-the-art
- Hybrid (IC-electric) vehicles needing advanced control and system integration will penetrate the market
- Fuel Cell automotive applications will start from APU and then develop to prime mover applications
Active and passive safety: objectives and identified breakthrough technologies

Passive safety:
In spite of the significant improvements in vehicle safety which were achieved in the past 25 years, the current number of deaths and injuries plus all the associated social and economic costs must still be regarded as unacceptable. The feasibility of a ‘maximum-safety-vehicle’ needs to be investigated. New ways for safe transportation of children need to be developed, as well as systems for automatic restraint of luggageOBJECTS. A particular challenge in the field of vehicle safety is the trend towards smaller and lighter, more fuel-efficient vehicles and presumably the increased usage of electrical or hybrid vehicles for environmental reasons. An optimal combination of various technologies is required to offer passengers of these lighter vehicles a similar level of protection to that of conventional vehicles. General strategies to improve passive safety aspects are the influence on crash conditions, for instance by improving the environment (e.g. deformable guide rails), by improving vehicle crashworthiness (e.g. energy absorption), by influencing the impact motion of the human (e.g. seatbelt). New safety concepts such as so-called ‘intelligent’ or ‘smart’ restraint systems that adapt to the actual accident condition and to the particular occupant shall be able to protect car occupants better than current restraint systems. These systems shall require information obtained from sensors in the car and shall be able to intelligently manage the levels of restraining forces and how they are applied to the occupant. Prerequisites for further research are comprehensive accident statistics and investigations (e.g. creation of an international accident database). Apart from these technologies a further potential to significantly improve road safety lies in the development of education and training programmes for drivers.

Active safety:
Active safety embraces a number of areas from pre-crash warning and prevention to post-crash rescue management. Active safety as a production technology is very much in its infancy, with huge potential to create an impact on the harmful effects of road traffic accidents, both to occupants, pedestrians and third parties. The ultimate goal is often seen as an "accident-proof vehicle", which informs the driver of hazards and intervenes where necessary to avoid disaster. Linked to this topic is the issue of "driver support". Again this is a complex issue, starting with simple provision of information (navigation, route planning, avoidance of traffic), and then assisting or taking over handling functions from the driver (smart cruise control, lane following, road trains, and ultimately full self driving), a highly attractive proposition but facing a major hurdle of public acceptance and legal problems to overcome.

Short term research needs (~2010) are generally aimed at making the first active safety technologies robust, affordable and desirable. Medium term needs (~2020) are aimed at the introduction of desirable and affordable partially-autonomous vehicles with a high degree of integrated on-board intelligence. For the long term (+2030) the focus is on a successful transition to autonomous systems.

So the research topics for the envisaged period will be:

- Adaptive passive safety systems to assure safety for all types of passengers
- Active safety and intelligent vehicle systems - sensing, processing, networking
- Road-vehicle interactions
- Advanced driver assistance
- X-by wire technology allowing autonomous driving
Exterior and interior noise: objectives and identified breakthrough technologies

In terms of noise-reduction, FUTURE focused only vehicle technologies and not the whole holistic approach (including infrastructure, landscape planning, traffic management, etc.) The main technologies for the reduction of exterior noise have to reflect the priority ranking of the noise reduction topics: tyres, engine, exhaust and intake system and vehicle driving condition. For the further development of quieter tyres, a still deeper understanding of the noise generation mechanism is required despite existing knowledge and the ongoing research activities in this field. For the reduction of engine noise, one approach will be the full encapsulation of the engine (and transmission) itself or the engine bay of the vehicle. In both cases, an improved, sophisticated thermal control of the encapsulated volume will be essential to overcome any heat balancing problems. Further research needed to improve the control of combustion noise also under critical operating conditions such as cold start and warm-up phases, low idle, part-load conditions and high-load accelerations.

Within the field of vehicle exterior noise, orifice noise emissions from exhaust and intake systems are suitable for active noise control applications which might also be applicable to tyre noise. However, technologies providing efficient, reliable, producible and low-cost solutions for this field of application are still to be developed. The same applies for highly damped materials for load-carrying structures of engines, gearboxes and other vehicle components, alternative powertrain systems (without internal combustion engine) and intelligent management of engine and transmission for optimum and quiet operation. The further development of simulation techniques has to be part of future research activities in order to simulate physical processes more precisely and to increase the accuracy of predicted results. Improved simulation approaches are needed for the noise emission behaviour of the whole vehicle and relevant noise sources as well as for the noise and vibration behaviour of individual vehicle components. Research activities must be continued to develop new or improved test methods for the vehicle noise emission which reflect the real traffic situations in a much better way than realised today.

The issue of interior noise (and vibration) in road vehicles is very different from exterior noise in the sense that the main driving forces are not coming from legislation but from customer as well as manufacturer requirements. Interior noise aspects cannot be seen independently from other critical vehicle performances such as passive safety, vehicle handling, fuel consumption, thermal comfort, durability, communication and entertainment. With some of these parameters, this leads to conflicting design requirements. The main sources for interior noise are combustion, rolling and aerodynamic noise. Passive noise reduction involves many of the solutions already discussed with exterior noise, such as local noise shielding, advanced mount and innovative high-damping low-weight materials, quieter tyres etc. However it will be difficult to make major breakthroughs, especially on the level of “brand” sound design purely with such material solutions. Active noise technology has been researched and developed for more than a decade but so far the successful applications in vehicle design remain very limited. Advances on the level of materials for realising low-cost, high-performance and reliable actuator solutions, or even solutions integrated with the structural material into smart components, have great potential. Especially in the context of low-weight designs, active control may be the only solution to achieve acceptable noise behaviour. And in view of sound “branding”, active noise control offers a direct solution, allowing adaptable target functions to be implemented. The real challenge to carry out the required performance in a design cycle of less than 18 or 24 months requires drastic front-loading of the functional performance engineering process at the earliest design stages and a link to multi-disciplinary optimisation, which is not yet possible at the required accuracy and speed.
In summary, the most important areas of research will be:

- Silent tyres, road surface/tyre interaction
- New damping materials
- Active noise control
- Holistic approaches to traffic noise control

### Vehicle structure: objectives and identified breakthrough technologies

As vehicle weight has increased in recent years through the addition of many comfort and safety devices, in the future, weight reduction will be one of the most important issues.

All investigations show a direct link between vehicle weight and fuel consumption. Reducing vehicle weight, in any component or in total, is a strictly accumulative measure and always advantageous. Lightweight design can be achieved with different methods focusing on material usage and vehicle construction. The possibilities seen here must be approached from a holistic point of view. So combining different materials such as steel, aluminium and plastics with different body structures such as frame structures and shell structures needs to be evaluated, taking into consideration all relevant criteria. This means that besides the technical realisation, life cycle analysis will also have to be considered. Major technology areas are the realisation of smaller and more flexible vehicle concepts, the downsizing of all possible vehicle equipment, X-by-wire systems without mechanical backup to optimise package and weight at the same time, connecting and joining technologies in order to support body modules and multi-material design, and frame structures to support high modularity. Furthermore, the design process particularly needs to take into consideration at an early stage all requirements for recycling and improved dismantling technology. Post-processing for automotive shredder residue, adequate separation of different material types, the quality of recycled materials (comparable properties to new materials) are also issues. It is very important that decision makers are aware of one contradiction: the need to decrease vehicle weight with high performance materials which are usually not easy to recycle and the desired recycling quotas put on standard vehicles. A further prerequisite is that compromises in vehicle safety are not permissible.

Concluding, the most important research areas for vehicle structures are:

- Lightweight vehicle concepts
- Advanced multi-material vehicle structures
- New improved recycling methods

### Conclusions

Road transport technology has historically followed an evolutionary path, with many small steps combining to achieve significant and remarkable progress in reliability, safety, comfort, performance and environmental impact. This study concludes that this evolutionary approach, promoted to a “fast track” pace by strategically-focussed research, is well placed to meet the challenges of 2020 and beyond.

In the year 2020 and beyond we will have increased plurality of different propulsion technologies, but internal combustion engines will still be dominant. Most of all, independent from future scenarios on propulsion systems or fuels, it will be essential to save energy wherever possible.
Adequate research investment in the evolution of proven powertrain technology, based on internal combustion engines and conventionally-based fuels, guarantees global competitiveness of the European Automotive industry together with reduced energy dependency and improved environment. Research in completely new technologies is an additional must to promote sustainable advances in environment and energy security. Apart from the needed technical research, only improvements in terms of production, distribution and storage will make fuel cell and hydrogen based powertrain systems a competitive alternative. Vehicle weight is crucial for both vehicle weight is crucial for both fuel consumption and safety issues. Intensive research for new materials and production processes including recycling technologies is needed. Active and passive safety show great research potential, and require an integrated approach to deliver the best results. The same applies regarding noise: future vehicle technologies focus on road/tyre interaction, the engine, exhaust and intake system and the vehicle driving condition. Advanced simulation techniques are necessary to establish basic detailed knowledge in order to simulate physical processes more precisely and to increase the accuracy of predicted results. A holistic system approach which integrates the concerned stakeholders (infrastructure, vehicle manufacturers, research providers etc.) and the concerned scientific areas (materials, electronics, telematics etc.) will lead to remarkable technological progress. The integration of specific and generic technologies as well as development tools and platforms will lead to better, faster and cheaper research results, finally crucially strengthening the sustainable development of the European road transport sector.

To summarise:

- Research investment is necessary in the evolution of powertrain technology, based on IC engines and conventional-based fuels, thus guaranteeing global competitiveness of European Automotive industry together with reduced energy dependency and improved environment.

- Research in completely new technologies is an additional must to promote sustainable advances in environment and energy security.

- Importance of energy consumption reduction measures needs to be regarded as very high, independent from future scenarios on propulsion systems or fuels.

- A holistic system approach integrating specific and generic technologies as well as development tools & platforms will lead to better, faster and cheaper research results.
2 INTRODUCTION

2.1 Background of FURORE

Individual traffic will remain the major pillar of European surface transport in the next 30 to 50 years. A further increase of individual mobility can be predicted, as a consequence of continuous economic growth and the enlargement of the European Community. Individual mobility is also ranking very high in the evaluation of life quality and has turned into a need for the growth of economy. Nevertheless a more sensitive use of mobility by individuals and transport organisations needs to be encouraged, leading to a balanced modal mix of transport means.

To compensate the negative impact of individual road traffic increase on the environment, energy resources, as well as individual health and safety, an integrated research approach for future vehicles is essential. The introduction of new technologies for vehicles and fuels will reduce the environmental concern. It is the responsibility of the EU Commission to encourage and support research and development of more efficient, less polluting and safer vehicles. The most important instruments to do so are the European Framework Programmes for RTD.

Guiding this research in a sensitive manner towards future needs of the society requires a good understanding of the many factors which enable or prohibit the introduction of new road transport technologies. Legislation and policy makers need different independent sources of information so that they can overview all the changes in global environment which may be possible by the introduction of new technologies. The breakthrough of a new technology needs many favourable factors and an evolution will have better chances than any revolutionary approach. Too little attention is sometimes devoted to the boundaries such as infrastructure needed and other essential aspects. On the other hand the opportunities of completely new technologies must not be underestimated and it is necessary to be open towards different possible approaches which may lead to the clearly defined objectives, even if they are very ambitious and risky and, as a consequence, to adequately invest in research & development.

These technologies have the potential for a sustainable improvement of the environmental, economic and social situation in the European Community and therefore need to be considered well in a good planning process. Road transport research will play a major role in achieving two of the most ambitious goals of the European Commissions research policy by 2010: Increase of R&D investment to 3% of GDP and to “establish Europe as the most competitive and dynamic knowledge-based economy in the world”.

2.2 Objectives and scope of FURORE technology R&D roadmap

The FURORE Technology Roadmap was initiated by EARPA - the European Automotive Research Partners Association and funded by the European Commission/DG Research within the 5th Framework Programme.

The nature of FURORE thematic network members enables a unique insight into future technologies. By combining a core team of independent research and technology organisations with representation from universities, national research institutions, component suppliers and automotive manufacturers (all of them currently participating in EU Framework Programmes), an independent and realistic view of the technology future can be achieved.

Automotive R&D has today become a more international, collaborative effort within and between research organisations, universities and industry. The present roadmap is a proof that improved strategic collaboration between research
organisations is possible. Co-ordinated and focussed activities of research networks can be performed successfully and synergies between organisations with different focus can be used.

Besides this technology roadmap it is the aim of the FURORE Network to establish an integrated, long-term research strategy for the European automotive sector, which is based on the specific point of view of leading engineering companies, RTD organisations and Universities and should complement the more product-oriented scenarios of OEMs.

The road vehicle of the future will obviously incorporate an array of technologies, but in consideration of the still uncertain basis of social and environmental conditions, the study tries to answer how and which technology routes should be followed to solve problems and conflicts faced by society in terms of energy consumption, emissions and safety, to meet the needs of future mobility.

### 2.3 Methodology and limitations

The scope of FURORE’s Automotive R&D Technology Roadmap document was to consolidate the specialist knowledge and the opinions of the participating organisations via several dedicated workshops, voting surveys among FURORE-experts and a comprehensive literature analysis for future transport scenarios and systems. The topics studied were: energy & fuels (incl. conventional and alternative fuels), powertrain technologies (today’s and future systems as well as emission & aftertreatment), and complete vehicle aspects (incl. vehicle structure, safety and noise). The topics were analysed according to their current technology status, R&D trends up to 2020 and technology visions beyond 2020. A review was made of the potential technologies which can fulfil these objectives, hurdles and barriers that might hinder the introduction of the potential technologies and finally the research demand needed to overcome major technological hurdles to successfully achieve the 2020-targets.

Right at the start, a grouping of the various vehicle classes was decided. Regarding the ACEA auto data of new registered vehicle types in the 15 countries of the European Community in 2001, the following classes comprise most of the European vehicle market:

- **Passenger cars**: 13,761,894 new registrations
- **Light commercial vehicles up to 3,5t (including mini-buses)**: 1,735,106 new registrations
- **Commercial vehicles over 3,5 t (including buses & coaches)**: 360,130 new registrations

Due to a strong overlap in a lot of issues it was decided to perform the enquiries and workshops according to two different categories:

1. **Passenger cars including class M1**
2. **Trucks and Buses including classes M2, M3, Nx**

Motorcycles were not selected due to their low importance in terms of sales figures and usage frequency. In comparison to the above-listed vehicles their environmental impact was considered as less important.
The outcome has been structured in two major parts, a strategic part which provides the overview and key messages and a technical part which provides the technological background by describing the technologies and mentioning their pros and cons. In the technical part the contributors tried to structure their chapters into the following sub-items:

- Description of the state-of-art or current technology status
- Targets, which shall be achieved in the special fields in the year 2020 and beyond
- Potential technologies which can fulfil the targets
- Hurdles and barriers which might hinder the introduction of the potential technologies
- Research demand needed to overcome major technological hurdles

As the future is unpredictable, evaluating technology options and their probability to find their way into large-scale markets in a study like this is a delicate matter. It is quite certain that technologies today on the market will develop further and some prototypes of today will gain maturity and might be introduced in a shorter term than expected in this study. All participants tried to avoid slipping into excessive optimism. From this, the study remains conservative in some areas and very cautious in its assumptions.

Technologies might change in unforeseeable ways in the next 30 years, therefore a study like this, undertaken in five, ten or more years might look very different. This calls for a regular update in defined periods.
In order to construct a Technology Roadmap it is necessary to understand both the status of technology at the start of the roadmap, and the factors in place at that time (such as Government policy and buyer / user demands) which will be driving further technological change. The FURORE roadmap looks at the year 2020 and beyond, a relatively ambitious timescale for technology forecasting. In order to facilitate this, a robust view of the period up to 2020 is required. In this section a view of scenarios up to 2020 and policy which may come into place in that timescale is examined, based upon an extensive review of literature [References 3.1 to 3.77] and a survey of member expertise and opinion. This information is used to suggest FURORE research targets for up to 2020 and beyond.

3.1 Summary of current EU, member state and global policy

3.1.1 EU Policy

EU policy for road transport is based upon principles laid down in the White Paper “European transport policy for 2010: time to decide” [3.9], published in 2001. The authors of this policy acknowledge that some areas are ambitious, but argue that the “status quo” alternative is less attractive. The White Paper is the first stage of a long-term strategy which it is claimed will lead, over the next 30 years, to a sustainable transport system. Key elements of the strategy proposed which are relevant to FURORE are:

- Shifting the balance between modes of transport, including re-vitalising the railways, adapting the maritime and inland waterway transport system, controlling the growth in air transport, improving quality in the road sector and linking up modes of transport
- Introduction of 20% "substitute" fuels for road transport by 2020, as a measure to address global warming and security of energy supply. Policy on exhaust emissions and CO₂ from conventionally-fuelled vehicles is not discussed - however, hybrid vehicles, compressed natural gas fuel (CNG) and Hydrogen - Fuel Cell vehicles are all specifically noted as showing future promise
- Halving the annual road transport death toll by 2010. Speed management systems, electronic “active safety” aids, vehicle front-end design and smart occupant protection (airbags) are all mentioned as promising technologies. Europe-wide agreements on electronic protocols, road-sign design and penalties for dangerous driving are suggested as being necessary

Outcomes will be monitored and a review in 2005 will assess whether targets are being met or whether adjustments need to be made.

Beyond the White Paper, the most significant element of EU policy is the voluntary agreement on CO₂ emission with the Association des Constructeurs Européens d’Automobiles (ACEA).

These policies have been backed up by recent calls for co-funded research consortia under the “Framework 6” program [3.59]. A brief abstract of these calls is included in the Appendix.

In summary, these calls indicate support for research in the following key areas relevant to FURORE:

- Fuels - alternatives, production, storage, distribution, use
- Re-balancing and integrating different transport modes
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- Increasing road safety - Active & Passive, Advanced Sensors and Communication Systems; integrating on-board safety systems that assist the driver; distributed intelligent agents, communications, positioning and mapping, and their integration; vehicle information infrastructure for safety and efficiency
- New technologies and concepts - Future generation of clean and economical engines; alternative and renewable fuels; integrating near-zero emission propulsion systems such as fuel cells; holistic noise abatement solutions; measurement/sensing technologies for optimum vehicle/infrastructure operation; innovative urban transport of persons & goods; analysis of future energy supply & transport scenarios
- Advanced design, production, maintenance and recycling techniques
- Micro and Nano Systems - Integrating Sensing, Actuating and Processing devices; Improving interaction between person and machine; adding functionality and reducing cost; demonstrating feasibility of large area systems integration (for example telematics)
* “Embedded Systems” - Embedded network systems for sensing and control; fault-adaptive control and management

3.1.2 EU Member States Policy

A summary of available information on member state national policy is given in the Appendix. Each member state has its own set of policies, broadly aligned to EU goals but with different implementation detail. Typical elements include:

- National targets for air quality, CO₂ reduction, noise levels, safety improvement and congestion abatement
- Tax and purchase incentives for clean and low CO₂ vehicles, vehicle conversions, and fuels, to a varying degree
- User concessions for “green” vehicles, such as exemption from traffic restrictions and charges, in certain places
- National research schemes which co-fund collaborative technology programs in a similar manner to FP6 (and regulated by EU State Aid rules)
- Government promotion of industry partnerships to bring about the use of cleaner or safer technologies
- Non-vehicle safety programs including training and local infrastructure development
- Joint programmes with other nations, usually within one region, and not necessarily restricted to the EU
- Active encouragement of public transport, cycling and alternative goods carrying modes, coupled with a variety of road-toll methods - some fixed tolls, some dependent on congestion level

3.1.3 Other Global Policy

A summary of available information on other non-EU national policies is also given in the Appendix. Again there is significant variation: there are many similarities to EU policy, and some key differences:

- Safety, congestion, noise and air quality are almost universally the subject of some kind of policy, with similar goals. Developing nations generally aspire to “catch up” with the environmental attainments of developed nations
- CO₂ abatement is the biggest source of difference, with some nations, notably the US federal government, not currently enforcing or promoting controls on road transport CO₂. There are also regional differences of philosophy as to whether CO₂ reduction is obtained by vehicle technology or alternative fuels
3.2 FURORE View on future Road Transport scenarios

3.2.1 Methodology

There is already a large quantity of public-domain information on this topic, particularly for the period up to 2020 [refs 3.1 to 3.77]. The FURORE project undertook a Literature Study to collate key issues from 77 public-domain reports deemed to be of greatest relevance. These reports were reviewed by specialists from within the FURORE team, and key information was collected on the following topics:

- A brief assessment of the quality of the data: impartiality, relevance to mainstream road transport, supporting analysis & expert input
- Road transport policy and future scenarios: traffic growth, vehicle usage, transport policy, global politics
- Powertrain: Environmental & other legislation, technology trends, penetration of new technologies, energy supply, alternative energy & propulsion
- Vehicle: Safety, Environmental and other legislation, technology trends, materials and recycling, user comfort and convenience, vehicle / environment interaction and information exchange

The second significant resource available to the project was the knowledge of FURORE project partners, many of whom are involved in Technology Roadmapping within their own organisations. To capture this knowledge a “Voting Survey” was conducted at two FURORE workshops, in which participants’ opinions for the year 2015-2020 were collected on these topics via a questionnaire of over 100 questions. The detailed results of the voting survey are available on the FURORE Internet site.

Finally, suggested research targets were created by FURORE members at project workshops, based on discussion of this information. It should be noted that any future targets suggested below are for the guidance of research, and do not constitute a recommendation for legislation or a suggestion that achievement of the target will be guaranteed feasible.

3.2.2 Targets, Policy & Scenarios for 2015-2020

Discussion of Targets, Policy and Scenarios in the Literature Study was found to relate to seven key areas:

- Fuels: Their supply, alternatives, taxation policy
- CO2: Global warming, fossil fuel usage
- Emissions: Exhaust and other sources, legislation
- Safety: Occupants, Pedestrians, Legislation
- Traffic: Growth in volume, congestion, policy, intermodality
- Noise: Vehicle, Road surface, vehicle technology vs local measures
- Recycling: Materials, future legislation

The overview given below is based upon the Literature Study, Voting Survey and other appropriate sources of information.
3.2.2.1 Fuels and energy supply

The future of energy supply has been the topic of much discussion in recent literature [3.4, 3.5, 3.7, 3.10, 3.11, 3.12, 3.21, 3.22, 3.24, 3.25, 3.26, 3.30, 3.35, 3.39, 3.47, 3.60]. Much attention has been given to the use of alternative fuels, with the aims of achieving more sustainable transport via reduced greenhouse gas emissions (dominated by CO₂), and reduced urban pollution. The EU has set targets for the introduction of alternative fuels [9]:

- Bio-fuel usage in each member state rising to 6% by 2010
- 20% usage of “substitute fuels” by 2020
- Tax exemption proposed for hydrogen, biofuels

Figure 3.2 below compares proposed targets for alternative fuel use, which indicate a clear consensus for rising penetration of alternative fuels.

Alternative Fuels which could account for this usage include:

**Biofuels** - fuels manufactured from biomass via extraction of natural oils, or fermentation. These may be used either on their own or blended with fossil fuels

**Synfuels** - liquid fuels manufactured from natural gas or similar

**Natural Gas** - consisting mostly of Methane, extracted from many worldwide locations. Used either compressed (CNG) or liquefied (LNG) on the vehicle

**Liquefied Petroleum Gas** (LPG) - extracted from crude oil either directly as a gas or by refining

**Methanol** - manufactured from Natural Gas or as a biofuel

**Hydrogen** - manufactured from Natural Gas or by electrolysis

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**Figure 3.2:** Targets for alternative fuel usage
The consensus view of FURORE members (Appendix), along with that of EUCAR and others in the literature, is that liquid fossil fuels - Gasoline and Diesel, will remain dominant in 2015-20, as shown in Table 3.1 below:

<table>
<thead>
<tr>
<th></th>
<th>Gasoline</th>
<th>Diesel</th>
<th>CNG/LNG</th>
<th>LPG</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>FURORE - Car</td>
<td>40%</td>
<td>50%</td>
<td>5%</td>
<td>4%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>FURORE - Truck</td>
<td>-</td>
<td>96%</td>
<td>3%</td>
<td>-</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>FURORE - Bus</td>
<td>-</td>
<td>90%</td>
<td>8%</td>
<td>-</td>
<td>2%</td>
</tr>
<tr>
<td>EUCAR - Car</td>
<td>40%</td>
<td>51%</td>
<td>8%</td>
<td>-</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

Table 3.1: FURORE and EUCAR views on future road transport fuels for 2015-2020

It is likely then that the majority of the growth in alternative fuels will come from the use of Biofuels and Synfuels, probably blended into the standard fuel supply to optimise its properties for lower emissions and to meet the requirements of new generation combustion systems. However it is also worth noting that the FURORE members, many of whom would benefit from the engineering effort required to prepare for alternative fuels, believed that the EU’s 20% substitute fuels target may not be met.

Looking forward from the 2015-2020 period into the future, it is likely that there will be significant debate at this time as to the preferred route to sustainable energy supply, and that the choices will be similar to today. Sustainably produced Hydrogen is seen by many, especially Governments, as the ultimate goal. Some sources predict that the period 2020-2030 is the timeframe in which Fuel Cell technology (which requires Hydrogen fuel either directly or via a reformer) is likely to be cost-competitive with advanced conventional vehicles [3.52], which will add a new dimension to the fuel supply debate. Conventional and alternative powertrain technologies are discussed further in section 4.

### 3.2.2.2 CO₂ and Greenhouse Gases

In recent years, the topic of greenhouse gas (GHG) emissions from road transport has been the subject of much discussion. The primary source of GHG emission from road transport is the gas Carbon Dioxide (CO₂), produced by the combustion of fossil fuels. Road transport in Europe accounts for an estimated 20% of total manmade CO₂ emissions [3.21].

The primary targets for CO₂ reduction are those agreed between the Association des Constructeurs Européens d’Automobiles (ACEA) and the Commission of the European Communities (CEC). This voluntary agreement applies only to passenger cars (“class M” vehicles) and stipulates a new car fleet average of 140 g/km by 2008, with a possible extension to 120 g/km by 2012 [3.53].

ACEA members have made significant progress towards meeting the 140g/km target [3.53], as shown in Figure 3.3 below. Significant factors in this achievement are:

- Over the period shown, Direct Injection Diesel engines have replaced Indirect Injection types which were significantly less efficient. The reduction in Diesel vehicle CO₂ is due mainly to this factor
Diesel penetration has also grown, from less than 30% to 40% in 2001. This shift has had a favourable impact on the fleet average.

Diesel penetration has been very high for larger vehicles, with some manufacturers reporting penetration of up to 80% for some markets in the "E" segment (luxury car). This means that the "average" Gasoline car is now a smaller vehicle with lower CO₂.

The pressure for lower CO₂ emissions is becoming similar in many other parts of the world, although Europe appears to be leading the trend via the ACEA agreement and high fuel taxation. Of significant note are:

- Political discussion in both California and Canada, indicating commitment to CO₂ reduction. Targets and timescales are not yet known, but if these commitments are confirmed they may lead to targets being set for circa 2010 onward.
- A variety of local initiatives in other nations, specifically in the Asia / Pacific region.

In the USA, legislation for reduction in fuel consumption has existed for some time in the form of the Corporate Average Fuel Economy (CAFÉ) scheme. The CAFÉ figure is calculated as a new car fleet average, but with a sophisticated system of "credits" for selling zero or near zero emission vehicles. However in terms of reducing CO₂ emissions the CAFÉ scheme has been criticised for three reasons:

- The legislated limits have been static for most of the past decade, and recent political debate suggests that they will remain so until the end of this decade (Figure 3.4 below, and (3.54))
- The legislation has a separate, less demanding category for "trucks" - meaning pick-ups, 4×4 sport-utility vehicles (SLVs), and vans. These have risen in popularity and now account for nearly half of all private vehicle sales in the USA (Figure 3.4 below).
3 FUTURE SCENARIOS

- The scale of fines for failure to achieve the target CAFÉ figures is such that paying the fine is considered cheaper than developing new technology, especially for lower sales volumes. While the indigenous US manufacturers generally meet the limits, imported brands usually do not.

**Figure 3.4: US C.A.F.E. trends [3.54]**

Due to the strong influence of politics, it is impossible to predict a far-future trend for new car fleet average CO₂. However a possible scenario can be indicated by the following, as shown in figure 3.5 below:

- The ACEA target of 140g/km by 2008 [3.53]
- The second, suggested ACEA target of 120 g/km by 2012 [3.53]
- The UK Foresight target of "10% reduction on 90g/km" by 2020 [3.3]
- Other public domain targets - specifically those stated by the German ministry of traffic [3.16] and environment agency UBA [3.11]
- The FURORE members’ opinion (Appendix), which indicates an achievement of around 100 g/km fleet average by 2015-20
- The FURORE WP3 workshop, at which participants suggested targets of 95 g/km for 2020, and 80 g/km for 2030

The equivalent trend for other types of vehicle - delivery vans, buses and trucks - deserves mention. Currently, operating costs are considered sufficient incentive for technologies that reduce CO₂ emission. However, it is entirely possible that similar incentives and agreements to those for passenger cars could be brought into effect, and the opinion of FURORE members is that this is probable (Appendix). The most significant near-term CO₂ reductions can be expected in vehicles with stop/start duty cycles - delivery vans and buses - where in principle, technologies such as Hybridisation can have a similar or greater impact to that for passenger cars on the New European Driving Cycle (NEDC) test. Here, FURORE suggests a target of 40% reduction by 2020. Larger, long distance trucks are reliant on improvements in steady-state
efficiency only, and are likely to see less reduction in CO$_2$ until alternative, low or zero CO$_2$ fuels become widely used. A reduction of 10% is suggested for 2020.

Further, a detailed discussion of low CO$_2$ technology is given in section 4.

### 3.2.2.3 Emissions

Emissions are the result of “imperfections” in the combustion process and evaporation of fuel or oil vapour from the powertrain and its fuel tank. All are considered in some way harmful to health if present in sufficient quantity. Legislation governing the quantity of these other emissions has been in place in Europe for over a decade, with incremental reductions in the quantities permitted. These emissions are:

- CO  Carbon Monoxide
- HC  Hydrocarbons
- NO$_x$  Oxides of Nitrogen
- PM  Particulate matter

The quantity of these emissions produced is not directly proportional to the amount of fuel burned, as other factors have a far greater influence, namely:

- The specification of the engine’s combustion system - fuel/air mixing, the ratio of air to fuel, and the completeness and temperature of burning in the cylinder
- The specification of emission control and “aftertreatment” devices - catalytic converters, particulate traps, evaporative canisters etc - fitted to the vehicle
- Vehicle-related factors such as its weight, gear ratios, nature of usage, etc
The introduction of emission legislation over the past decade is already impacting significantly on the total emissions from road transport, and is expected to continue to do so. The data shown in Figure 3.6 is from the Auto-Oil II project [3.21], and predicts (for the EU) reductions in all the legislated emission types to less than 20% of 1990 levels by 2020, despite significant traffic growth.

Similar trends are projected in the UK (figure 3.7 and [3.6]), these predictions also indicate:

- A greater reduction in NOx from cars than trucks over the period 1990-2010 (figure 3.7), suggesting that NOx legislation for trucks will continue to become more stringent after a plateau has been reached for cars
- A short term growth in PM from Diesel cars over the same period (due to growth in numbers), but this issue being addressed thereafter
The implication of this is that, while there will probably remain a need to address certain emission issues, there will be a diminishing return from continuing general lowering of permitted emission levels. In view of the negative impact of emission control equipment on fuel economy and CO₂, it is important that future emission targets are based on objective understanding of the impact of these emissions on human health and the environment.

For the purposes of this study, research targets for emission levels have been suggested (Table 3.2) based upon:

- Results of the FURORE WP3 workshops
- For comparison, the FURORE voting survey (see: www.furore-network.com and Table 3.3)
- For comparison, targets from the UK “Foresight Vehicle” program ([3.3], Table 3.4)

### FUTURE SCENARIOS

#### Table 3.2: FURORE suggested emission targets for 2020 and beyond

<table>
<thead>
<tr>
<th></th>
<th>Car</th>
<th>Truck &amp; Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>50% EU IV gasoline</td>
<td>25% EU IV</td>
</tr>
<tr>
<td>HC</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CO</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PM</td>
<td>0.01 g/km (40% EU IV Diesel)</td>
<td>0.01-0.02 g/kWh (50% EU IV)</td>
</tr>
<tr>
<td>PM &lt;0.1 micron</td>
<td>10% EURO IV Gasoline</td>
<td>-</td>
</tr>
<tr>
<td>Other</td>
<td>Realistic driving cycle and lifetime assessment to be included</td>
<td>Consider other emissions: H₂S, Aldehydes, NH₃, CH₄ Emission requirements may be specified by local authorities</td>
</tr>
</tbody>
</table>

#### Table 3.3: FURORE Voting results - for comparison, referring to 2015-2020

<table>
<thead>
<tr>
<th></th>
<th>Car</th>
<th>Truck &amp; Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>25 - 50% EU IV Gasoline</td>
<td>25% EU IV</td>
</tr>
<tr>
<td>HC</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CO</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PM</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Other</td>
<td>Further legislation in certain sensitive cities</td>
<td>Other legislation beyond this period</td>
</tr>
<tr>
<td></td>
<td>There will be further emission legislation beyond this period</td>
<td>There may be legislative measures for environmental impact of manufacture as well as use</td>
</tr>
</tbody>
</table>


3 FUTURE SCENARIOS

<table>
<thead>
<tr>
<th></th>
<th>Car</th>
<th>Truck &amp; Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>50% EU IV Gasoline</td>
<td>Not explicitly stated</td>
</tr>
<tr>
<td>HC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td>20% EU IV Diesel</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>PM 0.1 to be below 20% of a typical EU IV Gasoline vehicle</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4: UK Foresight targets for 2020 [3.3]

There is reasonable consensus that by around 2020, passenger car legislation will have reached a plateau at around half EURO IV Gasoline levels, while Truck legislation will remain the subject of further aggressive reduction. To achieve this at reasonable cost without compromising fuel economy is a significant challenge.

Legislation is likely to be introduced in stages, as illustrated in Figure 3.8 below. Further, detailed discussion of emission reduction technology is given in section 4.

![Figure 3.8: Possible introduction of emission legislation. It is likely that Gasoline vehicles will reach a plateau of legislation first, Heavy Duty Diesels last](image)

**3.2.2.4 Road Safety**

Improvements in road safety are a major concern of governments worldwide [3.9, 3.14]. The current annual road transport death-toll is 40,000 in the EU, and a similar number in the USA. In both regions, the stated desire is to halve this figure by 2010 [3.9, 3.14].
Data from the USA suggests that smaller, lighter vehicles result in a higher occupant fatality rate ([3.55], and figure 3.9 below). This is perhaps unsurprising, as the smallest vehicles will more often be in collision with a larger vehicle. However, this data suggests that initiatives to encourage low fuel consumption via light weight structures may struggle to gain public acceptance on the grounds of perceived safety.

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Road deaths 50% today’s level, all classes of road user to enjoy equal improvement, similar reduction in non-fatal injuries and accidents. Warning systems reduce collisions and insurance costs, and are accepted by customers.</td>
</tr>
<tr>
<td>2020</td>
<td>Road deaths 25% today’s level. Lane control, vehicle-vehicle warning systems and truck road trains further reduce collisions and insurance costs.</td>
</tr>
<tr>
<td>2030</td>
<td>Autonomous driving enabled in selected conditions.</td>
</tr>
<tr>
<td>2050</td>
<td>Zero road deaths. Autonomous driving enabled in all conditions.</td>
</tr>
</tbody>
</table>

Table 3.5: Suggested FURORE safety targets
The EURO NCAP scheme has been influential in improving passenger car safety. The FURORE Voting exercise (Appendix) suggests that more stringent “maximum score” targets will be required for 2015-20, with the injury criteria (body impact force) for front and side impact being around 50% of today’s levels, and pedestrian impact criteria 50-75% of today. This exercise also suggested that similar assessment schemes will probably be introduced for trucks and buses. However, the Voting survey suggests that the targets for reducing deaths are ambitious, with a death toll of circa 60% of today’s level likely by 2015-20. Finally, this survey points out that significant gains can be achieved by improving the standards of all EU countries towards those of the best. Again, achievement of such reductions represents a significant challenge in active and passive safety engineering. These topics are discussed in section 4.

3.2.2.5 Traffic and Congestion

There are numerous predictions of future increases in traffic volume [3.3, 3.6, 3.9, 3.11, 3.16, 3.21]. In particular, freight traffic as a result of the accession of former Eastern bloc countries to the EU is forecast to increase dramatically. The data is compiled in Figure 3.10 below, indicating a general trend of circa 35% increase by 2020.

![Traffic Growth](image)

Figure 3.10: Forecasts of growth in traffic volume [3.3, 3.6, 3.9, 3.11, 3.16, 3.21]

These projections are confirmed by the Voting survey which suggests that projections of traffic growth are likely to be realised, that urban goods delivery enabled by Internet shopping will replace some personal travel, but that it is not certain that Internet business meetings will reduce business travel. While it is suggested that the Internet and IT advances will enable better, more integrated public transport, the results suggest that motorists will be encouraged to use it because of worsening traffic, not because of better public transport. Finally, it is probable that congestion will become a deciding electoral issue by 2015-20.
The consequences of this level of growth are likely to be:

- Increased journey times - perhaps +20% by 2030, +40% by 2050 if no action is taken [3.6]
- Increased costs to businesses and individuals - perhaps +140% by 2010 [3.9]
- Increased driver stress, risk of "road rage", and accident rates
- Increased pollution and fuel usage

Policy on controlling traffic growth and road-building is beyond the scope of this study. However, the following suggested targets relate to vehicle technologies which may assist in reducing the effects of increased traffic (Table 3.6):

<table>
<thead>
<tr>
<th>Year</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Network congestion management systems in place</td>
</tr>
<tr>
<td>2020</td>
<td>X-by-wire / telematic technology enables congestion and stress-free highway driving</td>
</tr>
<tr>
<td>2030</td>
<td>Autonomous driving and road trains reduce congestion</td>
</tr>
<tr>
<td>2050</td>
<td>Congestion-free driving enabled by technology?</td>
</tr>
</tbody>
</table>

Table 3.6: FUTURE targets for traffic management

In addition, measures to improve safety will of course reduce congestion caused by accidents, while other improvements in the environmental performance of the vehicle will counteract the effects of increasing traffic. However, congestion remains one area of future road transport that vehicle technology itself cannot properly address, and the targets suggested in Table 3.6 above will be impossible to achieve without significant action. This issue is certain to be top of the transport agenda by 2015-20.

3.2.2.6 Noise from road transport

Significant reductions in individual road vehicle noise, typically up to 3dB(A) every ten years, have been achieved over the last two decades when measured over a legislative test cycle. However, these improvements have not always been realised in terms of actual traffic noise [3.56], due to a combination of factors including traffic growth, real world conditions which differ from the legislated test, and the interaction between tyres and road surfaces. These issues are the subject of ongoing study by the CALM thematic network [3.56].

A review of the literature (Figure 3.11) suggests a continuing desire for traffic noise reduction at a similar rate of circa 3dB(A) per ten years [3.3, 3.18, 3.56]. However, most sources agree that achieving this via further per-vehicle legislation will be difficult or impossible [3.38, 3.56]. An integrated approach is called for, involving per-vehicle reductions (with heavy trucks likely to be subject to more stringent demands [3.3, 3.56]), optimising the road surface/tyre interaction, traffic management and local noise control measures such as noise-absorbing surfaces.

These views were also reflected in the Voting survey, which suggested that by 2015-20 there would probably be legislation for road surfaces relating to tyre noise, and that local action plans would probably be a major factor in noise control. Legislation for the noise properties of tyres as a stand-alone item was considered possible in this timeframe. A weighting of the votes (appendix) suggests a per-vehicle noise reduction of 6-7 dB(A) for cars, 8-10 dB(A) for trucks (a more
conservative 5dB(A) truck target was suggested at the WP3 Powertrain workshop). Exterior noise will still be the dominating noise issue in vehicle design (although comfort and refinement will remain a top priority for buyers, especially cars), and it is likely that yet further reductions will still be sought beyond 2020.

The significant future challenge here is the integration of noise policy to achieve overall benefit while achieving cost-effective solutions for vehicles and infrastructure.

3.2.2.7 Recycling

There is relatively little information on recycling in the literature studied, compared to other topics. Where mentioned [3.51], increasing use of recycling towards 100% is mentioned, with a suggestion of circa 95% by 2010-2020. Critical issues in this time-period will be cost-effectiveness, energy-effectiveness and the development of materials which can be used in “closed loops”.

The Voting survey (Appendix) suggests that between 80% and 90% recycling (by weight) will be achieved in 2015-20, reflecting the difficulty of moving towards 100%. It was also considered possible that the environmental impact of vehicle production may be assessed against legislation, the most likely mechanism for this being a “cradle to grave” life cycle metric.

Discussion at the WP4 Workshop suggested that a 95% recyclability target was reasonable for the period 2020-2040.
3.2.3. Influence of political climate

The prevailing political climate in Europe and the rest of the world will exert a strong influence on the pace of change and technology introduction discussed above, and hence on the attainability of the targets discussed above and summarised in section 3.3 below. The primary factor is the balance between concern for the environment and human living conditions, and concern for economic growth and industry profitability. As a general rule, the state of this balance dictates the pace at which new technologies are introduced, but does not influence their nature much. However, a secondary factor is often also influential, as illustrated in two examples below.

Figure 3.16 below indicates the influences which may impact upon low CO₂ technologies. Here, the primary factor is the degree of political pressure for change, at the possible expense of industry profitability. However, a strong secondary factor is the choice between using powertrain and vehicle technology to achieve CO₂ reduction, or mandating alternative fuels.

Likewise, Figure 3.16 also illustrates a similar scenario map for safety technologies. The primary driver is the known political will to reduce road fatalities, which is balanced against the impact of drastic safety measures on industry profitability and the perceived freedoms / rights of the driver. This latter issue is a secondary factor in its own right, as the degree of acceptance of self-driving or intervention by automated systems will strongly influence the path taken to achieve the primary goal of better safety. In this case another secondary factor will be the willingness of governments to invest in infrastructure.

The FURORE targets are intended to be based on “middle ground” scenarios, with a recognition that some change is necessary but that the most ambitious political targets may not be met.
3.3 FURORE research targets up to 2020 and beyond

The information discussed above relates to the likely status of achievement by 2015-20, and to issues which will be most topical at that time, which will represent future research and policy challenges for 2020-2050. These may be summarised as a set of targets for the period 2020-2050, as shown in Table 3.8 below.

<table>
<thead>
<tr>
<th></th>
<th>Car</th>
<th>Truck</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuels</strong></td>
<td>2020: Achieve EU target 20% substitute fuel, fuel / combustion optimised together, significant depot-fuelled fleets (e.g. bus) using CNG and H2</td>
<td>2020: -10% on today</td>
<td>2020: -40% on today</td>
</tr>
<tr>
<td></td>
<td>2030: Routemap to sustainable transport identified and enacted</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CO₂ / GHG</strong></td>
<td>2020: 95 g/km</td>
<td>2020: -10% on today</td>
<td>2020: -40% on today</td>
</tr>
<tr>
<td></td>
<td>2030: 80 g/km</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Emissions</strong></td>
<td>2020: 50% EU IV + PM 0.1 control</td>
<td>2020: NOx &lt;25% EU IV, PM &lt;50% EU IV, inclusion of unregulated compounds, local control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2030: Understanding of the true needs of the local environment achieved</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>2020: Road deaths -75%</td>
<td>2030-2050: Introduction of autonomous driving</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2030-2050: Introduction of autonomous driving</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Traffic</strong></td>
<td>2020: Telematics and traffic management enable congestion and stress free highway driving</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>2020: Adequate noise level to the ambient. Holistic approach for real world noise reduction.</td>
<td>2030-2050: Further reduction in urban noise towards WHO targets</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2030-2050: Further reduction in urban noise towards WHO targets</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Recycling</strong></td>
<td>2020: 85% introduction of useable cradle-to-grave analysis standard</td>
<td>2040: 95% by weight, low environmental impact of disposal of the last 5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2040: 95% by weight, low environmental impact of disposal of the last 5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.7: Key FURORE targets for 2020-2050

These targets may be summarised as relating to these three key themes:

- An integrated approach to sustainability of road transport, which considers fuels and raw materials in the context of overall energy and raw material supply, and considers real world, well-to-wheels, cradle-to-grave performance.
- An integrated approach to the local environment which links understanding of human health effects and environmental needs, individual vehicle noise and gaseous emissions to the road infrastructure and intelligent control.
- An integrated approach to safety which links together active and passive safety, road infrastructure and the possible trend towards increasingly autonomous driving.
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3.27 Investigation of the feasibility of achieving EU V heavy-duty Diesel emission limits by advanced emission controls, Association for Emissions Control by Catalyst (AECC), 2002


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Car manufacturers, research institutes and the automotive industry are developing several future technologies for advanced powertrain and vehicles. These technologies show potential for the next generation of vehicles with regard to improving environmental indicators like Green House Gas emissions (GHG), toxic emissions, noise and active/passive safety etc. up to the year 2020 and beyond.

This chapter compiles a comprehensive overview of breakthrough technologies for future road vehicles and indicates timeframes for supposed market relevance. For a detailed description of the technology features, their potential and specific research & development demand, refer to part B „Technical Part“.

4.1 Introduction: The Impact of Future Technologies on Environmental, Energy Sources and socio-economic Conditions

The vehicle technologies themselves have directly an impact on the environment regarding their objectives shown in Figure 4-1 caused by the direct use of the vehicles. To derive the impact on future scenarios for road transportation, additional global impacts of vehicle technologies have to be considered as well:

- Resource and recycling
  - Efficiency in production and recycling process
  - Economic efficiency of recycling
  - Future availability of resources (costs)
4 FUTURE BREAKTHROUGH TECHNOLOGIES

- Infrastructure
  - Availability
  - Redundancies
  - Differences of technology levels between countries or regions
  - Costs
- Environmental impact
  - Trade-off with future environmental objectives
  - Emissions (waste, gaseous emissions, noise, etc.)
  - Creation of totally new environmental impacts/problems by new technologies
- Policies and social aspects
  - Conformity of new technologies with today’s and tomorrow’s policies regarding environment energy, social aspects and taxes
  - Acceptance of new technologies regarding different cultures and regions (global view)
- Safety
  - Conformity of new technologies with existing and future safety standards
- Energy consumption
  - Energy efficiency from well to wheel (including consumption in production and recycling)
  - Availability
  - Costs
  - Transport and distribution

Figure 4-2 Embedded powertrain/vehicle technologies
All defined breakthrough technologies for conventional gasoline and Diesel engines are the first step to improve future fuel consumption and reduce GHG in the close future. They help so that the running time for gasoline and Diesel engines on the market is extended with lower environmental impact until alternative technologies are applicable for mass production.

These powertrain technologies are based on today’s technology and use common fuels. The global impact is minor with the exception of the environmental improvement for GHG, particles and further emissions. For fuel production and distribution to the network of fuel stations, the infrastructure is already existing and available. In the distant future the ongoing reduction of the crude oil resource will become more significant and will require an increased use of renewable energies, the exploration of new resources and/or the generation of alternative/synthetic fuels.

Concerning safety aspects in a technical point of view there is no influence, but with variable engine technology, that enables driving at low speeds with higher low-end torque, aggressive driving behaviour may be reduced. Furthermore, advanced strategies assisted by this engine technology, like adaptive braking, may increase driving safety as well. The production and recycling of increased use of multi-material cylinder blocks to obtain overall weight reduction will be more complex than today as well as the increased number of electronic control devices, sensors and wiring. The specific industrial processes will have to be improved, not to increase the required power consumption.

Renewable and alternative fuels will become more and more available. The market for natural gas will increase. The large scale integration into the transport systems requires possible solutions for production, storage, distribution, use.

Natural gas makes efficient use of the huge resources world-wide. Energy type diversification complicates the unification and requires an intelligent engine management system in combination with gas sensors, which determine the quality. The distribution grid is existing, but investments have to be made to extend the nation-wide supply.

Pure biomass fuels require a huge agricultural terrain; therefore this natural resource will not be capable of mass production. Monocultures would have be the conclusion, but that would not be acceptable regarding environmental aspects for circumspect natural land use and the expectations of the society. A more favourable aspect regarding resources and environmental impact is the generation of biomass fuel in a combined processing of waste products. Using biomass as a blend in conventional liquid fuels is the most realistic trade-off concerning resource, infrastructure and environment.

Synthetic fuels have the highest grade of compatibility to conventional fuels. They give independence of natural crude oil resources and political crisis in oil-delivery countries. Because of the similarity to conventional fuels, the infrastructure for distribution can be adopted and safety aspects are the same.

For all alternative fuels not only the tank-to-wheel improvement must be considered, but furthermore the well-to-wheel evaluation. The energy consumption for the whole production run and distribution to the vehicle needs to be regarded to define the benefits on the energy site. This is an important aspect especially for hydrogen, the most favoured and controversially discussed technology for the future. Up to now the strategy for hydrogen production and distribution is not developed. Producing hydrogen requires high energy consumption. Nowadays conventional possible solutions like vehicle reformer technology or producing hydrogen from fossil resources do not represent the real well-to-wheel potential of this energy technology. Alternative power plants using solar energy or hydroelectric power etc. with the lowest environmental impact and best well-to-wheel characteristics seem not sufficient for providing enough energy to use hydrogen nation-wide as fuel for road transportation. Nuclear technology, which is in a high state of development and also has optimal well-to-wheel characteristics, is a highly politically and sociologically sensitive issue. For the significance of effective and cost-saving production, hydrogen is seen as a vector for generation of electric energy. Further problems to be overcome are safety risks in onboard storage and distribution and the missing infrastructure, which results in huge investments.
Alternative fuels require mostly different storage conditions in the vehicle and fuel stations than conventional gasoline and Diesel fuel, which can be stored at ambient temperature and pressure conditions. Storage of gaseous fuels, e.g. under high pressure, increases the effort to ensure the same safety standard than for conventional liquid fuels not only for crash situations but with regard to long-term operation and service. Failure due to leakage has to be prevented or rather detected by reliable sensors. Attention has to be paid to the many interfaces from production to distribution into the vehicles. The safe, low temperature storage of liquefied fuels is critical concerning passenger protection against leakage flow.

For the successful establishment of alternative fuels in the market and management of the required high investments for the build-up of production and distribution networks, political decisions have to be made. Furthermore, the unification of energy politics between different countries would be necessary.

For pure electric vehicles that are operated mostly with batteries, the energy problem is similar to the hydrogen production. While battery vehicles are suitable for zero emission urban and suburban traffic, an effective electric power generation is required to maintain the good tank-to-wheel balance with well-to-wheel. For large production of battery resources e.g. for noble materials and chemicals, the infrastructure for their recycling has to be ensured. Furthermore health and safety aspects resulting from normal operation modes, like gaseous emissions during charging, high voltage in vehicles, electromagnetic fields surrounding the vehicle and crash behaviour, are significant for acceptance of this technology by the customer. Pure battery vehicles are available nowadays. But customer acceptance degenerates pure battery vehicles, due to their limited operating range and size, to, at most, secondary vehicles. Because of their high price and low utility value, they are niche products. This image problem has to be faced. Besides their zero emission, the noise level of traffic will be reduced as well. This might result in less recognition of the traffic by pedestrians or cyclists and in worst case to an increased number of accidents.

The increasing number of electrically-driven devices with X-by-wire, active safety and driver support systems in future vehicles extends the required wiring, electronic control units and sensors. Again this increases the effort of recycling processes to separate reusable materials. On the other hand, operating fluids are replaced by electrical actuators. Telemetric information will be fed to an intelligent vehicle system and be used for traffic control, speed control and route assistance. This will result in reduced environmental impact of road transportation because of traffic congestion prevention and reduction of road transport deaths. A European unification of these systems and telemetry is necessary for effective usage in international traffic. Furthermore, elderly and disabled persons can improve their mobility by driver support systems. On the other hand, supporting systems have to be considered carefully. If the driver’s task is made too great two effects occur: firstly, the customer acceptance is far worse if these systems make up the driver’s mind for him; secondly, the drivers attention to the traffic is reduced. Whenever considering the driver, the personal integration in the system ‘vehicle’ should not be neglected. Legal responsibilities of ‘the invisible driver’ have to be checked.

The demand for lightweight vehicles results, besides improved design efforts, in the usage of lightweight materials. Advanced design and production technologies will ensure the economical and ecological production process. The dismantling of these material composites and their separation for reuse will also enlarge the recycling process and have to be integrated in the design process for the vehicle from the beginning. The production of lightweight materials is very energy- and cost-consuming, (see: aluminium). The additional energy consumption and secondary pollution by emissions and by-products have to be considered. Again a sound well-to-wheel analysis must show the real benefit. Lightweight vehicles must demonstrate the same safety standard as todays vehicles as a minimum requirement, including a proven fire resistance when thinking about plastics and composite materials. Otherwise lightweight technologies will not meet with customer acceptance.
In future, many advanced non-conventional breakthrough technologies are necessary to fulfil environmental objectives. From the technological point of view many seem to be solvable, but cost/benefit analyses in terms of reducing CO₂, noise and harmful exhaust emissions, have to be done. This requires further investments on the one hand for research and development and on the other to build-up the necessary infrastructure.

The prevailing political climate in Europe and the rest of the world will exert a strong influence on the pace of change and technology introduction, and hence on the attainability of the targets. The primary factor is the balance between concern for the environment and human living conditions, and concern for economic growth and industry profitability. As a general rule, the state of this balance dictates the pace at which new technologies are introduced, but does not influence their nature much.

4.2 Energy and Fuels

The FURORE consortium believes that in 2020, the main fuels for transportation, i.e. gasoline and Diesel fuel, will not change dramatically but fuel specifications could further evolve. Gasoline and Diesel fuels will become practically sulphur-free, and other property improvements should be evaluated strictly with regards to well-to-wheels CO₂ impacts.

Encouraged by the European Commission's above-mentioned target for alternative fuels, the portfolio of available fuels will become more heterogeneous. The introduction of several new fuels is a challenge due to the costly proliferation of many different engine and emission control technologies, and a parallel proliferation of supporting fuel infrastructures. In some cases these new fuels or blends may be synergistic with new combustion modes, but this remains to be verified. In general, hydrogen bound to carbon in liquid fuels (=hydrocarbons) provides the best energy density, few storage problems and is therefore to be preferred for transportation purposes.

Conventional Fuels: The main fuels for transportation, i.e. gasoline and Diesel fuel, will not change dramatically but fuel specifications could further evolve. Both will become practically sulphur-free (10ppm Sulphur achieved in 2009), and other property improvements should be evaluated strictly with regards to well-to-wheels CO₂ impacts.

Advanced conventional fuels are mainly mineral-oil-based like syn-fuels and blended fuels. They are directly linked to future engine requirements or optimisation constraints. Pure or blended fuels must be considered. For liquids from natural gas or coal, cost and CO₂ have to be tracked.

Alternative fuels: Natural gas, biomass to liquid fuels, bio-fuels and hydrogen are the main candidates of the very ambitious alternative fuel proposal. Large scale production facilities are still missing and it can be estimated that there is still an optimisation potential in the production processes, when building up those production facilities. Nevertheless the major issue with these fuels is how to produce, store and distribute them at a competitive price. It is assumed that pure hydrogen could only attain a non-negligible market share beyond the considered time period, by 2030 and later, for example also as a valuable ‘add-in’ for biomass-based renewable fuels. Production of hydrogen out of hydrocarbons either in the plant or in the vehicle is not efficient in relation to CO₂ and the security of supply objectives, and doesn’t seem to be a feasible long term solution. Production of hydrogen out of electricity via electrolysis in the needed quantities could be envisaged only by the use of nuclear power which will lead to general political discussions of energy supply. The other alternative liquid fuels are in a slightly better cost situation even if there are concerns about massive biomass production in relation to effects on target food land.

Hydrogen and some other alternative fuels could serve only as an intermediate vector for use of electricity in road transportation. As the electricity distribution grid is largely existing and competitive, research on on-board electricity
storage development should not be forgotten as an interesting solution, especially when combined with CO$_2$ control of power generation (CO$_2$ centralised sequestration process potential).

Research Demand
For further development of conventional fuels, two major research routes can be identified:
The determination of optimal formulations serving or assisting the new combustion processes such as controlled auto ignition (CAI), homogeneous charge compression ignition (HCCI), combined combustion system (CCS); therefore, formulations able to support very low speed or very low load regimes or, at the opposite end, high speed / heavy load regimes are in focus.
The definition of new characteristics (or the renewal of existing characteristics), especially improvements in sulphur content and other properties like aromatics. Changes will be required to chemical composition and the auto-ignition characteristics (hydrocarbons, oxygenated species,...), also the physiochemical characteristics linked with the vaporisation process will be changed.

To reach 20% of alternative fuels in 2020, the following research activities need to be introduced as listed below. Currently bio fuels are 2 to 4 times more expensive (before adding tax) than conventional fuels and the ratios are even bigger for hydrogen.

- Cost reduction from well-to-wheel is the key action for the alternative fuels in general, as most of them, particularly biofuels, LPG or NGV can be considered demonstrated; in this way the elaboration of technical and socio-economical strategy to avoid the chicken-and-egg dilemma is dramatically crucial.
- Storage technology for gaseous fuels to ensure an optimal range for vehicles.
- Hydrogen production, for instance via electrolysis with higher performance (but this way will be deeply dependant on the electricity production system for its environmental efficiency) and more generally, global environmental evaluation of this energy vector.
- Safe and inexpensive distribution system for hydrogen to ensure a future public and regulator acceptance
- Use of electricity in road transportation. Research into on-board electricity storage development could be at last the best solution with regards to the CO$_2$ balance of the power generation.
4.3 Powertrain

Vehicle propulsion system technology development is an evolutionary process. The powers which influence this process are the requirements of customers, the legislative boundary conditions like emission and safety standards, the energy resources and prices influenced by production/distribution costs and taxes. For a better explanation of the propulsion technology evolution in the future, this chapter is divided into the “State of the Art Technology until 2007”, the “Technology Trend until 2020” and the “Technology Visions beyond 2020”. In general, the targets for the technology trends and visions are energy consumption reduction, near zero emissions and alternative fuel compatible power systems.

4.3.1 Technology Status for 2007

General Trends

Due to the necessity of more flexible and variable engine sub-systems in almost every engine type, engine costs will grow significantly. There will be a challenge to reduce costs by detailed improvement of engine components and consolidation of product ranges to obtain various outputs from common units. In this field of trade-off between engine costs and fuel consumption benefit, the new improved gasoline engine concepts will have a very important position in comparison to the increasingly successful but costly Diesel engines. So for conventional powertrains there will be a special research
demand in a detailed optimisation of variability and materials for the engine, the exhaust gas aftertreatment and the combustion. With the growing degree of variability, the engine management system together with special sensor concepts (cylinder pressure, ion sensing, position sensors, etc.) and actuators will be more and more important to reduce the fuel consumption and the emissions.

**Spark ignition engines**

In the near future, the importance of down-sized spark ignition engines will increase considerably. Boosting (supercharging and turbocharging) will be combined with static down-sizing, sometimes with redesigned engines. The possible reduction in cylinder displacement is up to 40 percent, with a corresponding benefit in fuel consumption and carbon dioxide emissions of up to 20 percent. The adoption of direct injection will be another way to improve engine efficiency, but in terms of costs, these engines with a stratified combustion are more expensive than conventional spark ignition engines due to the need for advanced injection technology and additional nitrogen oxide aftertreatment. As an interim step, direct injection with a homogeneous combustion (enabling conventional emission control) in combination with supercharging will take a growing market share. Variable valve trains enable a significant fuel economy increase and CO₂ reduction up to 20%. Another option are concepts with a variable compression ratio (VCR) in combination with downsizing, which offer (for supercharged engines) a potential up to 25% CO₂ reduction. Finally, first low cost, belt-driven starter generators operating at 14V will reduce fuel consumption by enabling automatic stop/start, but without re-generative braking and torque support, which require 42V systems. Naturally, many of these technologies can be effective in combination but research work has to be done to find a cost-effective solution for high fuel economy for each vehicle type.

**Light-duty Diesel engines**

The significance of down-sized Diesel engines will also grow in the next decade, because of increased supercharging rates and intercooling as well as the possibility of electrically-assisted turbochargers and variable valve train concepts, which enable an optimised torque and transient characteristic. A specific power output up to 70 kilowatt per litre seems to be reachable. Compared with current Diesel engine technology, a fuel consumption benefit of up to 25 percent is predicted as a result of major down-sizing and reduction of friction losses. Advanced fuel injection systems, which allow an adapted injection characteristic such as pilot, split and post injection as well as rate shaping, will reduce the local emissions substantially, perhaps avoiding the need for additional particulate and NOx control devices in small to medium vehicles. Also injection nozzles with variable injection-hole size will be a part of these advanced Diesel engine concepts.

**Heavy duty Diesel engines**

The challenges for the heavy duty engine are similar, with greater emphasis on emission control but a stronger market desire for efficiency in order to reduce operating cost. Fuel consumption and NOx/PM emission will be addressed by combustion process improvements, including application of flexible high-pressure injection, four valves per cylinder, improved boosting, electronic control and low oil consumption. There are a variety of combustion process philosophies with corresponding emission control needs. Exhaust gas recirculation (EGR), particulate traps, Lean NOx traps and Selective Catalytic Reduction (SCR) based on urea in combination with oxidation catalyst will be used.

**Aftertreatment**

Aftertreatment systems for 2007 are mostly visible today. Existing aftertreatment technologies - three way catalyst, DeNOx catalyst, oxidation catalyst and Diesel particle filter - will be continuously improved regarding cost, size and efficiency.
The first Selective Catalytic Reduction systems based on urea will be implemented for truck engines. Some of these systems can be highly effective in addressing emission control needs, however there will always remain a desire to avoid the additional cost associated with complex aftertreatment.

Transmission and Driveline
The desire for CO₂ reduction, combined with a market demand for driving enjoyment, will cause a significant change in the European transmission market. It is unlikely that the conventional automatic transmission will gain a much larger market share, due to its fuel economy penalty, although the adoption of six or more ratios will mitigate this effect. Continuously or infinitely variable types (CVT, IVT) offer improved efficiency, at best equalling manual types in the NEDC test. Robotised transmissions (Automated-manual, AMT) offer significant fuel economy benefits (typically 5%) but the driving experience will remain compromised by the interruption of torque during shifting; developments are ongoing to avoid this disadvantage. Market penetration will be significant but limited to smaller vehicles. The Dual Clutch transmission (DCT) offers almost as much benefit but with seamless shift quality under most conditions. This technology could achieve very significant penetration of the market if manufacturing costs prove competitive in high volumes. The popularity of four wheel drive will continue to increase in this timeframe, particularly in lifestyle-oriented vehicles based on front-wheel-drive platforms. Premium vehicles will adopt increasingly sophisticated technologies for distributing drive torque between the wheels in a safe manner.

4.3.2 Technology Trends up to 2020

General Trends
IC engines with conventional fuels will remain dominant in 2015-20. Diesel penetration (today at 40% in Europe) will grow to around 50%. Hybridisation of IC engine powertrains will be very significant in this timescale. An evolutionary approach from mild to full hybrids is likely. Only the most aggressive predictions suggest penetration of Fuel Cell passenger cars beyond 1% of the market.

Truck and Bus powertrains show the Diesel engine as the dominant power source in 2015-20. Hybrid technologies may play a small role: in particular, smaller classes of truck, subjected to stop-start or urban use are likely to see the greatest uptake of this technology, while urban delivery vans will probably adopt a technology profile more similar to that for Passenger Cars. Especially for busses, the stop-start nature of the duty cycle and the environmental needs of cities suggest a greater penetration of Hybrid technologies and Natural Gas as a fuel. These same factors create the greatest opportunity for Hydrogen and Fuel Cells, bus applications being the only type of vehicle where either is expected to see over 1% penetration.

Spark ignition engines:
By 2020 it is likely that most spark ignited engines will use combinations of the previously described improving technologies - down-sizing with boosting, lean-burn with direct injection, variable valve actuation (including cylinder de-activation and multi-stroke load control) and variable compression ratio - and will feature advanced, adaptive control of these flexible sub-systems, perhaps using new sensor technologies. In combination with variable valve timing and/or variable compression ratio, controlled auto-ignition with very low engine-out emissions can be realised in a wide engine map area and without full-load penalties. Some evolution of fuel properties may support this new combustion philosophy.
Spark ignition engine technology is fully compatible with both Natural Gas and Hydrogen, and if energy policy promotes these fuels into the marketplace, combustion systems tailored to these fuels will emerge. Extreme-charged, lean-burn, spark-ignited combustion processes are promising in this respect. This combustion technology achieves extremely low NOx emissions and only needs an oxidation or three way catalyst (no further NOx aftertreatment systems).

**Diesel Engines:**
To obtain further reductions in emissions and fuel consumption, sub-system variabilities will increase for both heavy duty and light duty Diesel engines. Variable valve timing (including cam-less systems in heavy duty applications), possibly variable compression ratio, and variable injection timing with rate shaping and increased fuel injection pressure, are all likely to feature, again enabled by advanced control systems. To increase the degree of down sizing, in-cylinder peak pressure will increase. For this, new improved materials and engine design concepts are necessary including new high-boosting devices. With single cycle control, emission will decrease further. A greater step in NOx emission reduction in a wide mapping area will be expected for the HCCI in the part- load range without full-load penalties.

**Aftertreatment:**
In this timeframe it is Diesel engines which present the greatest aftertreatment challenge. Key technologies for most stringent NOx and PM control are cooled EGR, high-pressure fuel injection, Diesel oxidation catalyst, Diesel particulate filter, catalytic reduction of NOx by SCR or NOx-adsorber, and combinations of these depending on needs of market and exhaust emission regulation for world-wide emission development strategies. System integration including electronic on board diagnostics (EOBD) is an absolute must, i.e. combustion systems, mechanical systems, control systems, aftertreatment systems, and measurement systems have to be optimised as a whole to meet market demands and legislation requirements. Durability and reliability of the various systems still need to be proven before production release. The time for this is very short. This applies particularly to aftertreatment systems for NOx and PM, since NOx-adsorbers and Diesel particulate filters for heavy-duty Diesel engines are still in the laboratory development phase. The combination of NOx trap and particle trap in one system offers cost and fuel consumption advantages. Improved SCR technology with improved reduction agents can reduce the cost for NOx aftertreatment systems. Non-precious metal aftertreatment systems are the hope for the future out of cost and resources reasons. However, the pollutant transformation efficiency still needs intensive research work.

**Hybrid and Auxiliary Power Units**
Increasing on-board electric power requirements, together with a desire for powertrain efficiency improvement, creates a need for hybrid-electric technology and auxiliary power units.

Hybrids with an integrated starter generator and “42 Volt boardnet”, in combination with a downsized engine, are seen to become a widespread measure for reducing fuel consumption and emissions, especially in city traffic. This “mild hybrid” technology provides good fuel saving potential by applying engine shut-off and brake energy recovery, and by using the electric motor to assist improved launch of vehicles with down-sized engines. Costs, weight, reliability and increased complexity were identified as the hurdles and barriers for this technology. Research has to be done on the electric machines, the integration of the starter generator, the control system and the reduction of weight.
First hybrid vehicles like the Toyota Prius and the Honda Insight are already on the market. Nevertheless hybrid technology with a high share of electrical power calls for a greater change to the powertrain of a conventional vehicle. New transmissions, clutches and big electric machines are needed, together with high electrical power batteries, which remain very expensive and not sufficiently developed. Research is needed on the components in a hybrid powertrain, like new transmissions, electric motors and batteries. Also the integration and control of all the components is an important issue. Considering the additional complexity and components compared with the conventional powertrains, full hybrids will only slowly penetrate the market. Particularly the cost/fuel saving ratio has to be considered.

An alternative which avoids the many issues related to batteries and electrical energy storage is the use of small, efficient auxiliary power units (APU) to supply base power needs, supplemented by a main internal combustion engine providing high power. Fuel cells or combustion engines (perhaps innovative linear types) are suitable as an auxiliary power unit. Fuel cell systems as APUs require significant reduction in cost, weight and size, both of the stack itself and also for the fuel and air system and the heat management. Reforming of liquid fuels, or feasible hydrogen storage will be required. The reformer adds complexity and costs to the fuel cell system. Reformers for gasoline and Diesel are in a very early technological stage and a lot of research is needed to guarantee the hydrogen generation in the transient operation in a vehicle.

The linear engine combines the combustion engine with electric power generation. The advantage is that they can run with conventional fuels and can use knowledge from the combustion engine. The technological breakthrough depends on the available battery technology and linear electric motor technology as well as a combined combustion process in terms of emission, fuel consumption and control.

Engine concepts close to conventional combustion engines

A lot of research and development has been applied in the past to alternative combustion engine types, including the Stirling engine, micro-turbine, steam engine and free-piston engine as well as thermo-chemical combustion processes with thermal drive. Often they offer advantages in terms of low emissions, but these can be offset by low efficiency, high production cost, poor transient behaviour, high weight and reduced durability. Finally, all would require massive change to the existing engine manufacturing and service infrastructure and are unlikely to succeed outside niche applications, unless a technology breakthrough enables significant advantage to be shown.

Near-zero emission will be reached with improved combustion and aftertreatment technology applied to the conventional combustion engine on a reasonable cost level, so it appears that there is little driving force to invest research money in current alternative technologies.

4.3.3 Technology Visions beyond 2020

It is likely that the “variable” combustion engine, with highly variable sub-systems under the control of a sophisticated powertrain management system, will continue to evolve in combination with improved, partly renewably-sourced fuels. The Diesel homogeneous charge compression ignition (HCCI) and gasoline controlled auto ignition (CAI) combustion processes, which have many similarities, may merge along with fuel properties into a “Combined Combustion System”. Due to improved aftertreatment technologies, zero impact emissions will be reached. If the political will to replace liquid fossil fuels remains in place (and it probably will), gaseous-fuelled engines will be highly charged, lean-burn and down-sized.
In combination with advanced transmissions (probably dual-clutch or infinitely variable type) with high efficiency and flexibility, the energy consumption of vehicle power trains will be reduced further. Together with new materials and design philosophies, a specific engine power of 150 kW/litre for gasoline and 75 kW/litre for Diesel engines can be expected. Electric hybridisation may be commonplace beyond 2020, both as an efficiency enabler and provider of power for x-by-wire systems. Significant improvements, and possibly a breakthrough, in energy storage technology can address the major hurdle facing this technology, provided that the research effort has been supported in the intervening years. Thus, if there is more CO₂-free electrical energy available from renewable or nuclear sources, battery-electric vehicles have to be discussed again. Pure battery vehicles already exist in niche applications and have been under research for decades. The main research field is consequently the battery, which has to be improved concerning energy and power density, reliability as well as with regard to cost reduction. For the electric powertrain itself new, more cost-effective production methods for electric motors might be an issue.

Fuel cell vehicles running on hydrogen have the advantage of being real zero-emission vehicles. Technologically, they can be considered as electric vehicles in which the battery has been replaced or supplemented by a fuel cell. In many applications a secondary, conventional battery will be needed for start-up and for conditioning of the fuel cell. Fuel cell stacks show best efficiency at part load, which is favourable for inner city driving. The stack is only one part of the fuel cell power train efficiency - it is necessary to take into account the air system, the heat management, the cabin heating/cooling, the cooled climate start (freezing of combustion water in the cell), the electric machine and the power converter, which decrease the overall powertrain efficiency. On top of this, the efficiency of the reformer (if used) and well-to-tank efficiency of fuel production have to be considered. Combining these factors, today’s fuel cell vehicles using non-renewable hydrogen do not offer an improvement in well-to-wheels efficiency over the best IC-engine hybrid technologies. As the fuel cell technology is relatively new, high basic and applied research is necessary to reduce production cost, increase overall energy efficiency and to reduce size and weight. To overcome these problems, real breakthroughs in the stack and fuel storage technology are necessary. The market chances of fuel cell vehicles are generally assessed as more pessimistic than a few years ago expecting them mainly in niche applications also for the period after 2020. Perhaps an internal combustion engine using hydrogen represents an equally likely long-term solution.

4.3.4 Research Demand Powertrain

In the recent years the main driver for technology development has been emission legislation. In future, fuel consumption reduction and CO₂ commitments will also be the major drivers.

SI Engines

Currently some most promising engine technologies are under investigation, whose common target is to increase the process efficiency especially at part load conditions. These technologies are:

- Downsizing, eventually combined with supercharging and cylinder deactivation
- Lean burn engines (direct injection)
- Fully variable valve train (including multi-stroke operation)
- Variable compression ratio
- New improved charging concepts

Massive research demand can be seen in finding the most cost effective solution compared to the fuel reduction benefit for these multivariable engine concepts. This refers especially to sensors, actuation and control systems including the preferred new materials.
Further research demand can be identified in:

- combustion systems (Controlled Auto Ignition (CAI), Homogeneous Charge Compression Ignition (HCCI)), especially to enlarge possible operation range, transient response and suitable combustion control systems (requirement for cycle-to-cycle control)
- Aftertreatment systems which are less sensitive to sulphur and nitrates
- Adsorber catalyst with improved thermal consistency
- Failure diagnostics
- Reliability and durability especially of aftertreatment systems.

**Diesel Engines**

For the Diesel engine, the technologies which need constant further development and optimisation are:

- Injection system (unit injector, common rail, fuel properties)
- Fully flexible electronic control unit (ECU) with extended features
- Gas exchange (intake system, number of valves, super charger, EGR, variable valve-train concepts)
- Friction, weight reduction measures
- Oxidation catalyst improvements
- Particulate and/or nitrogen aftertreatment measures
- Fuels with ultra-low/no sulfur content

Key technologies which have to be optimized and where high research demand is existing are:

- New low-temperature combustion processes (processes with early intake closing (Miller etc.), HCCI) and suitable control systems
- Advanced injection systems (high pressure (HPFIE) towards 3000 bar, common rail and unit injector systems, injection rate shaping capabilities)
- Flexible systems analogous to SI engines (VVT, variable swirl etc)
- New advanced turbo-charging systems with intercooling, including turbo-compounding
- exhaust gas recirculation with exhaust gas aftertreatment
- Materials for particulate filters (DPFs) and catalysts featuring lower pressure losses
- New and further development of catalyst systems (oxidation catalysts, SCR, NOx Adsorbers) using new, non-precious metal catalysis and advanced coatings
- Solve the contradiction between costs, durability and efficiency of next generation exhaust gas aftertreatment systems
- Failure diagnostics (EOBD)
- Reliability and durability especially of aftertreatment systems

System integration is an absolute must, i.e. combustion systems, mechanical systems, control systems, aftertreatment systems, and measurement systems have to be optimised as a whole to meet market demands and legislation requirements.

With the introduction of HCCI and CAI combustion, the combustion principles of Diesel and gasoline engines will merge together more and more. Also here is a research demand necessary to force this trend. A key component of this new combustion process could be a new fuel that has been adapted for vaporisation and ignition behaviour.
So research should be carried out in parallel, on the one hand improving the engine process efficiencies by reducing losses such as low temperature heat losses (coolant), mechanical friction and auxiliary losses and, on the other hand, controlling the combustion process (and its related parameters) such that lowest possible engine-out NOx and PM emissions are achieved. Advanced new aftertreatment systems will then lead to zero-impact emission levels.

For alternative powertrain systems featuring especially pure electric, ic-electric hybrid and fuel cell vehicles, not only the integrated systems have to be optimised and tested, but in most cases basic research is still required to provide the technologies to meet the targets of costs, reliability, efficiency and performance.

The most important research demands on a system level are:

- Reliability of entire powertrain systems to the standard of conventional powertrains
- Optimise vehicle performance by the combination of powertrain operating strategy with route information
- Auxiliary power (APU) generation with fuel cells, for instance for truck and bus applications, for emissions reductions by optimal integration of internal combustion engine, crankshaft starter generator and auxiliary power unit (ICE + CSG + APU)
- Infrastructure for H2 distribution and storage
- 42V board net improvement regarding enhancement of safety standards (e.g. short-circuit protection) and cost reduction
- Gas turbines/fuel cell hybrids for trucks

The most important research demands on a component level are:

- New energy storage systems, especially enhanced battery technologies and super-capacitors with regard to improved power performance (e.g. power density, recharge time, weight) and reduced costs for use in electric and hybrid vehicles; Optimisation of flywheels with regard to self-discharging; Hydraulic storage systems have to be improved in weight, volume and noise reduction
- Research for new transmissions and electric motors for hybrid vehicles
- Improvement of reliability and cost/weight for ICE with ISG
- Fuel cell vehicles (H2)
- Cost reduction for several components
- Introduction of new production processes with regard to series production (e.g. membranes)
- Development of suitable storage systems
- Fuel cell vehicles (with reformer): Higher efficiency and reduction of emissions (especially CO poisoning) for fuel cells with reformers and APUs
## POWERTRAIN TECHNOLOGIES

### SI Engines
- Increased specific torque/power+boosting (+VCR)
- Direct injection (stratified)
- Fully variable valvetrain
- Controlled auto ignition CAI
- Variable engine with combined combustion systems
- Alternative gaseous fuels

### CI Engines
- Increased specific torque/power+boosting+intercooling
- Advanced fuel injection systems
- HCCI with combined combustion systems
- Variable engine (valvetrain)
- High speed concepts

### Hybrid
- ISG
- Parallel/series hybrids

### Electric
- Advanced batteries and supercaps
- Electric motors

### Fuel Cell
- H₂-storage systems
- H₂-infrastructure
- Stack technology

### Aftertreatment
- Advanced NOx adsorber catalysts
- Reduced precious metal catalysts
- Advanced HP injection
- Diesel particle filter
- Advanced sensors
- NOx-conversion
- Advanced catalyst coating
- Conversion unregulated
- 4-way catalyst

### APU
- Fuel cell reformer technology
- Fuel stack technology
- Innovative engine concepts

### Transmission
- Automated manual
- Automatic transmission
- CVT, IVT
- Dual clutch transmission
- Four wheel drive

### Propulsion System
- Reduction friction loss (oil free)
- Materials
- ECU: advanced control strategies
- Combined combustion system with designed fuel

### Time

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4.4 Vehicle Structure

4.4.1 Breakthrough Technologies

As the vehicle weight has increased in recent years by adding many comfort and safety devices, weight reduction will be one of the most important issues in the future. Reducing vehicle weight, in any component or in total is a strictly accumulative measure and always advantageous.

Lightweight design can be achieved with different methods focussing on material usage and vehicle construction. The possibilities seen here must be approached from a holistic point of view. Major technology areas are the realisation of smaller and more flexible vehicle concepts, the downsizing of all possible vehicle equipment, X-by-wire systems without mechanical backup to optimise package and weight at the same time, connecting and joining technologies in order to support body modules and multi-material design, and frame structures to support high modularity. Lightweight design can be achieved with different methods focussing on material usage and vehicle construction. The possibilities seen here must be approached from a holistic point of view. Therefore, combining different materials such as steel, aluminium and plastics with different body structures like frame structures and shell structures need to be evaluated, taking into consideration all relevant criteria. This means that besides the technical realisation, life cycle analysis will also have to be considered.

Furthermore, the design process particularly needs to consider already at an early stage all the requirements for recycling and improved dismantling technology.

Post-processing for automotive shredder residue, adequate separation of different material types. The quality of recycled materials (comparable properties to new materials) is an issue too. It is very important that decision makers are aware of one contradiction: the need to decrease vehicle weight with high performance materials which are usually not easy to recycle and the desired recycling quotas put on standard vehicles. Compromises in vehicle safety are not permissible.

4.4.2 Research Demand Complete Vehicle

Research Demand Vehicle Structure

- More intensive basic research on lightweight materials (e.g. new combination of several materials) and their synergy with new body structures, joining and construction techniques
- Earlier identification of conflicting interests to improve lightweight vehicle concepts analysis with a high spectrum (not only focussing on lightweight components or certain vehicle parts)
- Enhancement of simulation technologies (e.g. material models, optimisation, combination of technologies)
- Further development of testing methods for materials and structures, especially for favourable non destructive testing methods applicable in development and production
- Research on new production technologies (mass production for today’s „high tech” materials, assembly and handling of „fully modularised” vehicles)
- Creating recycling technologies for advanced lightweight materials and structures
- Better knowledge of the influence of future technologies (e.g. fuel cell) on recycling process
- Optimising recycling methods in consideration of high volume and automated recycling methods to achieve better separation technologies as well as better alternatives to shredding
Research demand for Truck & Bus Vehicle Structures

New lightweight materials have to be applied also to bus and truck vehicle concepts. When focussing on the vehicle requirements, the advantages of these materials need to be elaborated and the disadvantages minimised. Besides the application of new materials and concepts, manufacturing requirements also need to be investigated in an early research stage.

An investigation into the aerodynamic optimisation of different combination of truck / trailer systems offers energy-saving potential. But in order to achieve these, a flexible system probably needs to be developed, in order to adapt to different boundary conditions of the individual trailer systems.

The most important research demands for truck and bus applications are:

- Deeper basic research on lightweight materials
- Higher application of lightweight body structure concepts
- Developing innovative repair strategies for lightweight design body structures
- Reduction of aerodynamic losses

![Diagram showing future breakthrough technologies](image)
4.5 Safety

4.5.1 Passive Safety

In spite of the significant improvements in vehicle safety which were achieved in the past 25 years, the current number of deaths and injuries plus all the associated social and economic costs must still be regarded as unacceptable. The feasibility of a ‘maximum-safety-vehicle’ needs to be investigated. New ways for safe transportation of children need to be developed, as well as systems for automatic restraint of luggage/objects.

A particular challenge in the field of vehicle safety is the trend towards smaller and lighter, more fuel-efficient vehicles and presumably the increased usage of electrical or hybrid vehicles for environmental reasons. An optimal combination of various technologies is required to offer passengers of these lighter vehicles a similar level of protection to that of conventional vehicles.

General strategies to improve passive safety aspects are the influence on crash conditions, for instance by improving the environment (e.g. deformable guide rails), by improving vehicle crashworthiness (e.g. energy absorption) and by influencing the impact motion of the human (e.g. seat belt).

New safety concepts such as so-called ‘intelligent’ or ‘smart’ restraint systems that adapt to the actual accident condition and to the particular occupant shall be able to protect car occupants better than current restraint systems. These systems shall require information obtained from new sensors in the car and shall be able to intelligently manage the levels of restraining forces and how they are applied to the occupant. Prerequisites for further research are comprehensive accident statistics and investigations (e.g. creation of an international accident database), biomechanical research in order to study injury mechanisms and tolerances of the whole population at risk and improved physical/virtual assessment tools and test methods including virtual testing. Further research demand is required in energy-absorbing structures and new (lightweight) materials, new intelligent safety concepts, sensor technology and control systems and the interaction with other technologies.

Apart from that, the development of education and training programmes is essential to significantly improve road safety.

4.5.2 Research Demands Passive Safety

Interdisciplinary research programmes are required in order to accelerate knowledge development and to integrate technologies. More medical expertise is required in the field of accident investigations and biomechanical research. ICT technologies should be applied in order to enhance the research activities and disseminate the knowledge.

Further biomechanical research is needed, especially in the area of brain/nerve and neck/spine injuries, injuries resulting in long-term impairment, as well as research in the field of child injury criteria.

Vehicle crash test methods should be developed that are based on real-world accidents, in this way taking the changing vehicle fleet population (e.g. SUV) into account.

Material research programmes are required that bring together experts in the field of impact energy management, production processes, recycling and repair techniques. Improved material characteristics are needed with respect to weight / energy-absorption ratio in different environmental conditions.

Research programmes looking for new safety concepts and structures should be stimulated. The feasibility of a ‘zero-injury-car’ should be studied.
The research needed to develop the technologies to fulfil the objectives in the field of passive safety for 2020 and beyond are summarised as follows:

- Develop and maintain international accident databases at different levels (base, intermediate, in-depth) based on harmonised procedures.
- Evaluate the effect of new legislation and consumer test programmes by real-world accident investigations.
- Biomechanical research in order to study injury mechanisms and tolerances of the whole population at risk.
- Develop and maintain international database with biomechanical data.
- Measure and develop database of anthropometry of next generation of car occupants.
- Develop more realistic, validated assessment tools representing the whole population at risk.
- Develop vehicle crash test methods based on real-world accident data and cost-benefit models, integrating more than one accident scenario, as well as integrating virtual testing techniques.
- Develop new lightweight, energy-absorbing materials and intelligent crash structures, including mathematical simulation features.
- Study new safety concepts, including zero-injury-car and interactions with other technologies (e.g. X-by-wire).
- Develop more reliable sensors and control systems.
- Develop virtual testing techniques to integrate active and passive safety features, as well as other technologies (e.g. power-/drive-train).
- Develop education and training programmes.

4.5.3 Active Safety

Active Safety embraces a number of areas from pre-crash warning and prevention to post-crash rescue management. Active safety as a production technology is very much in its infancy, with huge potential to create an impact on the harmful effects of road traffic accidents, both to occupants, pedestrians and third parties. The ultimate goal is often seen as an “accident proof vehicle”, which informs the driver of hazards and intervenes where necessary to avoid disaster. Linked to this topic is the issue of Driver Support. Again, this is a complex issue, starting with simple provision of information (navigation, route planning, avoidance of traffic) and then assisting or taking over from the driver (smart cruise control, lane following, road trains, and ultimately full self driving). This is a highly attractive proposition but faces a major hurdle of public acceptance to overcome.

4.5.4 Research Demand Active Safety

FURORE identified a wide range of future breakthrough technologies and research demand. Short term needs (~2010) are generally aimed at making the first active safety technologies robust, affordable and desirable. Medium term research needs (~2020) are aimed at the introduction of desirable and affordable partially-autonomous vehicles with a high degree of integrated on-board intelligence. For the long term (+2030) the focus is on a successful transition to autonomous systems. In detail:
**FUTURE BREAKTHROUGH TECHNOLOGIES**

**Short Term - For 2010**
Research needs in this timeframe are generally aimed at making the first active safety technologies robust, affordable and desirable. They include:

- Definition of advanced vehicle power requirements (hybridisation plus X-by-wire) and strategies for efficient power management
- Development of better, cheaper sensor and actuator technology - especially new materials
- Creation of design rules, methodologies, codes of practise and protocols for physical systems, information networking, control algorithms and human-machine interfaces
- Exploration of synergies between on-board active safety, improved powertrain control, and road network-based congestion and pollution management systems
- Assessment and improvement of system reliability and fault tolerance
- Development of simulation tools for physical and electronic systems as an aid to virtual development
- Development of manufacturing technology for the components and systems above
- Market research and legal studies to facilitate successful technology uptake

**Medium Term - For 2020**
Medium term research needs are aimed at the introduction of desirable and affordable partially-autonomous vehicles with a high degree of integrated on-board intelligence. Despite the longer time horizon, it is appropriate to initiate or continue research in these areas now:

- Second-generation sensor technology (object recognition etc) - reliability, accuracy, cost
- Strategy development - communications standards, fail-safe methodologies, complete vehicle communication, sensor fusion and control integration
- Human impacts of E-smog - health effects of electromagnetic transmissions, psychological impacts of information overload
- System test and validation methods - safety, compatibility; E-smog & EMC
- Traffic management - vehicle interfacing, infrastructure needs, intelligent road technology, central or distributed control

**Long Term - For 2030+**
Here, the focus is on a successful transition to autonomous systems. The enormity of this task is such that it remains appropriate to initiate research now:

- Autonomous systems - reliability, compatibility with legacy vehicles and their drivers, cost reduction
- Long term health effects of electromagnetic pollution
- Mobility research - intermodality, mobility management, new concepts

These needs can be summarised as follows:

- Development of each element of the technology roadmap - building block technologies and materials, integration, development of high robustness and low cost
- Systems integration - communication protocols, sensor and actuator fusion, strategies for vehicle and road network, integrated vehicle management and holistic optimisation
- Impacts of change - health effects, public acceptance, human-machine interface, setting standards and legal frameworks to enable change
## Passive & Active Safety

### Passive Safety
- Accident statistics and investigations
- Biomechanics & improved physical, virtual assessment tools
- Improved and new vehicle test methods
- Energy absorbing structures & new lightweight materials
- New intelligent safety concepts & structures
- Advanced sensor technology

### Driver Info, Warning & Comms
- Lane following - warning
- Image enhancement / night vision
- Image recognition
- Vehicle-interactive traffic management
- Vehicle-vehicle-infrastructure warning systems
- Active distress systems

### Driver & Driving Style Monitoring
- Driver alertness and health monitoring
- Black-box systems
- Intervention / auto takeover

### X-by-Wire Systems
- Brake-by-wire
- Steer-by-wire
- Weather-reactive chassis control

### Hazard Recognition
- GPS / road topography
- Telematics enabled traffic flow
- Image recognition

### Smart/Self Driving
- Smart speed limiters
- Lane control
- Road train - truck
- Road train - car
- Auto braking
- Auto swerving

### Time
- 2005
- 2010
- 2015
- 2020
- 2025
- 2030

**RESEARCH DEMAND:**
- Basic research
- Applied research
- Tech. development
4.6 Noise, Vibration and Harshness

In terms of noise-reduction FURORE focused only vehicle technologies and not the whole holistic approach (including infrastructure, landscape planning, traffic management, etc.)

4.6.1. Exterior Noise

The main technologies for the reduction of exterior noise have to reflect the priority ranking of the noise reduction topics: tyres, engine, exhaust and intake system and vehicle driving condition.

For the further development of quieter tyres, a still deeper understanding of the noise generation mechanism is required despite the existing knowledge and the ongoing research activities in this field. For the reduction of engine noise, one approach will be the full encapsulation of the engine (and transmission) itself or the engine bay of the vehicle. In both cases, an improved sophisticated thermal control of the encapsulated volume will be essential to overcome any heat balancing problems.

There is further research needed to improve the control of combustion noise also under the critical operating conditions such as cold-start and warm-up phases, low idle, part-load conditions and high-load accelerations.

Within the field of vehicle exterior noise, the orifice noise of the exhaust and intake system is suitable for active noise control which might also be applicable to tyre noise. However, technologies providing efficient, reliable, producible and low cost solutions for this field of application, are still to be developed. The same applies for highly damped materials for load carrying structures of engines, gearboxes and other vehicle components, alternative powertrain systems (without internal combustion engine) and intelligent management of engine and transmission for optimum (quiet) operation.

The further development of simulation techniques has to be part of future research activities in order to simulate physical processes more precisely and to increase the accuracy of predicted results. Improved simulation approaches are needed for the noise emission behaviour of the whole vehicle and relevant noise sources as well as for the noise and vibration behaviour of individual vehicle components. Research activities to develop new or improved test methods for the vehicle noise emission which reflect the real traffic situations in a much better way than realised today must be continued.

4.6.2 Research Demands Exterior Noise

Technologies providing efficient, reliable, producible and low cost solutions for active noise cancellation are still to be developed. Research is required to establish the basic and detail knowledge which is needed for the development of new technologies. An important role is played here by computer simulation. Powerful simulation tools enable the “straight” development of complex and sophisticated solutions leading to the new technologies. Therefore, the further development of simulation techniques has also to be part of future research activities in order to simulate physical processes more precisely and to increase the accuracy of predicted results.

Such improved simulation approaches are needed for the noise emission behaviour of the whole vehicle, but in addition also for the noise and vibration behaviour of individual vehicle components. This leads to the following research demands in the fields of simulation:

- Improved modelling of the road/tyre/vehicle interaction leading to simulation tools with higher accuracy (when the interaction is investigated, vehicle and tyre cannot be considered without road)
- Modelling of the relevant vehicle noise sources with increased accuracy
Simulation of air flow and temperature within encapsulations

Modelling of relevant noise sources of alternative powertrain systems

The other research demands are directly related to the new technologies as listed above. These research demands are to be summarised as follows:

- Deeper investigation of the road/tyre contact for better understanding of the interactions;
- Development of flat track test benches for the research and development of low-noise tyres
- Advanced research on DI Diesel and DI gasoline combustion to make it more clean, more efficient and more quiet without “acceleration noise”
- Enhanced research on high strength materials for significantly higher damping with productivity on an economic cost level
- Specific research on the noise behaviour of alternative powertrain systems and their relevance for the future road transport noise
- Further research on active noise control technologies for intake and exhaust orifice noise to provide efficient, reliable and production-feasible solutions on a economic cost base
- Research on further application fields for active noise and vibration control in the automotive section (e.g. for tyre noise control?)
- Development of intelligent management systems for quieter powertrain (vehicle) operation
- Research on improved acoustic properties of light-weight materials used in the automotive sector

Finally, it must not be forgotten that the legislative limitations of the vehicle noise emissions which have the purpose to protect the environment, should be efficient for noise reduction in the real world of road traffic. As known, this is not sufficiently the case today. Therefore, many research activities are in hand to develop new or improved test methods for the vehicle noise emission which reflect the real traffic situations in a much better way.

4.6.3 Interior Noise

The issue of interior noise (and vibration) in road vehicles is very different from exterior noise in the sense that the main driving forces are not coming from legislation but from customer as well as manufacturer requirements. Interior noise aspects cannot be seen independently from other critical vehicle performances such as passive safety, vehicle handling, fuel consumption, thermal comfort, durability, communication and entertainment. For some of these parameters, this leads to conflicting design requirements. Mastering the multi-attribute compromise and pushing the global performance envelope imposes very difficult design challenges. The main sources for interior noise are combustion, rolling and aerodynamic noise. Passive noise reduction involves many of the solutions already discussed with exterior noise, such as local noise shielding, advanced mount and innovative high-damping low-weight materials, quieter tyres etc. However it will be difficult to make major breakthroughs, especially on the level of “brand” sound design purely with such material solutions.

Active noise technology has been researched and developed for more than a decade but the successful applications in vehicle design remain very limited so far. Advances on the level of materials for realising low-cost, high-performance and reliable actuator solutions, or even solutions integrated with the structural material into smart components, have a great potential. Especially in the context of low-weight designs, active control may be the only solution to reach acceptable
noise behaviour. And in view of sound “branding”, active noise control offers a direct solution, allowing adaptable target functions to be implemented. The real challenge to carry out the required performances in a design cycle of less than 18 or 24 months requires a drastic front-loading of the functional performance engineering process at the earliest design stages and a link to multi-disciplinary optimisation. This is at present not yet possible at the required accuracy and speed, requiring major breakthroughs not only on the level of simulation methods.

4.6.4 Research Demands Interior Noise

Research demands can be summarised as follows:

- Research on novel designs for advanced materials with low weight, high damping and good acoustic properties
- Research on high-performance but low-noise combustion processes and engine designs
- Research on tyre/road interaction for road noise reduction
- Research on the noise behaviour of alternative powertrain systems
- Research on the practical introduction of active noise and vibration control for vehicle interior noise application, with particular emphasis on the development of innovative materials for structural and structural/acoustical actuation
- Research on analysis and engineering methods to capture the human perception of vehicle sounds in view of vehicle brand design, and to link this perception to the actual vehicle design and engineering models
- Research on advanced simulation methods for the vibro-acoustical performance of vehicles at the earliest possible design stage, including the link to multi-disciplinary optimisation
- Research on proper target setting and target deployment at the various vehicle design levels
- Research into mastering the problems of design uncertainty and variability, introducing uncertainty into the virtual prototype models and leading to robust design solutions

### EXTERIOR AND INTERIOR NOISE - NVH

<table>
<thead>
<tr>
<th>Exterior Noise</th>
<th>Interior Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>New concepts for low-noise tyres incl. tyre/road interaction</td>
<td>Quieter idle &amp; acceleration noise</td>
</tr>
<tr>
<td>Highly damped materials / new powertrain design concepts (chassis)</td>
<td>Alternative low-noise powertrain system</td>
</tr>
<tr>
<td>Quieter idle &amp; acceleration noise (engine)</td>
<td>Advanced materials / design concepts</td>
</tr>
<tr>
<td>Active noise control</td>
<td>Standard testing procedures / target setting / human perception</td>
</tr>
<tr>
<td>Encapsulation with improved thermal control for enhanced shielding</td>
<td>Active NV cancellation</td>
</tr>
<tr>
<td>Alternative low-noise powertrain system</td>
<td>New concepts for low-noise tyres incl. tyre/road interaction</td>
</tr>
<tr>
<td>Intelligent management of powertrains for quiet operation modes</td>
<td>Intake / exhaust / sub-systems incl. simulation</td>
</tr>
<tr>
<td>Concept to decrease low frequent noise</td>
<td>Aeroacoustics</td>
</tr>
</tbody>
</table>

**Research Demand:**
- Basic research
- Applied research
- Techn. development

### Time:
- 2005
- 2010
- 2015
- 2020
- 2025
- 2030
Over recent decades the European car and truck manufacturing industry has been able to maintain or even to increase its competitiveness. One of the main enablers of this improvement has been the development and introduction of new technologies. As a result, the European share of the automotive market has shown a positive trend.

The need to stimulate and support automotive R&D activities has already been recognised by the EC a long time ago. As a consequence, over the years, a large number of research and demonstration projects have been funded by the EU in different areas of automotive technology. These projects improve aspects such as vehicle pollutant emissions, NVH, safety and fuel consumption.

In the previous European Framework Programmes a lot of projects were initiated, most of them with ambitious goals and targeting (in line with budget limitations) specific areas of automotive technology. Until now this approach has paid off. Within the above mentioned time frame, European manufacturers have contributed significantly towards the innovation in the global automotive industry. A clear illustration of this has been the development of more efficient and clean Diesel engine and aftertreatment technology. At the same time it became obvious that these research programmes suffered to some extent from a lack of integration. Research projects were sometimes overlapping with each other and/or with R&D efforts taking place on a national level. Integration was implicitly assumed to take place outside of the EU research programme, either on a company or group level.

Also, in line with this approach, there was no clear and generally accepted all-embracing technology roadmap available that could provide support or guidance when directing EU research efforts towards meeting its global objectives or when selecting between research projects. As a consequence, there was always a danger that parts of the puzzle were not dealt with in time or that some opportunities for synergy were not identified in a timely manner.

In response to the need for more integration, already in the Fourth Framework Programme, so-called Thematic Networks were created. One such network was the Premtech Thematic Network. (followed by Premtech II in FPS). The idea of the Premtech Network was to gather a large number of projects on the development of efficient and low emitting automotive propulsion technology, in order to facilitate networking between the organisation involved, to co-ordinate activities between them and to exchange and disseminate knowledge. Similar Thematic Networks have been defined to deal with noise (CALM), vehicle material technology (FLOAT, COMPOSITE), vehicle efficiency (SUVA) and vehicle passive safety (PSN1 and PSN2).

Obviously the above mentioned networks are a first level of integration. At the same time, given its objectives, the participants to such networks have been mainly (if not exclusively) members from industry and research organisations that are active in a specific field of automotive engineering.

To solve future EU environmental or transportation policy objectives, integration should move to an even higher level. Furthermore, not only automotive but also other industries such as the fuel manufacturing industry should be involved.

This was demonstrated in the European Auto-Oil Programme. As input to this programme, members of ACEA and EUROPIA worked together in an effort to extend the information on the relationship between fuel properties and engine technology. The results of this cooperation (called European Programme on Emissions, Fuels and Engine Technologies or EPEFE) were used in identifying cost-effective measures towards meeting air quality objectives.

To come up with optimum over-all sustainable solutions for achieving clean, efficient and cost-effective fuel and vehicle technology, it will be necessary to gather the expertise of all stakeholders, to make sure that all the complex interactions involved and resulting trade-offs are properly taken into account.

Integration should however not only be on a higher level and scale. To have a maximum effect, such integration should not be limited to a retrospective activity between different groups of research activities. Preferably it should be an intricate part of the definition of these research activities themselves.
FURORE is an effort to contribute towards achieving this goal. In FURORE, members from different stakeholders in the automotive and fuel industry are gathered in an effort to identify a roadmap for European automotive road transport technology.

FURORE participants come from independent research organisations and universities across Europe. They have been and are involved in many of the EU-funded projects and networks that were mentioned before. FURORE furthermore involves representatives from the European automotive vehicle manufacturers (EUCAR) and fuel manufacturers associations (CONCAWE). This Automotive R&D Technology Roadmap of FURORE is therefore a valuable input for the planning of future research initiatives. In addition, the FURORE networking activity itself is a source of ideas for future research activities.
6.1 Energy and Fuels

6.1.1 General scope / Introduction

This chapter describes the future situation for conventional and alternative fuels that will be used for transport in 2020 and beyond (their objectives, available technology options, hurdles and barriers but also the research demand. Concerning the fuel approach, 2 items appear directly:

- to propose fuels which are the best solutions for the engines which will be on the market in 2020 and beyond,
- to search for new approaches to propose conventional and alternative ways to improve air quality, fuel economy and GHG emissions.

It appears that internal combustion engines will continue to dominate the market from today until 2020, with no real market impact of non-conventional power-trains. Nevertheless, a lot of new technologies for gasoline and Diesel engines will replace the existing systems. So the future conventional powertrains based on internal combustion engines will utilise enhanced and upgraded technologies that will be detailed in the following sections of the document.

The general engine-fuel overview can be summarised as shown in figure 6.1-1.

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**Figure 6.1-1: Engine-fuel couple overview**

**Energy scenario for the next 30 years?**

Between now and 2010, the number of road vehicles on earth and their energy demand could increase by 50%. Rapidly developing countries will show a strong demand in volume, while OECD area will be primarily concerned by near-zero emission norms.

Fuels and engines for transport will have to satisfy these demands, while also remaining affordable for consumers, a global double challenge.
Even if conventional gasoline and Diesel advanced technologies including new combustion processes and new petroleum based fuels are expected to play a dominant role for many decades, the development of alternative energy sources and converters for transport must be stimulated because of their potential contribution to sustainable development.

For approximately a hundred years, oil based fuels have been the key partner of the development of road transport. The role of this liquid energy is almost total in this field due to its fundamental properties: energy density (more than 10,000 Wh/kg compared to less than 100 Wh/kg of electric battery), availability, logistics and cost which are ideally suitable for road vehicles.

Since the number of road vehicles on earth tends to increase with the global growth of the economy (figure 6.1-2), the problems related to the specific performance of the vehicle fuel consumption, pollutant and CO₂ emissions, are magnified by this growth.

The concern of society as a whole, during the recent past, with city air pollution and other problems such as noise caused by the automobile, has resulted in increasingly stringent vehicle emissions legislation and dramatic improvements in pollutant emissions from vehicles. More recently, the risk of global warming attributed to the increasing of green house gas emission is becoming of major concern for all politically responsible. The current challenge is to improve greenhouse gas emissions while maintaining low quantities of other regulated emissions.

Figure 6.1-2 indicates the quantities of energy used by road transport throughout the world during 2000. Whilst the consumption of conventional petroleum fuels is approximately 1550 mtoe which is divided between Diesel (40%) and gasoline (60%), total alternative fuels only represent about 25 mtoe, or less than 2% of total transport fuels. These figures are a clear demonstration of the low impact of alternative fuels as substitute for their standard petroleum equivalents. Ethanol, ETBE and FAME are not used in their pure state in dedicated engines, but as an additive for conventional fuels. MTBE is generally used as an alternative fuel.
6.1.2 State of the art

The development of clean technology in the automobile industry has required new fuel formulae such as lead-free gasoline in the early 1980s and sulphur-free gasoline and Diesel fuels in the near future. Starting in the 1970’s with virtually no control of exhaust emissions (in the range of 100 grams per kilometre of CO+HC+NOx), the 30 years of research into the clean automobile is about to result in the commercialisation of vehicles which comply with 2005 emission standards. This will produce a dramatic drop in these pollutant emissions even if there are still some concerns about acceptable levels for NOx and particulates (for Diesel). At the same time, fuel specifications have been strengthened in order to ensure the deployment of the new vehicle technologies to comply with the objectives of reduction of pollutant levels (table 6.1-1.)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Light Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gasoline</td>
</tr>
<tr>
<td></td>
<td>S (ppm)</td>
</tr>
<tr>
<td></td>
<td>Benzene</td>
</tr>
<tr>
<td></td>
<td>Aro</td>
</tr>
<tr>
<td></td>
<td>150 50</td>
</tr>
<tr>
<td></td>
<td>1% 1%</td>
</tr>
<tr>
<td></td>
<td>42% 35%</td>
</tr>
<tr>
<td></td>
<td>0,64 0,2</td>
</tr>
<tr>
<td></td>
<td>0,15 0,1</td>
</tr>
<tr>
<td></td>
<td>1 0,1</td>
</tr>
<tr>
<td></td>
<td>CO  HC</td>
</tr>
<tr>
<td></td>
<td>NOx</td>
</tr>
</tbody>
</table>

10ppmS max. for all fuels in Europe 01/01/2009, to be available in 2005

Table 6.1-1 - Fuel specifications and light duty vehicle emission Norms in EUROPE for 2000 & 2005
Fuel reformulation and refining technology

In the past and also currently, the world trend for improving fossil transportation fuel quality focused on two items:

- **Lead**: removal of lead in gasoline which is almost achieved. This has been attained, without reducing the market fuel octane level, by a mix of refining solutions: isomerisation, alkylation, catalytic reforming and use of new blend components like MTBE or ETBE (or direct ethanol).

- **Sulphur**: reduction of sulphur in both gasoline and Diesel fuels culminating in sulphur-free (10 mg/kg max S) fuels across the EU by 2009. This requires substantial changes to current refinery processes:

For gasoline, Fluid Catalytic Cracked (FCC) naphtha represents about 35% of the pool and more than 95% of its sulphur content. The implemented processes will combine a pre-treatment of the FCC feedstocks depending on the crude supply quality and various selective hydro-treatments taking into account the "octane" (olefins and aromatics) and the sulphur distributions as a function of cut boiling points (70% of S in the 130°C+ range). A specific challenge is to reduce sulphur while minimising loss of octane due to saturation of hydrocarbons.

For Diesel, the deep desulphurisation of gasoil has been tremendously studied in the last years (speciation of individual sulphur molecules, kinetics, more active catalyst, hydrogen management, inter stage H2S removal, fluid distribution); all these improvements as well as high pressure reactor implementation will meet the desulphurisation objectives. Even if hydrotreating is the most preferred approach, others have been developed like biodesulphurisation (technically demonstrated but not usually economical) or adsorption, probably more adapted as a polishing step. The difficulty of hydrotreatment will depend more on the chemical structure of the sulphur compounds in the crude than on the absolute sulphur level of the crude: as an example North Sea crudes are richer in refractory products (like benzo- and dibenzothiophenes) than Arabian Light.

While producing 10 ppm sulphur fuels is a significant refining challenge, which requires new capital investments, there are also important challenges to be addressed in the distribution system (pipelines, storage tanks, trucks) in order to avoid contamination with other products and to meet the 10 mg/kg maximum sulphur limit at the retail fuel pump.

It is important to mention that there are still today differences between European refinery installations due to historical demand trends as a relative heavy fuel oil demand in Southern countries or due to lighter crude supply in Northern ones. It is also clear that some Eastern European Countries refineries will have to implement more new technologies and catalyst systems because of a previous lack of investments.

### 6.1.3 Targets for future conventional fuels

Sulphur-free fuels are being introduced into the EU market in order to enable the next generation of engines and exhaust after-treatment systems to achieve very low emissions targets, with optimal fuel efficiency and durability. Nevertheless, there are continuing discussions regarding whether there are any additional benefits to be gained from further changes to other fuel properties. The recently updated EU Fuels Directive contains a review clause on other fuel properties, to be completed by 31/12/2005. This review should take account of the already implemented measures, the new technologies coming on to the market, the remaining air quality needs, GHG emissions targets and the cost-effectiveness of any additional measures.

The GHG impact of any proposed changes to fuel properties would need to be considered on a well-to-wheel basis. Europe's Auto-oil II programme has been an attempt to optimise the cost efficiency of various measures with regards to air quality targets for several European cities. For a large spectrum of fuel characteristics (from density to aromatics), several ranges of value have been evaluated. All of these simulations were based on a sulphur level of 50 ppm. Some of the issues with further restrictions on fuel specifications are discussed below:
• **Aromatics in gasoline**
  Control of the aromatics level of gasoline at a very low level would be a real issue as it is a key component in the pool for octane performance (the octane rating of virgin naphtha is low, typically 65-75), mainly produced in catalytic reforming, which is also today the best way to supply refineries with hydrogen. As FCC heavy gasoline is also rich in aromatics, a dramatic reduction of aromatics in gasoline pool would involve a complete review of the production scheme to maintain octane levels. With regards to the specific benzene content reduction (1%), the cutting of the precursor out of the catalytic reforming feed by naphtha splitter operation changes has been widely used with, in specific cases, benzene hydrogenation and benzene extraction unit implementation.
  There is no consensus today on the cost efficiency of the EU 2005 reduction down to 35% to improve air quality EU targets, taking into account all the other measures already in the pipe. As long as spark-ignition engines impose an octane constraint (in RON and MON terms), aromatics will have to continue to be a component of the pool.
  The other outlet for aromatics (benzene and xylenes) is the petrochemicals markets; but the growth which is expected in Western Europe for the next decades for benzene and paraxylene is around 0.4 Mt per year, which only represents around 1% of the aromatics in the gasoline pool.

• **Olefin Compounds**
  Control of olefin compounds will also impact the FCC unit, as the front end of the cut of the FCC stream is the main source of olefins in gasoline pool; etherification, alkylation or oligomerisation processes are potential options to convert a part of these olefins while minimising loss of octane.
  The same general remarks as for the aromatics case can be done. The reduction of the present limit 1.8% down to 1.4%, which has been envisaged by the European Parliament, is the maximal reduction without deeply implicating the FCC role.

• **Polyaromatics in Diesel**
  Control of polyaromatics in Diesel fuel, as a part of global aromatic content, is highly dependent on the crude origin. Nevertheless, cracked compounds like Light Cycle Oil (LCO) from FCC or gasoil from coker have the highest levels of polyaromatics associated with very low cetane number.
  In the context of European growing demand expected for Diesel fuel and jet kerosene, any changes to Diesel fuel specifications also have to be considered with regard to their potential impact on production volumes. The present maximum EU limit for polyaromatics content is 1.1%. Reduction in polyaromatics content would require new facilities like more active catalyst and higher pressure hydrotreatment (in order not only to saturate but also to open the rings).
  Beyond the quality issues, the Diesel fuel demand growth could also ask for new gasoil sources: hydrocracking or new high quality pool components (zero sulphur, high cetane...) from Gas-to-Liquids (Fischer-Tropsch reaction) projects may be considered.

Considering the fuel issue more in general, 2 questions can be identified:

• **what are the limits and the necessity of the reformulation:**
  It is well recognised that the development of clean technology in the automobile industry in relation to lead-free gasoline in the early 1980s and sulphur-free gasoline and Diesel fuel in the near future will result in the commercialisation of vehicles which comply with 2005 emission standards. But special attention will have to be given to particular city areas or to other transportation means such as two wheels.
A further delay of 7 to 10 years for park renewal will, unfortunately, be necessary before automobile pollution is likely no longer to be a major factor in the air quality in those countries which apply such severe norms. Any further constraints on fuel reformulation should be considered with regards to the potential air quality improvements versus extra costs and CO₂ impacts (well to tank and well to wheel).

- **what are the main requirements of the fuels used in future engines:**

  Figures 6.1-4 and 6.1-5 below list what the foreseen evolutions could be for gasoline or Diesel engine technologies and analyses the corresponding characteristics needed for fuels. At once, one can differentiate between what can be called:
  - A minimal change scenario, with limited changes in the engine requirements, without any clear-cut break. It would induce several steps, more or less deep, of fuel reformulation.
  - A maximal change scenario, which corresponds to a true breakthrough of technologies and could induce a complete review of the essential characteristics of fuels.

<table>
<thead>
<tr>
<th>Spark ignition Otto Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional combustion</strong></td>
</tr>
<tr>
<td><strong>Engine</strong></td>
</tr>
<tr>
<td>- Advanced after-treatment</td>
</tr>
<tr>
<td>- Indirect injection</td>
</tr>
<tr>
<td>- Direct injection</td>
</tr>
<tr>
<td>- homogeneous combustion</td>
</tr>
<tr>
<td>- stratified combustion</td>
</tr>
<tr>
<td>- Valve variable timing</td>
</tr>
<tr>
<td>- Down sizing</td>
</tr>
<tr>
<td>- E.G.R.</td>
</tr>
<tr>
<td>- external</td>
</tr>
<tr>
<td>- high internal rate</td>
</tr>
</tbody>
</table>

**Non - conventional combustion (CAI)**

Figure 6.1-4 : Fuel parameters and SI engine evolution
Each of these scenarios is now detailed to determine which are its consequences considering either the industrial or the research needs.

### 6.1.3.1 Fuel requirements regarding minimal change scenario

#### General sulphur requirements

For direct injection gasoline engines as well as for Diesel engines, to reach the lowest emission levels requires the use of after-treatment devices, which presently are very poorly tolerant to sulphur. Of course, the research for devices able to sustain sulphur is also important and could be a major improvement, especially for regions outside of the EU. Aftertreatment devices with improved sulphur acceptance would increase the flexibility of the sulphur content upper limit, and could help to reach a more favourable CO₂ balance (SO₂ is not the main driver, nor are road vehicles the dominant source of SO₂).

Specific gasoline requirements

The technical evolutions considering spark ignition engines could lead us to the following fuel features:

- **An significant penetration of gasoline direct injection systems, coupling stratified mode and homogeneous running conditions.**
- **Gasoline direct injection, especially under stratified running conditions could induce:**
  - An increased sensitivity to the fouling processes (mainly combustion chamber, injectors),
  - An increased sensitivity to the gasoline chemical composition,
- An evolution of the sensitivity to the auto-ignition gasoline characteristics,
- A change in the sensitivity towards gasoline volatility.

- The development of turbocharged direct injection engines, with notably reduced displacement. The reduction in the displacement of spark ignition engines is an important step towards the reduction of the energy consumption and, in line, the reduction of CO₂ emissions. Thus, it is an essential issue in the search for a fuel-saving engine/fuel system. This reduction in displacement could result in:
  - A shift or change of the octane requirement of engines, this possibly linked with a review of what an optimal octane number is, to reach the best possible performance.
  - A strong impact on fouling, but additives based on detergent property are generally used to be dealt with.
  - An impact on the chemical composition of gasoline.

Comments:
The efforts to understand the links between engines, fuels and emissions have to be continued, with special attention to the relationship between engines, fuels and fouling. The effect of the fuel on the combustion process will play an important role in reaching the most ambitious goals in term of consumption reduction.

Specific Diesel requirements
The wide-spread use of the direct injection high pressure systems, the increase in the injection pressures, the reduction of the size of the injector's holes and the increase in the recycling rates of exhaust gases are many parameters which could induce a change in the Diesel fuel requirements.

In combination with the above mentioned technologies, it is important to understand the impact of changes in Diesel fuel formulation, especially concerning the effect on the NOx/PM trade-off (figure 6.1-6). Polyaromatics content, cetane number and density are linked to engine performance, considering emissions. However, the technical evolutions that can be expected in the next 20 years make it necessary to closely examine the sensitivity of new engines and injection devices. The potential benefits from the engines/fuels interactions need to be weighed against air quality improvements and potential increased refinery CO₂ emissions from fuel changes.

As in the gasoline case, the fouling processes will get increasing importance, especially due to their possible effect on the quantities involved in the pre- and post-injection periods. Simultaneously with a significant increase in injection pressures and decrease in injection hole sizes, the vaporisation and combustion initiation processes will be notably modified, putting more emphasis on the chemical phenomena for the latter.

The chemical composition of the Diesel fuel need to be kept under review, as with direct injection under very high pressure, this could lead to some changes in the impact of the cetane characteristics. This depends on the running condition, as determined by the Diesel fuel components, which burn respectively during the premix flame and during the diffusion flame.

In addition, direct injection under high pressure and the increasing use of EGR may change the nature of the combustion, for example the relative importance of the premixed and diffused combustion.

Besides, the spreading of high pressure direct injection might increase the relative importance of other parameters already identified as important ones but still under-studied, considering their impact on injection. As an example, among the more relevant ones, we can mention viscosity, compressibility and superficial tension.

The impact of fuel physical and chemical properties needs to be kept under review as the engine technology develops. The results in the figure 6.1-6 show what changes could be made to Diesel fuel formulation to improve emissions Diesel
engines without aftertreatment. With NOx/PM aftertreatment systems, the level of “optimum” reduction of these characteristics is completely changed and significantly reduced.

6.1.3.2 Fuel requirements regarding maximal change scenario for advanced fuels

The development of the new combustion processes could be a breakthrough in engine history. HCCI, CAI, CCS are solutions which could presently turn upside-down today’s best fuel characteristics, even if they have been validated or adapted to enable their use in more conventional new generation engines.

For some experts, the changes in fuel requirements induced by this technical evolution might favour the determination of a unique fuel, yet at the same time engines using this technology may need to operate as conventional engines over part of their operating range, so the traditional fuel properties will still be important. A long transition is likely before these new concepts can replace conventional engines.

The analysis of these new combustion processes highlights especially the effect of characteristics such as vaporisation and auto-ignition. An example is shown in figures 6.1-7 and 6.1-8: with the CAI process, the wider possible running has no direct link with the fuel RON and MON. Previously, a set of studies carried out by IFP had shown that the sensitivity of direct injection gasoline engines, especially when running in stratified mode, is different considering MON from the sensitivity of MPI spark ignition engines. Although these results included a warning towards the interpretation of such an index, they were not such that its use should be completely reconsidered.

Figure 6.1-6 : Impact of fuel reformulation on NOx/PM trade-off for conventional Diesel engines
6 TECHNOLOGY EVALUATION POWERTRAIN

6.1.4 Fuel Technology Options

Reformulated fuels with higher Hydrogen content

Additional CO₂ emission in the refinery is directly correlated to a potential hydrogen imbalance, requiring new specific hydrogen plant (Steam reforming of natural gas and residue partial oxidation which could generate from 8 to 15 tonnes of CO₂ per tonne of Hydrogen). This extra demand could become likely more from the necessity to convert or "destroy" heavy residue than from extra quality for gasoline and Diesel, even if a dramatic reduction of aromatics will be highly hydrogen consuming and also impact the balance of hydrogen in the refinery.

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Figure 6.1-7: CAI operating range and gasoline RON impact

Figure 6.1-8: CAI operating conditions and gasoline MON Impact
The energy consumption for refining ranges from 4% for the simple hydroskimming type up to more than 10% for the most complex type of the crude input. But as is illustrated in figure 6.1-9, a part of this energy is transferred to the products in improving their quality.

![CO2 refinery emissions as a function of H/C of products](image)

**Figure 6.1-9: CO₂ refinery emissions**

Recent discussions on evolution in fuels have been focussed on improvements in air quality, but increasingly it is important to take into account the impact on fuel economy and global CO₂ emissions. Increasing the hydrogen content of fuels can lead to lower vehicle CO₂ emissions, but since this involves additional refinery processing, it can only lead to an improvement in global CO₂ emissions if the extra energy consumed in the refineries is compensated by an increase in the efficiency of the engines which consume the fuels. Any further developments in fuels should be focussed on those properties which enable efficiency gains on the engines and which are evaluated on a well-to-wheels basis.

Further penetration of the Diesel engine also in typical gasoline country such as the USA is the last but not the least uncertainty factor. This evolution would have an enormous impact on the product market equilibrium (price, import trade,...) and the refinery operations (shift from FCC conversion to Hydrocracking conversion), although existing technologies can do the job at least partially.

### 6.1.5 Alternative Fuels

The diversification of the sources of energy for traffic is a true challenge for the next 20 years. The main alternative fuels already used, some for a considerable time, are:

**Liquid petroleum gas (LPG) from refineries or from condensates associated in wet natural gas fields:**

LPG motor fuel is certainly the most commonly used alternative motor fuel. In 1999, 5.5 million vehicles worldwide ran on this type of fuel, with consumption amounting to 11.5 Mt/yr. This only represents about 6% of the global consumption of LPG, which is used mainly as a domestic heating fuel (nearly 50%). This butane/propane blend can either originate directly from gas recovery operations at the producing field or from the refining of crude petroleum. In France, refining
accounts for nearly 74% of LPG motor fuel production, 60% in California and 40%, on average, in the rest of the world. In Europe, the use of LPG motor fuel was introduced in the 1950s, especially in Italy and the Netherlands, where tax incentives made it more attractive. In France, for example, it has become less expensive than Diesel fuel, following the implementation of successive tax incentives since 1996 (-1F/l in 1996, -0.4 F/l in 1998 and -0.3F/l in 1999). In Japan and South Korea, the propane/butane blend is primarily used by taxis, which were granted subsidies to ensure their conversion from Diesel fuel to LPG. In the United States, the use of LPG motor fuel in the transport sector increased during the 1970s and ‘80s, especially in captive fleets of taxis, post office vehicles, buses, delivery trucks, et cetera.

It would be unrealistic to expect the generalization of LPG motor fuel to the entire automotive fleet. For one thing, there are issues to be resolved concerning local/regional availability or the distribution networks. This being said, the global volumes channeled into transport applications in the future could be fairly large. Gas consumption is expected to grow by 3 to 4% over the next two decades while LPG motor fuel production expands even faster (up 4.5 to 6% per year)[Jean Pierre Jonchère, Panorama 2001 report]. Another implication of using LPG is that, to some extent, the sources of transport energy supply could be diversified.

Today, most of the vehicles running on LPG motor fuel are commercialized with bi-fuel systems (gasoline and LPG motor fuel) in order to help compensate for the lack of filling stations. In France, LPG motorists can fill their tank at fewer than 10% of existing service stations. Of course, this solution does not optimize performance for either motor fuel. Yet new LPG engines produced by OEM’s achieve EURO 3 emission levels; however they do not comply with EOBD requirements. It is likely that with clever adjustments to the engine management system, they will also comply with EURO 4 regulations (including EOBD) In other words, the use of LPG motor fuel does not guarantee “clean” performance. Like conventional motor fuels, it will be necessary to develop the vehicle technologies specifically to obtain the desired levels of polluting emissions. This could prompt the industry to reconsider the dual-fuel concept.

Finally, vehicles running exclusively on LPG motor fuel turn in a good environmental performance:

- Thanks to a high/fairly high octane number, the propulsion system obtains good energy efficiency.
- It emits no sulfur except via odorant (contains S), lead, or benzene, and only low levels of evaporative emissions.
- In comparison with gasoline, it reduces in monobaruration mode the regulated vehicle pollutant emissions (HC= -73%, NOx = - 79%, CO = - 87% compared to the 2005 standards—Results obtained for the Peugeot 406 1.8l with direct injection of LPG); anyway this will depend on the relative levels of after-treatment on gasoline / LPG engines.

For CO2 emissions, it clearly outperforms gasoline fuel but does not achieve Diesel performances (cf. Table 6.1-2). The costs of this technology are slightly higher than those associated with traditional petroleum motor fuels, because LPG motor fuel is handicapped by greater distribution problems.

**Ethanol (ETOH) mainly in Brazil and the United States from wheat, sugar beet or sugar cane:**

In Brazil, the oil shocks of the 1970s marked the start of mass production of ethanol as a replacement fuel. Starting in 1979, the State assured the automotive industry that this fuel would be available in all major cities. This guaranteed the establishment of a market for dedicated vehicles, although it is also possible to use ethanol as a gasoline additive.

During the late 1980s and the early ’90s, the decrease in crude prices and the liberalization of sugar cane production made the latter more attractive. Furthermore, the State was forced to reduce its subsidies. It implemented a new policy that no longer encouraged the production of vehicles running exclusively on ethanol. For nearly 15 years, all of the gasoline sold has contained ethanol (content: about 22%). Today, the Brazilian automotive fleet includes nearly 4 million dedicated
vehicles and some 13.5 million vehicles using an ethanol-gasoline blend. Total consumption of ethanol as a motor fuel amounts to 5 Mt (nearly 40% of national production).

The second country to launch a large-scale initiative to promote ethanol was the United States. In 1978, President Carter inaugurated the first ethanol program by passing the Energy Tax Act to provide tax relief for its production. Ethanol is used as a replacement fuel, blended with gasoline: E10 (a blend that is 10% ethanol and 90% gasoline) and, to a lesser extent, E85 are the most commonly used. Since the late 1970s, ethanol has been granted a number of tax incentives. Until 1990, E10 benefited from a tax reduction of 60 cents/gal. of ethanol. This exemption, slated to end in 1990, was then extended: tax would be reduced by 54 cents on the gallon until 2000, then decline to 53, 52 and 51 cents/gal. until termination in 2007. On top of these federal incentives, some Corn Belt states offered exemptions of up to 20 cents/gal [Ethanol as a gasoline replacement – technical aspects – situation worldwide, IFP Report No. 56 141, X. Montagne, A. Jaecker, N. Jeuland, July 2001].

In European countries, ethanol is not consumed directly as a motor fuel. It is blended into gasoline, either in the form of ethanol or in the form of ETBE (produced from isobutylene and ethanol).

Basically developed in the wake of the oil shocks to further energy independence, the ethanol technology presents a contrasting environmental balance:

- It results in a slight improvement in CO and HC emissions.
- It is neutral or aggravates the situation with respect to NOx emissions.
- It can provide a positive contribution to the CO2 emissions balance, depending on the production processes used.
- In contrast, when blended with gasoline in proportions lower than 85%, ethanol increases evaporative emissions and can therefore adversely affect tropospheric ozone levels.

The most problematic issue concerning this motor fuel is certainly cost, situated well above that of oil technologies (cf. Table 3). Brazilian ethanol obtained the best performance for two reasons: the effects of scale due to mass production and also the use of sugar cane, a particularly favorable raw material that yields high energy and CO2 efficiencies.

In Europe, it will not be possible for this technology to reach economic equilibrium in the short term without subsidization. In the longer run, depending on technical progress and what happens to the price per barrel, these conclusions may be vulnerable to challenge.

Compressed Natural Gas (CNG) in Argentina and in Italy:

The industry has seen substantial growth in gas applications, especially in the domain of electricity. As a result, the natural gas vehicle (NGV) has attracted global interest since the early 1990s; some countries have undertaken ambitious development programs. They have implemented tax incentives according to their own scale to promote the use of this motor fuel. Today, there are 1.2 million NGVs worldwide.

This being said, NG motor fuel only accounts for a very small percentage of total consumption for this primary energy source (mainly used to produce electricity and for heating) and of the global automotive fleet. Nonetheless, we may expect to see policies promoting the use of this technology in the future. Its use is perceived to help attain objectives relative to energy source diversification and security of supply, considering that the world’s proven natural gas reserves are slightly higher than those of oil (about 150 billion toe). Security of supply for European Union will have to be kept under review as most of the reserves are concentrated in Russia and the Middle East. However, the NG motor fuel must
be stored at high pressure and requires capital-intensive infrastructure, two facts that inhibit large-scale development. Captive fleets of vehicles that make frequent trips in downtown areas represent its highest potential.

In addition, the NG motor fuel presents environmental characteristics that argue in its favor:

- Greenhouse gas (GHG) emissions from vehicles are good, about 3% lower than a Diesel fuel solution thanks to a favorable C/H ratio and a high octane number. However, due to the high well-to-tank GHG emissions, mainly associated with natural gas transport, the overall GHG emissions for natural gas are lower than for gasoline and slightly higher than for Diesel. (see Alternative Fuels Contact Group intermediate report). However these results are very sensitive to the engine technology choice for natural gas and to the assumptions for the natural gas transportation in the future.

- It performs well with respect to local pollutants (potentially obtaining results that are lower than California’s ULEV standard; Emissions for a NG-powered Honda Civic with a dedicated engine).

- On average, the effluents given off by NG-powered engines are two times less reactive to the formation of tropospheric ozone than those produced by gasoline engines.

- If used on a large scale, close attention will have to be paid to its methane emissions: methane has an especially harmful impact in terms of greenhouse gases (21 times greater than CO2).

As we previously noted for the LPG vehicle, it will not be possible to commercialize the NG vehicle without further development, to bring it into conformity with the required emissions levels and the EURO IV standards (2005). To improve the performance of an NG vehicle with respect to regulated pollutant emissions, it used to be enough to subject it to a summary adaptation based on a gasoline engine. But the levels required in 2005 will require substantial optimization, and might even lead to a reconsideration of the dual-fuel concept.

As things stand, NGV costs are relatively high and not necessarily very representative: it is still a fledgling technology. The selling prices posted at a service station in Guyancourt, not far from Paris (4.5 FFr/nm3) give us some idea of cost, knowing that they could drop due to the effects of scale. At present, given the low number of gas vehicles, consumer supply costs are higher and tax incentives are required to make them a viable option.

An issue which is very important with gas engines is the need to deal with fuel quality variation. Finally, natural gas could be a pathway to the introduction of hydrogen, as a fuel for transportation uses a blend of up to 20% of hydrogen with natural gas.

**Fatty Acid Methyl Ester (FAME) from vegetable oil biomass as an additive to Diesel.**

Vegetable oils produced from rape seed or sunflower seed, which cannot be used directly to power a modern Diesel engine, are transformed by transesterification with methanol to obtain vegetable oil methyl esters (VOME). Up to a concentration of 5%, it can be distributed at the pump without any specific reference to the customer. Today, most French refineries add it to the motor fuels for sale in proportions varying from 2 to 5%. At concentrations of up to 30%, it is used in captive fleets with no need for any deep technical restrictions but an extension of warranty is not given by all truck manufacturers. For private cars, there are few equipment suppliers (the Bosch one is restricted to 5% max.) and car manufacturers which go above 5%.

Since 1992, the French production of VOME has risen sharply (+357%), but it still does not cover demand emanating from the oil companies. Diester industry would like to open a new production unit (capacity: 100,000 metric tons). We note that this technology is highly dependent on an advantageous tax policy, because production costs are higher than
for petroleum motor fuels (Table 3). In addition, a difference can be seen between the costs of the French technology (which leads Europe in this domain) and those put forward by the IEA. For the VOME technology, cost is one of the most important inhibitors to a more general use, even if the environmental balance associated with this technology is favorable.

- It reduces the emission of particulates (-20 to -40%) for 30% blend, under current European driving cycle for EURO II/III private cars and trucks without any after-treatment means. In 2005, the impact will be clearly lower.
- It obtains a good GHG balance (lowering well-to-wheels CO₂ emissions by as much as 60%).

**Ethyl-tertiobutyl ether (ETBE) as gasoline additive.**

Substitute to MTBE because of its better bio-degradability; this latter oxygenated compound is currently being challenged. In California, it could be banned (effective early 2003) for reasons related to the contamination of drinking water systems. Ethanol is being considered as a replacement solution. No such measures are being considered in Europe at the present time.

The emerging alternatives can be studied considering 3 possibilities:

- **Fully interchangeable alternatives**

  These are energy sources that can be used instead of classical hydrocarbon fuels, without any technology concern. A close examination of these alternatives leads to a restricted set of options. Indeed, most of the possible alternatives can be used directly as such, but they could have an increased potential if they are accompanied by an improvement of the technology. Thus, only FAME and the hydrocarbon blends with low ethanol content will be kept in this first category.

- **Almost interchangeable alternatives, compatible with current conventional engine technology, but needing fuel production technology development**

  The alternatives that can be used directly on engines are quite numerous, and, in most cases a simultaneous improvement of the technology leads to a very significant improvement of the performance.

  - Gas-To-Liquids: due to their intrinsic characteristics, cetane number and chemical composition, GTL appear as a very promising complement to Diesel fuels, more as an advanced fuel. Used as a blending component, GTL Diesel could enable increased production of Diesel fuel meeting CEN EN590, to respond to increasing Diesel fuel demand in Europe. Used as pure fuels, they have lower emissions of regulated pollutants. However, their impact on the auto-ignition and on the combustion processes requires more study. Although they could enable a specific development of the technology to use these qualities at their best level, significant fuel consumption improvements with GTL fuels have not yet been demonstrated.

  Discovered in 1923, the synthesis of Fischer-Tropsch Diesel fuel has generally been implemented only when petroleum products are in short supply: in Germany during World War II and in South Africa during the oil embargo. In both cases, the synthetic fuel was produced from coal. Like many alternative solutions, this process was revived during the two oil shocks. Now, there are plans to produce F-T fuel from natural gas in order to exploit stranded fields. Many companies are exploring this avenue, including Shell, which led the market for many years in this technology. Since 1993, the Anglo-Dutch company has operated a production unit of this type in Malaysia (12,000 bbl/day).

  Fischer-Tropsch Diesel fuel seems especially attractive for the formulation of future Diesel fuels. It contains no sulfur or aromatic compounds, and has a high cetane number. This translates into good performance with respect to local
pollutants: unburned hydrocarbon and particulate emissions are significantly reduced depending on the blend volume (ref. Shell Esslingen paper). In contrast, more or less like DME, its production is penalized by high energy consumption. Consequently, compared to traditional motor fuels, this technology carries a handicap with respect to CO₂ emissions. In developing this technology in the future, it will be necessary to optimize the GHG aspects. Although we only have an approximate idea as to cost, the profile looks interesting, situated between DME and the petroleum products. This Diesel fuel would be easy to distribute because existing infrastructure could be used, without any particular modification or investment.

FT products can be seen as able to represent a significant market share. Integrated gas to liquids process from Syngas preparation to upgrading part (hydrocracking and isomerisation) through a Fischer-Tropsch unit, are rather investment intensive. In recent years, reduction of these costs has been achieved, linked mainly to the increased possible size of the project and to the specific equipment, as well as to catalyst activities.

- BTL and CTL: The case is similar to the above case, with a diversification of the carbon sources. Synthetic fuels obtained from the biomass could be a promising alternative, though practical scale potential will be an important consideration.

Alternatives needing new technologies

These alternatives requiring the development of dedicated technologies are:

- Blends with high biofuel contents (mainly ethanol or oil esters)
  These technologies are available, though as described earlier, costs are considerably higher than Diesel fuel and are only made feasible with tax incentives at the time.

- Dimethyl Ether or DME, produced in a very similar route as methanol without high toxicity character, can be considered as the equivalent of LPG for Diesel technologies.
  Produced from natural gas at a rate of about 150,000 t/an, DME is primarily used for the propulsion of aerosols. Comparable to an LPG motor fuel for a Diesel engine, this gas, whose production process is similar to that used for methanol, presents an environmental advantage with respect to local pollutants: DME vehicles give off very low emissions that meet California’s ULEV standards. In contrast, when produced from natural gas, it does not present any particular advantage in terms of GHGs (cf. Table 6.1-2). For now, its main disadvantage is the cost of the technology. Because the process attracting interest (ATR) is new, it is hard to cost. Initial estimates indicate relatively high values, given that the production process is very energy intensive and the distribution stage constitutes a handicap (as we saw for the LPG motor fuel). In addition, the vehicle would require adaptation, i.e. of the fuelling system.

**Hydrogen**

Generally used as an industrial gas (99%), hydrogen is used in the production of ammonia (50%), refining (37% and generally a by-product of naphtha catalytic reforming), methanol synthesis (8%) and the production of other specialty chemical products. A mere 1% of the world’s total volume of hydrogen is exploited as an energy source, in the space sector as rocket propellants.

For years, hydrogen has been the subject of heated debate: some hail it as the ultimate motor fuel, others call it an unrealistic solution. Often designated as the only sustainable alternative to petroleum motor fuels, hydrogen can combine easily with oxygen in the air to yield energy and, under the best of circumstances, water as its only by-product.
In the transport sector, the prospects of hydrogen are closely linked to those of fuel cells even if the use of hydrogen directly in an internal combustion engine has been also considered, generally in a fuel blend (an important problem in this respect is the NOx formation). Revived in the early 1990s by the Canadian company Ballard and subsequently by Daimler Chrysler, the PEMFC technology has received a lot of media coverage in recent years. In a process exactly the opposite of electrolysis of water, these membrane systems make it possible to produce electricity from a hydrogen source and air. The only emission given off by this conversion process is water vapor, providing an alternative to the electric car as a zero emission vehicle. It is interesting to note that the relative failure of electric cars in the 1990s as a credible solution to urban air pollution was partly responsible for bringing fuel cell technology into the spotlight. The fuel-cell automobile is exhaust-free like its battery-powered rival, but has none of the disadvantages of the electric car, namely the lengthy recharge time and the limited range between recharges. As things now stand, its principal shortcoming is that it uses hydrogen. If the goal is the large-scale development of private cars, this technology presents a number of handicaps: neither production nor distribution systems are in place and no suitable storage solution has been found for transport applications.

But there is a price to pay for this advantage: the production of hydrogen requires a great deal of energy. Two routes are more or less explored: “centralized” hydrogen production for storage on the vehicle and on-board hydrogen production to the benefit of the liquid raw material distribution and storage facilities.

“Centralized” hydrogen production
Today there are few methods for producing hydrogen that are currently used or under research and development: it is extracted from water by electrolysis (marginally ca. 5%) and mainly produced by steam methane reforming.

- Steam methane reforming
This is the most common among several similar processes, including autothermal reforming and partial oxidation. It is a two-step process: the first reaction is the conversion of a mix of methane and steam in a syngas (CO+H₂+impurities on nickel oxide catalyst at 900°C and 30-40 bar pressure), the second one is a water gas shift reaction to convert CO/H₂ in H₂/CO₂ (at about 200°C and 30-40 bars).

The energy efficiency for the conversion of natural gas in hydrogen is about 78%, but is reduced down to 58% if the carbon dioxide is captured and stored in a depleted oil field as an example.

Large scale production of renewable hydrogen is also a major issue because of the final cost of the biomass resource area, to be consistent with economic gasification unit size. For a capacity of 80,000 tonnes per year of hydrogen, 500,000 tonnes of biomass is required which requires around 50,000 hectares area.

- Electrolysis
This solution is not used on a wide basis because electricity (52 kwh/kg of hydrogen) is three to five times more expensive than the equivalent energy derived from hydrocarbons, except in some specific places where large hydroelectric facilities are available.

One of the limits of the system is the low overall energy efficiency (< 30%), which leads to high cost. Ideally it would be appropriate to operate the electrolysis cell at the highest possible temperature, which incurs operational difficulties due to the water vapor pressure and requires support components to be fabricated to operate at elevated pressures. Today many researches are working to reduce the extra cost resulting from more efficient electrolytes as Proton Exchanging Membranes (PEM).
Other advanced methods

There are less conventional ways to produce hydrogen from water by water splitting. These include thermolysis, steam hydrolysis, thermochemical splitting and biological processes. However all these solutions require long term research programmes before reaching commercial viability.

As an example, only very few of the thermochemical cycles are still thought to have any possible chance for future industrial use. One of these is the sulfur-iodine cycle which gives a very good idea of the huge problems to solve: high temperature (850°C), corrosive nature of many of the reactants (sulfuric acid)...

Table 6.1-2 below provides estimates of the relative efficiencies of various hydrogen production processes:

<table>
<thead>
<tr>
<th>Process</th>
<th>Maximum Process Temperature, °C</th>
<th>Overall efficiency, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Methane Reforming</td>
<td>900</td>
<td>78</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>90</td>
<td>20-30</td>
</tr>
<tr>
<td>High Temperature electrolysis</td>
<td>800</td>
<td>40</td>
</tr>
<tr>
<td>Sulfur iodine thermochemical cycle</td>
<td>850</td>
<td>45</td>
</tr>
<tr>
<td>Sources: IFP from SRI consulting</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

On-board hydrogen production

To get around the constraints associated with the distribution of hydrogen, several research teams have attempted to adapt fuel-cell systems to transport applications by incorporating a reformer to produce hydrogen from a liquid motor fuel (such as methanol, as mentioned previously, but also gasoline). Many of the problems relative to system compactness (fuel cell + reformer) have been solved, but substantial progress is still needed in a few areas, including engine start-up time (it now takes about 10 minutes) and overall dynamics (e.g. transitory speeds). One way to bypass these difficulties would be to use a battery to take over from the fuel-cell propulsion system during the start-up phase.

Compared to the solutions powered directly by hydrogen, this solution no longer enjoys the environmental advantage represented by the zero emission vehicle, because operating a reformer will generate pollutants at a level that has yet to be determined. It is true that test evaluations have not accounted for unit start-up, the most penalizing period.

Among the liquid motor fuels considered, methanol is the easiest to implement on the vehicle, though distribution issues would need to be addressed. Hydrogen is generated from methanol at a temperature of about 300°C. For GHG emissions, this solution represents an improvement over the conventional internal combustion engine. Other research is focusing on the development of on-board generators to produce hydrogen from petroleum product derivatives. This solution is not only more difficult to develop from the technical standpoint, but it substantially decreases the efficiency of the fuel-cell system. Therefore, this solution does not contribute any significant gains in terms of GHG emissions, compared to the conventional technologies. Refering to the GM WTW study - the difference between MeOH and gasoline reformer options is not sufficiently large to reject either one, especially since they all need further development.

These elements of information concerning the possibilities of using hydrogen as an energy vector for transport mainly serve to indicate the need for further research. In the event of fierce competition between the various engine/motor fuel
pairings of tomorrow, major advances—regarding hydrogen storage, for instance, or the reduction of production costs—will be needed to ensure the medium- or long-term development of options involving hydrogen. Compared to other alternative motor fuels, its estimated costs are among the highest. Moreover, the CO₂ balances present contrasting results, favorable or unfavorable depending on the type of hydrogen source and storage method selected. These conclusions demonstrate the need for substantial research, especially on the hydrogen storage problem, which seems to be the key to the future of these technologies.

Well-to-wheels analysis of the energy and greenhouse gas balance of the various fuel/power-train pathways is essential. This needs to be continually reviewed as the technologies evolve.

6.1.6 Hurdles and barriers

- the further development of conventional fuels:
The principal challenges for these fuels is likely to be the emergence of new characteristics to replace traditional octane and cetane number and the possibility of converging towards a unique fuel to meet the needs of HCCI engines. However, this transition would take a long time, since even HCCI engines would need to operate as conventional engines over part of their cycle.
- Alternative fuels: infrastructure, storage, toxicity, cost, supply

It was at one time considered obvious to attribute to alternative energy sources specific advantages regarding local pollution to the point where fuels would be considered « clean » as opposed to petroleum based fuels considered to be « dirty ». This approach is increasingly out-dated, since all vehicles, irrespective of the fuel used, must comply with ever more strict anti-pollution standards.

![Figure 6.1-10: Ozone potential of various engine/fuel couples](image)
Important work carried out by the oil industry, the automotive industry, and the European Commission, between 1990 and 2000, within the framework of the “Auto-Oil” programmes have perfectly demonstrated the irrelevance in the idea of “clean” as opposed to “dirty” fuel. A reversal of roles can even be observed. Hence the advantage of gaseous fuels over Diesel, due to the emission of particles, disappears, and is even reversed, as soon as Diesel vehicles are fitted with highly efficient particle filters.

Nevertheless, it is clear that all fuels, whether they be conventional or alternative, can possess special environmental properties. For example, Diesel losses due to evaporation are slight, ozone potential as shown by figure 3, and the toxicity of gaseous fuel (LPG, CNG) specific unburned hydrocarbons are very low, but only if the absolute values of these emissions are minimised by the technology of the vehicle. The progress of automotive cleanliness is strongly illustrated by the ever-increasing weight of emission sources that have been considered negligible in the past. For example, figure 6.1-10 shows that one single 2-wheeler with 14 grams/km has the same ozone potential as 700 CNG cars at 0.02 gram/km.

Global warming risk and fossil energy limits
The scientific working group in charge of climatic change (IPCC, International Panel on Climate Change) widely accepts that the rapid increase in CO2 and other greenhouse gases in the atmosphere gives the main explanation to the global warming since the beginning of the industrial age. This warming could generate long term perturbation in the ocean and atmospheric streams with potentially catastrophic effects for humankind. This is why CO2 emission control is becoming an increasing priority shared by most of the countries in the Kyoto protocol in 1997 and more recently in 2000 confirmed at the Marrakech conference.

Applied to the road transport domain, the CO2 reduction goal is highly correlated to the reduction of fuel consumption of the vehicles. This is of course a very positive step for the final consumer as well as for the general interest of fossil energy long-term management. For these reasons, all the stakeholders, policy makers, public authorities, car and energy industries should, with a strong priority, implement CO2 control and energy diversification strategies.

The CO2 evaluation of conventional and alternative fuels for road transport
Numerous CO2 evaluation studies of fuels, from “well to wheel” are carried out by major public and industrial players in the fields of energy and transport. Presented below is a synthesis of a large amount of data originating from publications and IFP internal studies (ref.2, 3).

Evaluations of CO2 emissions are expressed in grams of CO2 per kilometre. This evaluation results from the product of CO2 production by fuel energy unit by vehicle energy efficiency. These 2 factors respectively expressed in grams of CO2 per kWh and in kWh per kilometre are sufficiently decoupled to disassociate the impact of fuel production technologies from that of the vehicle energy efficiency. Table 2 shows a set of characteristic values for various considered energy + vehicle technologies.

Retained performance values are characteristic of average size private cars produced in Europe during 2000, and fitted with advanced technology engines such as direct injection for liquid fuels. Diesel engine vehicle performance has been selected at 0.54 kWh/km, which corresponds to a fuel consumption of 5.4 litres per 100 kilometres.

As a working hypothesis, a natural gas vehicle can have a performance which is near to that of a Diesel engine, given the properties of gas combustion (very high octane level). For all other spark ignition engine vehicles, a performance of 0.66 kWh/km was retained, i.e. 18% less than that of Diesel vehicles. Internal combustion engine performance has, apart
from reference values, a considerable potential for progress which will take shape, prior to the end of the decade, in the industrialisation of new processes which are at present in the research and development stage.

Variable distribution, new combustion processes by self-ignition, numerous methods of electrical-thermal hybridisation, weight reduction, are just a few examples of the most promising options. Hybrid gasoline-electric can be credited with 20% energy efficiency improvement and 15% for Diesel-electric.

The performance of Proton Exchange Membrane (PEM) fuel cell vehicles using pure hydrogen fuel has been established at 0.4 kWh/km since this corresponds to values demonstrated by one highly-developed prototype vehicle. This efficiency is 66% better than that of a vehicle with a gasoline engine.

Primary energies implemented for the production of final energies should be mentioned. Fischer-Tropsch Diesel, Dimethyl Ether (DME), hydrogen (compressed or cryogenic liquid) are all derived from natural gas. Hydrogen can also be produced by electrolysis with carbon-free electricity if supplied by nuclear, hydraulic or solar energies. Biofuels such as ethanol (ETOH) and fatty acid methyl ester (FAME) are produced from wheat, sugar beet, sugar cane and vegetable oil bio-mass.

Gasoline and Diesel, both complying with European specifications for 2005 (very low sulphur content) are derived from the refining of oil. LPG is produced from oil refining but also from oil and gas fields.

Values listed in table 6.1-3 require the following remarks:

In the domain of conventional fuel, the Diesel engine is an outstanding energy converter for road transport and hence provides low CO₂ emissions. Hybrid electric-gasoline and electric-Diesel bring further advantages in terms of efficiency and pollution by optimising the use of the internal combustion engine in its cleanest and best efficiency range. As described earlier, natural gas lies between gasoline and Diesel on well-to-wheels CO₂ emissions. This positioning stems from the excellent hydrogen/carbon ratio and high octane number of natural gas, counter-balanced by the energy needed.
to transport it to the market. Direct use of natural gas in an internal combustion engine optimised for this purpose is more efficient than other alternative fuels derived from natural gas, due to the energy consumed in the conversion processes.

It should especially be noted that the use of cryogenic hydrogen in a fuel cell converter emits twice as much CO₂ per km as the direct use of natural gas in an internal combustion engine. LPG, due to its favourable hydrogen/carbon ratio, compensates for poor engine performance and has a CO₂ emission performance per kilometre placed between Diesel and gasoline. Fischer-Tropsch Diesel emits 22% more CO₂ than conventional Diesel, which cannot be compensated for by an improvement in performance originating from the quality of this synthetic gas oil.

Bio-mass fuels deserve a special attention. Since 50% (for FAME) and 70% (for ethanol) of the CO₂ produced originates from the capture by photosynthesis in the ambient atmosphere, the corresponding amounts are simply recycled and do not contribute to the increase of the CO₂ concentration in the atmosphere. The only CO₂ to be considered is due to fossil energy used in the production process of these bio-fuels. As a consequence, they have become more attractive, vis-à-vis their CO₂ evaluation, if the energy required for their production and distribution limits the use of fossil carbon. But this should be completed by an in-depth ecological analysis.

**Economics of conventional and alternative fuels**

The end-user price of conventional fuels for transport consists of the market price plus tax, for which precise figures are easily established. Alternative fuels without significant market can only be evaluated for their cost, the tax strategies being an open and very difficult question. Since many decades, transport fuels are powerful tax collectors in many countries. In the 15 countries of the European community, the amount of tax on gasoline and Diesel represents more than 70% of the final price and represented 180 billion Euros of public income in 2000. The average tax per litre of gasoline is more than EUR 0.70 and more than EUR 0.40 per litre of Diesel.

A number of sources estimating the production and distribution costs of alternative fuels have been compiled in addition to internal IFP studies (ref.4 and 5). It seems important to differentiate production and distribution costs, the first being sensitive to the nature and the cost of the primary energy, the second being sensitive to the physical nature of the fuel i.e. liquid, gaseous, and its characteristics such as safety, toxicity. The results are presented in table 6.1-4. For Diesel and gasoline, the European average (1998-2000) market prices are given. For alternative fuels without market, ranges mini-maxi of estimated costs are given. It is not surprising to observe that alternative fuels are much more expensive than conventional gasoline and Diesel. The distribution costs vary from a low EUR 0.08 for gasoline and Diesel to a high EUR 0.72 for compressed hydrogen at 300 bar. The first alternative fuels already with niche markets, i.e. LPG, CNG, FAME have their tax adjusted to a very low level to make them attractive to the consumer. Figure 8 gives an overview of the prices of the various energies and their CO₂ emissions well-to-wheel, combining data of tables 6.1-3 and 6.1-4. The range of European tax on gasoline and Diesel is also given to suggest some flexibility in this parameter to adjust the consumer price of alternative fuels to attractive levels.
All the fuels below the trend curve i.e. Diesel, CNG, ethanol and FAME have at the same time good CO₂ and economic performance. Synthetic Diesel FT, DME and hydrogen from natural gas are more questionable. Some CO₂ value can be drawn from such an analysis.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Engine</th>
<th>Production cost estimate</th>
<th>Distribution cost estimate</th>
<th>Energy price without tax estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Europe</td>
<td>Diesel</td>
<td>0,16</td>
<td>0,08</td>
<td>0,24</td>
</tr>
<tr>
<td>gasoline Europe</td>
<td>SI</td>
<td>0,19</td>
<td>0,08</td>
<td>0,27</td>
</tr>
<tr>
<td>Diesel FT</td>
<td>Diesel</td>
<td>0,28 0,42</td>
<td>0,10</td>
<td>0,38 0,52</td>
</tr>
<tr>
<td>GPL</td>
<td>SI</td>
<td>0,17 0,25</td>
<td>0,20</td>
<td>0,37 0,45</td>
</tr>
<tr>
<td>NG</td>
<td>SI</td>
<td>0,10 0,18</td>
<td>0,25</td>
<td>0,50</td>
</tr>
<tr>
<td>FAME</td>
<td>Diesel</td>
<td>0,39 0,57</td>
<td>0,10</td>
<td>0,49 0,67</td>
</tr>
<tr>
<td>EtOH Brazil</td>
<td>SI</td>
<td>0,36 0,49</td>
<td>0,15</td>
<td>0,51 0,64</td>
</tr>
<tr>
<td>EtOH France</td>
<td>SI</td>
<td>0,65 0,85</td>
<td>0,15</td>
<td>0,80 1,00</td>
</tr>
<tr>
<td>DME</td>
<td>Diesel</td>
<td>0,20 0,33</td>
<td>0,20</td>
<td>0,40 0,53</td>
</tr>
<tr>
<td>comp.H2 ex NG</td>
<td>FC</td>
<td>0,26 0,36</td>
<td>0,72</td>
<td>0,98 1,08</td>
</tr>
<tr>
<td>comp.H2 Elec.France</td>
<td>FC</td>
<td>0,84 1,12</td>
<td>0,72</td>
<td>1,56 1,84</td>
</tr>
</tbody>
</table>

Table 6.1-4: Estimated price of alternative energies compared to conventional

Figure 6.1-11: Energy price without tax and CO₂ emission
6.1.7 Research demand

Conventional fuels

The completion of the set of indices establishing this prospective view is of major importance as the penetration of these new combustion processes leads to two main axes for research:

- The determination of optimal formulations for running in CAI, HCCI, CCS, ... mode;
- The definition of new characteristics (or the renewal of existing characteristics).

The combustion modes CAI and HCCI are new steps of the technological development and their needs considering the fuel may require a major change in fuel formulation. The studies to be done at first should focus on the determination of formulation that is unavoidable to help to enlarge the running range of non-conventional engines. Yet, with the present knowledge, the running range of the CAI and HCCI modes is narrow and this weakens their capacity. Formulations able to support very low speed or very low load regimes or, at the opposite, high speed / heavy load regimens would then have a first line of interest. Besides, nowadays some conditions can only be reached with conventional combustion modes. The challenge for the fuel of the future would be to enable running all over the engine map.

The studies should focus on two major aspects:

- The chemical composition and the auto-ignition characteristics (hydrocarbons, oxygenated species, ...);
- The physicochemical characteristics linked with the vaporisation process.

Advanced and alternative fuels

- Cost reduction from well to wheel is the key action for the alternative fuels in general, as the technical potential for most of them, particularly biofuels, LPG or NGV can be considered as demonstrated. In this way, the elaboration of technical and socio-economical strategy to avoid the chicken-and-egg dilemma is dramatically crucial. If there are no improvements in this area, alternative fuels will remain marginal or for niche markets or will wait to become competitive from the future fossil fuel prices or long-term public subsidies.

- Storage technology for gaseous fuels to ensure an optimal range for vehicle,

- Safe and inexpensive distribution system for hydrogen to assure a future public and regulator acceptance,

- Hydrogen production from renewable source / via electrolysis with higher performance (but this way will be deeply dependant on the chosen electricity production system for its environmental efficiency) and more generally, global environmental evaluation of this energy vector.

- Is there a place for multiple (4 or 5?) massive transportation fuels with dedicated engine technology, while today only two are dominant with very close engine technologies and the same distribution system.

Beyond these direct technological issues, the key question is to achieve a vision of what could be the “mobility” demand of the society in the future: the same as today all over the world, only corrected by environmental techniques or one quite “different” with new collective/individual modes to be related with the population location trends (megapoles and deserts?)
6.1.8 Summary

The European Commission has presented (end 2001) a proposal to reach 20% of alternative fuels in 2020 (ref.6). The main data of this proposal are summarised in table 4. Natural gas, bio-fuels and hydrogen are the main candidates of this very ambitious proposal. According to table 3, bio fuels are 2 to 4 times more expensive (out of tax) than conventional fuels and the ratios are even bigger for hydrogen.

Breakthroughs are quite necessary to expect to reduce price of H2 in order to be competitive without tax incentives for a long time. The other alternative fuels are in a better cost situation even if there are concerns about massive biomass production in relation to food target land affectation. Do not forget that hydrogen is only an intermediate vector for use of electricity in road transportation. As the electricity distribution grid is largely existing and competitive, research on on-board electricity storage development could be at last the best solution with regards to the CO2 balance of the power generation.

If such a strategy is adopted to bring alternative fuels to the market, the volume of tax lost by the states will raise a major question around the balance of the public finance of these countries. The economic questions raised by the market development of alternative fuels are at least as difficult to solve as technical matters related to their production and distribution. Globally-alternative fuels, as long as they appear much more expensive than conventional fuels, will have to face the chicken-and-egg problem.
Vehicle propulsion system technology development is an evolutionary process. This chapter describes the potential of future powertrain technologies for passenger cars, Light Duty Vehicles LDV and Heavy Duty Vehicles HDV in the time period 2020 and beyond, their objectives, technology options, hurdles and barriers but also the research demand.

The influence on the development is a composition of environmental aspects forced by legislative boundary conditions like emission and safety standards, the energy resources and prices influenced by production/distribution costs and taxes and furthermore customer requirements.

Related to the scenario evaluation for urban and suburban road traffic in the time period 2020 and beyond (see chapter 3 of the Strategic Part A) the technical objectives for the passenger car-powertrain are summarised as listed below, see also Figure 6.2-1:

- GHG (CO₂) emission reduction
- fuel consumption reduction
- power output improvement
- torque response improvement
- reliability improvement
- recycling capability
- noise reduction

Figure 6.2-1 Requirements for future passenger car powertrains
Compared to passenger cars, the future objectives for trucks & buses, that will influence the development, are different and have to be separated in long haul and city usage. Reliability, durability, engine efficiency and the extending of maintenance intervals are most important objectives for long haul trucks and buses. They are substantial for an improved operating economy for fleet operators, see Figure 6.2- 2. For city trucks and buses, the reduction of emissions (particulates, NOX etc.) will be the main emphasis of development. Power output is less important than torque response for fast acceleration in the drive-up phase.

![Figure 6.2- 2 Requirements for future state-of-the-art powertrains](image)

Related to the scenario evaluation for road transportation of goods in the time period 2020 and beyond (see chapter 2), the technical objectives for the truck & bus-powertrain are summarised as listed below:

- durability and reliability improvement
- GHG (CO2) emission and fuel consumption reduction
- power output improvement
- PM reduction
- reduction of untreated emissions
- NOX reduction
- weight reduction, package improvement
- noise reduction
- engine brake function improvement

For a better explanation of the propulsion technology evolution in the future, this chapter is divided into the “State of the Art Technology until 2007”, the “Technology Trend until 2020” and the “Technology Visions beyond 2020”. In general, the targets for the technology trends and visions are energy consumption reduction, near zero emissions and alternative fuel-compatible power systems.
6 TECHNOLOGY EVALUATION POWERTRAIN

6.2.1 State of the Art Powertrain

The state of the art technology options until 2007 for mass production powertrains focus almost on state of the art technologies which are in an advanced development phase.

6.2.1.1 Emissions Standards

Regarding emissions, a distinction between local and greenhouse emissions needs to be made. Generally, reducing the greenhouse emissions can be seen as the major topic of this study and refers directly to the fuel consumption (CO₂). Therefore greenhouse emissions will be discussed in many chapters of this study.

This chapter will focus on the local, toxic emissions but effects, which have an influence on fuel consumption, especially in the field of aftertreatment will be considered as well.

Local emission influences the direct surroundings of the emission source and thus affects urban areas especially. Exhaust emissions may cause health problems such as lung diseases and may cause damage to buildings.

The following Table 6.2-1 shows the local effects of automotive emissions:

<table>
<thead>
<tr>
<th>Direct toxic and Nuisance effect</th>
<th>CO causes short term toxicity, blocking the uptake of oxygen by haemoglobin. This problem occurs mainly in confined areas such as garages.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO₂ causes respiratory problems in lungs.</td>
</tr>
<tr>
<td></td>
<td><strong>Particulate matter</strong> mechanically overloads the lungs; soot in combination with SO₂ forms an acute toxic.</td>
</tr>
<tr>
<td></td>
<td><strong>Aldehydes</strong> irritate the bronchi and other mucous membranes, and are acute toxics, especially the aldehydes with the lower molecular weights.</td>
</tr>
<tr>
<td>Summer smog (ozone)</td>
<td><strong>Ozone</strong> causes respiratory problems and irritations of the mucous membranes, damages biomolecules and probably diminishes resistance to virus infections. Ozone and other photochemical oxidants are formed by volatile organic compounds (VOC) and NOx under sunlight.</td>
</tr>
<tr>
<td>Long Term Toxicity</td>
<td><strong>Benzene</strong>, a haematotoxic, is also a suspected carcinogen. Toluene and xylene are less toxic.</td>
</tr>
<tr>
<td></td>
<td>Each of the <strong>Polycyclic Aromatic Hydrocarbons (PAHs)</strong> in exhaust gases has some mutagenic and carcinogenic activity. Soot is mutagenic and carcinogenic and increases allergic reactions.</td>
</tr>
<tr>
<td></td>
<td><strong>SO₂</strong> causes cell destruction.</td>
</tr>
<tr>
<td></td>
<td><strong>Lead</strong> affects the psychic development of children.</td>
</tr>
<tr>
<td>Material damage</td>
<td><strong>Soot</strong> fouls buildings. <strong>SO₂</strong> in combination with nitrogen compounds and photochemical oxidants, generates material damage.</td>
</tr>
<tr>
<td>Winter smog</td>
<td><strong>Particulate matter</strong> and <strong>SO₂</strong> together cause winter smog.</td>
</tr>
</tbody>
</table>

Table 6.2-1 Local effects of automotive emissions
Because there is no standardised procedure to aggregate all local effects of vehicle emissions, the different emissions components need to be handled separately. In this study, focus will be in the regulated emissions of hydrocarbons (HC), CO, NOx, and PM. In the US, methane is excluded from the regulation of hydrocarbon and the so-called non-methane hydrocarbon portion (NMHC) is limited.

Generally, as Figure 6.2- 3 shows, the trend for both heavy- and light-duty vehicles (Diesel driven) is worldwide towards zero emission.

A further analysis of the considered limits by means of emission indices in “g emission per kg fuel consumption” on the basis of fuel consumption over representative cycles (213 g/kWh for the HD engine and 6.6 l/100km for the LD engine) as demonstrated in Figure 6.2- 4, show that for HD engine regulatory limits, the emphasis has been the trade-off between the total particulates, in favour of increased NOx emission and - directly linked - low fuel consumption.
In future, emission limits will converge, but it has to be considered that the duty cycles of both applications are different - as can be detected out of the terms light- and heavy-duty - in reality as well as in the particular emission test cycles.

6.2.1.1 Regulations

Light Duty Vehicles
Among the state of the art light duty vehicle prime movers, the multi-point fuel injection gasoline engine (MPFI), the proportion of direct fuel injection engines (DI) is growing. Besides the HSDI Diesel engine, the gasoline engine with direct fuel injection, both characterized by high efficiency and excellent driving performance, are having increasing market shares. Nevertheless, the challenge for the DI powertrain development is and will be to an increased extent in the future, the fulfillment of the emission legislation. Since January 2000, light duty vehicles have to comply with EURO III (see Table 6.2- 2).
Valid and amended European Directives

- Directive 2002/80/EC, October 03, 2002

Table 2: European Exhaust Emission Standards EURO III for On-Highway Light Duty vehicle ≤ 3.5 tons GVW

Simultaneously with the introduction of the new standards, the driving test cycle MVEG-B (Urban "ECE + extra-urban cycle "EUDC") was changed. The 40 seconds idling period prior to bag sampling start were deleted and the bag sampling start is now simultaneous with engine cranking.

Heavy Duty Vehicles

Today and even more in the future, exhaust emission legislation is and will remain the main technology driver for the development of heavy-duty Diesel engines in the focused period.

Since October 2000, HD engines have to comply with EURO III standards according to directive 88/77/EEC, which has been amended by directives 1999/96/EC and 2001/27/EC. Together with the introduction of EURO III standards, changes in the engine test cycles have been introduced. The old steady-state engine test cycle ECE R-49 has been replaced by two cycles: a stationary cycle ESC (European Stationary 13 Mode Cycle) and a transient cycle ETC (European Transient Cycle). Smoke opacity is measured by the ELR (European Load Response) test.
Emissions limits for Diesel fuelled engines:

<table>
<thead>
<tr>
<th>Stage &amp; Year of Implementation</th>
<th>Emission Standards in g/kWh</th>
<th>Test Cycles &amp; Comments</th>
<th>Fuel Sulphur Content***)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
<td>CO</td>
<td>NOx</td>
</tr>
<tr>
<td>EURO III 2000</td>
<td>0.66</td>
<td>2.1</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>0.78</td>
<td>5.45</td>
<td></td>
</tr>
<tr>
<td>EURO IV 2005</td>
<td>0.46</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>EURO V 2008</td>
<td>0.46</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- All emission standards and dates are for Type Approval
- ESC = European Steady State Cycle (also known as OICA/ACEA test cycle)
- ETC = European Transient Cycle (also known as FIGE test); for EURO III ETC is optional
- ELR = European Load Response test for smoke peak limitation, measured by The absorption coefficient in (m⁻¹)
- ($) = For engines with swept volume of less than 0.75 dm³/cylinder and rated power speed ≥ 3000 1/min, higher PM limits allowed
- (**) = as per EURO V, test cycles may change to new worldwide harmonized diesel cycles (steady state and transient version) along the Worldwide Heavy Duty Certification (WHDC) activities currently being finalized
- (***) = Fuel sulphur content in EURO IV and V will most probably be reduced to 10 mg/kg

Table 6.2-3 European Exhaust Emission Regulations for Heavy-Duty Diesel Engines for On-Highway Vehicles > 3.5 tons GVW

An overview including the legislation in US and Japan is given in Figure 6.2-5. It also shows that the emission legislation and market demand are conflicting with each other.
A more detailed description of the international legislation and for the corresponding test cycles can be found in 6. The emission limits for Diesel and gas fuelled engines introduced in this decade, specifically from 2005 and 2008, can be taken from Table 6.2-3 and Figure 6.2-5.

It is expected that the emission limit values set for EU 2005 and 2008 will require all new Diesel-powered heavy duty vehicles to be fitted with exhaust gas aftertreatment devices, such as particulate traps and DeNOx catalysts. A review to either confirm or modify the 2008 NOx standard had been planned for December 31, 2002 but did not happen and no new date is fixed so far (per October 2003).

Furthermore, from October 2005 all types of vehicles shall be equipped with an on-board diagnostic system (OBD) or an onboard measuring system (OBM) to monitor in-service exhaust emissions and conformity of vehicles in service shall be examined by appropriate measures.

6.2.1.1.2 Future Planned Emission Limits

Light Duty Vehicles

In addition, the worldwide trend to commonize emission regulations for Diesel and petrol light duty vehicles during this decade is obvious. The US TIER 2, beginning with phase-in in the year 2004 will not differ between Diesel and petrol. The overall emission target is an average manufacturer fleet NOx standard of 0.07 g/mi.

Also for Europe, common limits are expected for the next emission stage EURO V. Based on the regulation stage EURO IV, which will be introduced in the year 2005 (see table 3), several proposals for the following stage EURO V regulation exist.
### Valid and amended European Directives

- Directive 2002/80/EC, October 03, 2002

The current most stringent proposal was published by the German Federal Environmental Agency (UBA) and is listed in Table 6.2-5.

---

#### Table 6.2-4 European Exhaust Emission Standards EURO IV for On-Highway Light Duty vehicle ≤ 3.5tons GVW

<table>
<thead>
<tr>
<th>Vehicle Category</th>
<th>Reference Mass (kg)</th>
<th>Engine Type</th>
<th>CO (g/km)</th>
<th>HC (g/km)</th>
<th>NOx (g/km)</th>
<th>HC + NOx (g/km)</th>
<th>PM (g/km)</th>
<th>Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 1) Passenger Cars</td>
<td>all</td>
<td>Gasoline</td>
<td>1</td>
<td>0.1</td>
<td>0.08</td>
<td>-</td>
<td>-</td>
<td>1.1.2005 / 1.1.2006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diesel</td>
<td>0.5</td>
<td>-</td>
<td>0.25</td>
<td>0.3</td>
<td>0.025</td>
<td>1.1.2005 / 1.1.2006</td>
</tr>
<tr>
<td>N1 2) Goods Vehicles</td>
<td>≤ 1305 Category I</td>
<td>Gasoline</td>
<td>1.00</td>
<td>0.10</td>
<td>0.08</td>
<td>-</td>
<td>-</td>
<td>1.1.2005 / 1.1.2006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diesel</td>
<td>0.5</td>
<td>-</td>
<td>0.25</td>
<td>0.30</td>
<td>0.025</td>
<td>1.1.2005 / 1.1.2006</td>
</tr>
<tr>
<td></td>
<td>1305 ≤ 1760 Category II</td>
<td>Gasoline</td>
<td>1.81</td>
<td>0.13</td>
<td>0.10</td>
<td>-</td>
<td>-</td>
<td>1.1.2006 / 1.1.2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diesel</td>
<td>0.63</td>
<td>-</td>
<td>0.33</td>
<td>0.39</td>
<td>0.04</td>
<td>1.1.2006 / 1.1.2007</td>
</tr>
<tr>
<td></td>
<td>&gt; 1760 Category III</td>
<td>Gasoline</td>
<td>2.27</td>
<td>0.16</td>
<td>0.11</td>
<td>-</td>
<td>-</td>
<td>1.1.2006 / 1.1.2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diesel</td>
<td>0.74</td>
<td>-</td>
<td>0.39</td>
<td>0.46</td>
<td>0.06</td>
<td>1.1.2006 / 1.1.2007</td>
</tr>
</tbody>
</table>

1) Passenger vehicles with up to eight seats in addition to the driver’s seat not heavier than 2.5 tonnes
2) Including PCs with more than 6 seats (including the driver’s) or maximum mass > 2.5 tonnes
3) NTA: New Type Approval, ANR: All New Registrations
4) NTA: With effect from 1 January 2005 for vehicles in category M — except vehicles the maximum mass of which exceeds 2 500 kg —, for vehicles in Category N1 Class I, and, with effect from 1 January 2006, for vehicles in Category N1 Classes II and III, as defined in the table above, and for vehicles in category M whose maximum mass exceeds 2 500 kg.
Additionally, an onboard diagnostic system (EOBD) for detection of emission thresholds to identify systems/components failures will be stepwise introduced for Diesel passenger cars in the period from 1.1.2003 to 1.1.2007 (introduction for gasoline engines beginning EURO III 01.01.2000). According to Directive 98/69/EC dated 13/10/98 (in force, amendment 99/102/EC dated 15/9/99) EOBD will be mandatory for Diesel passenger cars (vehicle category M1+N1) for new types from 1.1.2003 and all types from 1.1.2004.

**Heavy Duty Vehicles**

It can be estimated that the following limits will be introduced around the year 2015.

- NOx-Limit: much lower than 1.0 g/kWh, following an amendment proposal of the German UBA. This could even happen with the introduction of EURO V in the year 2008.
- PM-Limit: 0.002 g/kWh definitely enforcing Diesel particulate filters (DPFs)
- Limitation of particulate-size and particulate-number

There might also be a change in test procedure by that time when the negotiations for the introduction of the WHDC (Worldwide Harmonized Heavy Duty Certification) will be completed. It is assumed that two harmonised test procedures will be introduced:

- **WHSC** — Worldwide Harmonized Stationary Cycle
- **WHTC** — Worldwide Harmonized Transient Cycle
6.2.1.2 Spark Ignition Engines

6.2.1.2.1 Design Trends and Combustion Technologies

For state of the art SI-combustion engines the technology options to fulfil these targets can be defined as follows:

- variable displacement
- downsizing with supercharging and variable compression ratio
- variable turbine geometry and improved compressor technology
- direct injection (homogeneous and stratified)
- variable valvetrain (cycle to cycle combustion control)
- multi stroke operation
- material improvement to reduce heat capacity and friction losses (oil free engine)

In the near future, the importance of down-sized spark ignition engines will increase considerably. Boosting (supercharging and turbo charging) will be combined with static down-sizing, sometimes with redesigned engines. The possible reduction in cylinder displacement is up to 40 percent, with a corresponding benefit in fuel consumption and carbon dioxide emissions of up to 20 percent.

The objective to reduce the GHG emission especially by reducing the fuel consumption requires, independently from the combustion process, an engine with low displacement. This stands in contrast to an improvement in torque response and rated power output. The key technology to solve these contradictory requirements is the variable engine (see Figure 6.2-6), which can adapt to the specific requirement of the actual driving condition and driver command combined with an overall optimised efficiency.

Variable Engine

Especially for throttled large-displacement gasoline engines, a simple technology to increase the efficiency at low loads combined with a high torque and power output is variable cylinder displacement. For low loads several cylinders can be deactivated. The combustion efficiency due to the load shift and dethrottling for the remaining fired cylinders is increased and as a result, emissions and fuel consumption are reduced. If the driver commands high torque for acceleration or power for high speeds, the full displacement is made available. For the state of the art piston engine, the variable displacement requires a variable valve train to keep the valves for the deactivated cylinders closed, in order that no gas exchange is possible. This can be realised with switchable tappets, switchable finger followers or a camless, fully-variable valve train. The variable displacement technology is available today in laboratories but not yet EU-wide in production. The costs for these systems are today very high.
An extended application for variable displacement is multi-stroke operation. This can be defined as a rotating cylinder deactivation. In contrast to a fixed cylinder deactivation, all cylinders are operated one after the other, first in deactivated and then in fired condition, see example for a 4 cylinder engine Figure 6.2-7.

With multi-stroke operation the ignition interval can be extended. The fired cylinders are operated especially for gasoline engines with an increased efficiency due to the shift to higher cylinder loads. The variable valve train is a requirement for the multi-stroke operation as well as for a fixed cylinder deactivation.

### Multi-stroke Operation Modes for a 4 Cylinder Engine

<table>
<thead>
<tr>
<th>Type</th>
<th>Ignition Interval</th>
<th>Firing Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-stroke</td>
<td>180°CA</td>
<td>1-3-4-2</td>
</tr>
<tr>
<td>4-stroke 2-cylinder</td>
<td>360°CA</td>
<td>1-4</td>
</tr>
<tr>
<td>multistroke 12-stroke</td>
<td>540°CA</td>
<td>1-2-4-3</td>
</tr>
</tbody>
</table>

Figure 6.2-7 Multistroke operation modes for a 4 cylinder engine
**Downsizing combined with supercharging**

Downsizing combined with supercharging is an effective way to reduce fuel consumption and exhaust gas emissions, and to increase ICE torque and power output when needed. Recently designed impulse charging systems show high potential for increasing volumetric efficiency. The advantages of supercharged systems are:

- high output to weight ratios
- supercharged engines are smaller in comparison to naturally aspirated engines with the same maximum power output, which may lead to reduced fuel consumption
- favourable torque characteristic even at low engine speed with mechanical supercharging
- exhaust gas supercharger acts as a muffler and lowers noise emissions

The disadvantages of supercharged systems are:

- increased back-pressure in front of the turbine in exhaust gas supercharging systems
- poor responsiveness at lower engine speeds with exhaust gas supercharging systems
- additional energy consumption because of the use of power to drive mechanical superchargers partially offsets the increase in output power
- to cover the entire range of engine speeds, exhaust supercharging systems need a waste gate to prevent the pressure in front of the turbine rising too high and to avoid damage at higher engine speeds
- to prevent uncontrolled combustion, the compression ratio of a supercharged gasoline engine has to be lowered. This influences the process efficiency, especially in part-load operation

**Variable turbine or compressor**

Approaches to improve the poor responsiveness of superchargers at low engine speeds include supercharging systems with a variable turbine nozzle geometry. These systems permit better utilisation of exhaust gas pressure by using adjustable turbine vanes. The turbine rotor diameter influences the acceleration behaviour of the turbocharger. Small turbochargers accelerate faster, but smaller turbine rotor diameters decrease efficiency, while pumping loss is increased at higher load.

The challenges in designing turbocharger systems are:

- achieving high charge pressure at low engine speed
- small turbine geometry for better responsiveness
- low back pressure at high speed and full load

The geometry of variable turbines permits the designer to reduce the turbine diameter, so that the pressure in front of the turbine can be increased at low engine speeds. At high engine speeds, the adjustable turbine vanes open and the exhaust gas back pressure lowers. The load increase through supercharging cannot be extended arbitrarily.

Intercooling is very important for supercharged gasoline and Diesel engines. Intercooling cools the compressed combustion air, which results in an increase in available air mass and a reduction in process temperature to reduce the nitrogen emissions. In gasoline engines, intercooling pushes back the knocking combustion border. Consequently, the ignition point can be optimised to give higher loads and lower fuel consumption.

Figure 6.2-8 shows the benefit in fuel consumption from downsizing for a Diesel engine. Downsizing, i.e. reducing engine displacement, results in a reduction in fuel consumption by up to 20 percent.
Variable Valvetrain

The thermodynamic engine process is heavily dependent on valve timing, which has a big influence on efficiency, consumption, emissions, maximum torque and engine power. Constant valve timing and valve lift are a compromise between different running conditions, such as cold start, warm-up, partial load and full load.

The reason for variable valve timing and lift is to reduce pumping losses and hence fuel consumption. Regarding only the possibility of cam phasing (i.e. offsetting the angle relation between crank- and camshaft, a reduction in fuel consumption in the NEDC of approximately 4% is possible for a midsize vehicle equipped with a 2.0l-engine. Valve lift variation together with a cam phaser on the intake camshaft shows a potential of up to 7%. Other benefits are optimisation of power and torque characteristics and also lower emissions. Modern systems combine camshaft phasing and variable valve lift so that valve lift and camshaft phasing can be varied freely depending on engine condition. These systems are able to run the engine unthrottled so that throttle losses can be reduced in the partial load range. They yield a fuel consumption benefit of approximately 10%.

Current variable valvetrain concepts usually vary valve timing using cam phasers. There are only a few systems that use cylinder deactivation, and only one concept that uses a mechanically variable valvetrain. The third generation of these concepts permits both valve timing and lift to vary (Figure 6.2- 9).

Load control for an engine equipped with fully variable valve train is no longer performed by a throttle but rather by valve timing, see Figure 6.2- 10.

The total reduction of the pumping losses is an important efficiency improvement compared to camshaft-driven gasoline engines. Furthermore the residual gas control to increase combustion efficiency and reduce emissions can be optimised individually for each operation point. Tests on vehicles equipped with an electromechanical valvetrain show that, in the
New European Driving Cycle (NEDC), a fuel consumption improvement of approximately 18 percent can be achieved for a midsize vehicle.

Full load behaviour shows great improvement especially in lower speed ranges because of the variable valve control system. In comparison with state of the art valve trains, a significant gain in torque is achieved through speed-dependent adjustment of the valve timing (load and residual gas control). Compared with the best state of the art concepts, an increase in torque of about 20 percent is achievable at low speeds.

The variable valve train opens possibilities for valve and cylinder deactivation and also the cycle to cycle load control and is a necessary demand for multi stroke operation modes as well as for new combustion strategies like CAI. This technology makes an additional cost intensive, close coupled catalyst, secondary air injection, or an electrically heated catalyst unnecessary.

Therefore, in these systems significant modifications to the engine’s electronic control system are necessary. The additional degrees of freedom and variability allow considerations of new concepts for the vehicle’s electronic systems. These concepts are driven by the desire for enhanced information and energy management systems in the vehicle. The main components of the EMVT system are the electronic engine control unit (ECU) with extended functionality, the valve control unit (VCU), the electromechanical valve train and the energy management system - vehicle electrical systems.

Figure 6.2-10 Fully variable valve train concepts² left side, 1 right side.
Variable Compression Ratio

The maximum compression ratio is determined at full load conditions. The compression ratio always stays the same, even when the engine is running at partial load. Consequently, the engine is not perfectly adapted to the respective needs. The continuously variable compression ratio can be achieved with an adjustable liner or cylinder head, permitting the compression ratio to vary between $\varepsilon = 8 - 14$. Another possibility to vary the compression ratio is to mount the crankshaft eccentrically. For each engine load condition there is an optimised compression ratio which avoids uncontrolled combustion. This results in a maximum indicated mean effective pressure. The variable compression ratio avoids a decline in efficiency of highly supercharged engines while under full load. Engines with variable compression ratio and supercharging can generate an improvement in fuel consumption up to 25 percent in the NEDC. Because of the stoichiometric operation, exhaust gas after treatment with a three-way catalyst is sufficient to meet regulatory targets in all developed markets.

Direct Injection Gasoline Engine

The adoption of direct injection will be another way to improve engine efficiency, but in terms of costs, these engines with a stratified combustion are more expensive than state of the art spark ignition engines due to the need for advanced injection technology and additional nitrogen oxide aftertreatment. As an interim step, direct injection with a homogeneous combustion (enabling state of the art emission control), in combination with supercharging, will take a growing market share.

Fuel is directly injected into the cylinder of a direct injection gasoline engine. The time between injection and ignition determines the mixture formation. Early injection during the intake stroke guarantees a mostly homogeneous mixture, enabling the engine to operate with a high engine load and at high speed quantity control. With stratified engine operation, the injection happens at the end of the compression stroke. In combination with an unthrottled engine, fuel consumption can be reduced over a wider engine range. Stratified engine operations use quality control, see Figure 6.2-11.

Load control by throttling has the effect that decreasing load demand causes a rise in pumping losses. The result is low efficiency in the low load area, especially during idling. Consequently, the benefit of unthrottled engine concepts is high in this area of the engine map.

Figure 6.2-11 Gasoline direct injection operating mode

Load control by throttling has the effect that decreasing load demand causes a rise in pumping losses. The result is low efficiency in the low load area, especially during idling. Consequently, the benefit of unthrottled engine concepts is high in this area of the engine map.
The advantages of a direct injection gasoline engine in comparison to a state of the art gasoline engine are:

- mixture cooling caused through fuel vaporization, this results in higher volumetric efficiency and higher knock resistance (engine performance)
- unthrottled partial load operation (lean combustion), reduction of pumping losses and therefore decreased fuel consumption
- minimization of wall heat losses for stratified charge operation and improvement of internal process efficiency
- reduction of fuel consumption by 12 - 16 percent in the NEDC test cycle

The disadvantages are:

- additional NOX aftertreatment (lean burning)
- reduction in mechanical efficiency (high pressure injection pump)
- cleft combustion chamber

Most current vehicles with SI engines are produced with MPI concepts, although there has been a rising trend towards DI gasoline engines.

Due to the introduction of direct injection gasoline engines, improvements of fuel consumption from 12 to 16 percent became possible, depending on the size of the engine, although all production combustion principles for DI gasoline engines use a combination of wall and air guided processes. With the aid of the spray-guided process, which is currently under development, and the use of a multi-hole nozzle with increased injection pressures of up to 200 bar, better charge stratification is possible. Better charge stratification results in improvements in fuel consumption of another 2-3 percent in the NEDC. Spray-guided injection systems will probably be introduced from 2005 on.

And finally, the first low-cost belt-driven starter generators operating at 14V will reduce fuel consumption by enabling automatic stop/start, but without re-generative braking and torque support, which require 42V systems.

Naturally, many of these technologies can be effective in combination but research work has to be done to find a cost-effective solution for high fuel economy for each vehicle type.

### 6.2.1.2.2 Emission Reduction Technology Options

#### Gasoline Engines with Port Injection

For gasoline engines EURO IV application combustion systems are used, which accept extremely retarded spark timing for accelerated catalyst heating. Also “lean warm-up” capability is required, if secondary air supply is not applied. Sufficient combustion stability is achieved by use of intake generated charge motion. Some engines are equipped with variable charge motion devices (tumble or swirl), which have a high tolerance towards charge dilution (EGR or lean operation).

Many new engines are equipped with cam phase shifting devices, which are primarily used for improvement of WOT (Wide open Throttle) performance and for residual gas control at part load (internal EGR). Fully variable valve actuation systems have been introduced for fuel economy improvement.

Generally the technology to achieve future legislative emission limits is available. The major tasks for future development are the improvement of fuel economy and to realise $\lambda = 1$ engine operation in the entire engine map to allow three-way catalyst operation. Especially the latter requires improvement in exhaust line component temperature stability.

The layout of the exhaust gas aftertreatment system for EURO IV engines with air excess $= 1$ closed loop controlled combustion - close coupled catalyst, or starter + under-floor catalyst - depends on the combustion system features, and on packaging conditions in the vehicle. Catalysts with thin wall substrates (metal or ceramic), increased cell density and tri-metal loading are used preferably. The noble metal loading varies:
Close coupled start catalyst: 80 to 150 g/ft³ (Pd/Rh or Pd/Pt/Rh)
Close coupled main catalyst: 30 to 50 g/ft³ (Pd/Pt/Rh)
Under floor catalyst: 40 to 60 g/ft³ (Pd/Pt/Rh or Pt/Rh)

Secondary air supply is applied, especially for engines with higher displacement and for turbo-charged engines. A major task for meeting future emission limits is to achieve fast catalyst light-off. Control strategies for catalyst heating include functions for spark retard, lean mixture operation and early exhaust valve opening, if an exhaust cam phase shifter is available.

**Gasoline Engines with Direct Injection**

First GDI-engines with charge stratification have been introduced in Europe, which are capable to meet EURO IV emission regulations. Currently, wall guided combustion systems, i.e. fuel injector located remote from spark plug, injected fuel guided to the spark plug by the piston crown surface and by charge motion, are in production. The next generation of combustion systems with close spacing between spark plug and injector, which offers a higher fuel economy and low HC-emission potential, is still under development.

Stratified charge concepts require a high-pressure injection system with fuel pressure levels between 4 and 12 MPa, and high-energy ignition systems, to achieve the necessary mixture preparation quality and combustion stability. Engine out NOx-emission control is managed by external EGR with flow rates up to 40%.

The useful stratified lean operation range is limited due to deterioration of combustion with higher loads, due to restrictions from the exhaust gas aftertreatment (temperature limits, catalyst regeneration frequency), and due to deterioration of mixture preparation at higher engine speeds. Therefore the theoretically achievable fuel economy benefit of GDI-engines cannot be realised with current concepts.

A high potential to further increase fuel consumption saving in combination with lowest emission is seen in new combustion systems like CSI (Compression Spark Ignited). Compression ignition can be initiated at part load (1 - 4 bar BMEP). Feeding high EGR rates at opened throttle, more or less NOx-free operation in this part load area is possible with a significant reduction of engine-out emissions and the consequence of shortened catalyst regeneration frequency.

Stratified charge concepts require an exhaust gas aftertreatment system, which is capable of reducing NOx-emission at lean operation, and which has adequate HC-conversion capability, as HC-emission is higher compared to port injected engines. The NOx-adsorber technology has turned out to be suitable for compliance with EURO IV regulation. A typical exhaust system layout consists of a close-coupled starter catalyst and a DeNOx-catalyst in under-floor position. The DeNOx-catalyst includes the NOx-adsorber and a three-way catalytic function and has bigger volume than typical TW-catalysts for stoichiometric engines. Depending on the exhaust system packaging, specific exhaust system cooling measures have possibly to be used for temperature conditioning of the NOx-adsorber.

For stratified charge engines torque based engine management systems are usually used, which are most suitable to control the different operating modes and for the transitions between the modes. Due to the specific features of the NOx-adsorber technology, special control strategies such as NOx-storage model, NOx-purging function and Sulphur regeneration function are required.
6.2.1.3 Light-Duty Diesel Engines

6.2.1.3.1 Design Trends and Combustion Technologies

The significance of down-sized Diesel engines will also grow in the next decade, because of increased supercharging rates, intercooling as well as the possibility of electrically assisted turbochargers and variable valve train concepts, which enable an optimised torque and transient characteristic. A specific power output up to 70 kilowatt per litre seems to be reachable. Compared with current Diesel engine technology, a fuel consumption benefit of up to 25 percent is predicted as a result of major down-sizing and reduction of friction losses.

Advanced Injection Systems

Apart from internal engine measures, fuel mixing in Diesel engines is of great importance. Advanced fuel injection systems, which allow an adapted injection characteristic such as pilot, split and post injection as well as rate shaping, will reduce the local emissions substantially, perhaps avoiding the need for additional particulate and NOx control devices in small to medium vehicles. Also injection nozzles with variable injection hole size will be a part of these advanced Diesel engine concepts.

All advanced injection systems have adopted electronic controls. Through the use of electronics, new control functions have been introduced and existing functions, such as torque curve shaping or smoke control, have been improved. Electronic controls in Diesel fuel injection systems range from electronically controlled racks (commonly known as electronic governors), through solenoid valve actuated injectors, to sophisticated control algorithms in the common rail system and piezo injectors.

The most important requirements for a direct injection system are:

- high pressure generation and supply
- exact control of injection timing and injected fuel quantity
- thorough fuel dispersion and mixture preparation together with the in-cylinder charge motion

The main reason for high injection pressure is to transfer the quantity of fuel into the cylinder within a limited time period; the small spray holes are a requirement for good mixture preparation, allowing control of emissions. Regarding the future, an increase of injection pressure and further improvements in supercharging will generate a further power output increase, as shown by past developments. At part load, high injection pressure can improve the particulate/NOx-trade-off and is one necessary measure to meet the EURO IV standards.

To attain higher injection pressure, new injection nozzles have to be developed. Conventional solenoid valves still have a too long dead time caused by the inductivity of the electric coil. The nozzle needle must be pointed directly, thus more degrees of freedom for injection are attainable. The ability to freely choose the lift and speed of the nozzle needle is important to freely shape injection characteristic. Common rail injection systems feature a continuously working high-pressure pump and a high-pressure storage ‘rail’ or accumulator, see Figure 6.2-12.
Different strategies for fuel injection can be applied to further improve engine characteristics regarding acoustics, emissions and power output (Figure 6.2-13). High flexibility regarding injection timing and shaping can be used to meet the demands of the combustion process. Developments in injection rate-shaping allow improvements that are valid as well for magnetic injection nozzles:

- pre-injection strategies featuring one or more pilot injections can be used to reduce the delay time until the start of combustion. Due to the reduced amount of spontaneously combusting fuel, this results in smooth combustion with significantly reduced noise level
- an additional far-advanced positioned pre-injection enables a partly homogeneous combustion and improvement of the cold drivability
- split injection produces lower particulate matter, because of an additional turbulence level and the minimization of insufficient prepared fuel mass at the end of injection
- post injection with high pressure and good spray preparation can provide necessary temperature levels, air fuel ratios and HC-levels in the exhaust gas, needed for future exhaust gas aftertreatment systems like NOx- and particulate traps
- an additional post injection for particulate filter and NOx trap regeneration and supporting of post reaction
Regarding the future, higher flexibility in injection characteristics and increased multiple injections are expected for common rail systems as well as for unit injectors.

### 6.2.1.3.2 Emission Reduction Technology Options

Two different ways, by principle, of tail-pipe-out emission improvements have been identified. Up to a vehicle inertia test weight of about 1600-1800kg, sophistication of the combustion system related elements will be sufficient to meet the requirements for 2005. For heavier vehicles additional active exhaust gas aftertreatment will be a must. Generally two successive steps for combustion improvement are possible.

1. Based on the engine technology of the year 2002, a potential for emission improvement of approximately 25% is seen by extension of function, variability and flexibility of current technology, e.g. by introduction of
   - Low geometric compression ratio
   - Charge management (VGT, E-booster, 2 stage TC, flaps, charge cooling / heating etc)
   - Variable Swirl (wide range, fully flexible)
   - EGR with temperature control up to cylinder individual introduction
   - Fuel system (injection pressure increase, multiple injection, nozzle configuration, new FIE architecture)
   - ECU extended sensors and functionalities
   - Flexible valve actuation (not fully flexible)

2. Furthermore, the transformation of mixture preparation and combustion to lower air / fuel ratios and lower combustion temperatures, the so-called alternative combustion, offers additional 40% potential for emission improvement (please see also 1.3.3.1).
Based on today's development status it is expected that EU 2005 standards can be achieved with passenger cars up to a inertia test weight of approximately 1800 kg with an oxidation catalyst only - the current standard exhaust aftertreatment device - (Figure 6.2-14).

Nevertheless, heavier passenger cars together with lighter SUVs (Sport and Utility Vehicles) and goods vehicle have to be equipped with advanced aftertreatment technology to reduce PM and NOx. The increasing knowledge regarding health risk caused by particulate matter forced the Diesel particulate filter (DPF) to be the preferred solution. However, for heavier vehicles, a poor load factor additional NOx reducing aftertreatment will be required.

**Short overview on emission reduction systems:**

**Oxidation Catalyst**

A Diesel oxidation catalyst is an add-on device, installed in the exhaust system to convert the exhaust gas components of hydrocarbons (HC), carbon monoxide (CO) and the soluble part of the particulates (PM\textsubscript{sol}) to carbon dioxide and water. It does not require any specific control or regeneration devices and basically relies on the temperature of the exhaust gas to work reliably. In addition to the exhaust gas temperature, HC, CO and PM\textsubscript{sol} conversion rates depend on catalyst specification, space velocity and emission concentration. The conversion rates are in the range of:

- $\eta_{\text{CO}} > 90\%$
- $\eta_{\text{HC}} > 85\%$
- $\eta_{\text{PM}_{\text{so}}l} > 85\%$

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**Figure 6.2-14 Passenger car EURO IV Emission Technologies and achievable emission levels**

Measured Emissions. MVEG Vehicle test data

Optimum air management and variable swirl
Cooled EGR with temperature management.
High pressure FIE. Control sophistication.
Rapid engine warm up.
Improved LT-Oxicat with passive DeNO\textsubscript{x} capability.
Reduced power losses.

**Exhaust aftertreatment**

**Oxidation catalyst**

**Particulate filter first**

~1600 kg ~1850 kg
A Diesel particulate filter (DPF, Figure 6.2-15) filters the particulate emissions during engine operation, allowing the exhaust gases to pass through, but retaining the fine material making up the particulate matter (PM). The majority of filters have very high efficiencies and reduce the PM by more than 90%, e.g. the conversion rate of wall flow filters are $\eta_{PM} > 90\%$. However, the accumulated PM in the filter must be removed by regenerating the filter after a period of time and converting the PM to CO$_2$ and H$_2$O. The PM can be regenerated either continuously via the so-called Continuously Regeneration Trap technology (CRT - soot oxidation via NO$_2$ reduction) or with residual oxygen from the exhaust gas. Both regeneration mechanisms are related to engine operation (NO$_2$/Soot ratio, O$_2$ concentration, exhaust gas temperature) which depend very much on the operating condition as well as on the ambient conditions. As a continuous self-regeneration cannot be guaranteed under all conditions, enforced regeneration has to be considered, i.e. to prevent any critical conditions leading to high temperature gradients within the cat structure (and subsequently cracks) and ash sintering (and subsequently plugging). Therefore, monitoring of the trap loading and condition together with a regeneration control system are mandatory, which requires control hardware in addition to the filter.

The addition of a catalytic additive (see Figure 6.2-16, PSA System) to the fuel to lower the regeneration temperature of the filter is an additional method of ensuring more reliable filter regeneration. This additive is then collected in the trap as ash, which has to be removed at regular intervals. Currently, a DPF system utilising an additive supported regeneration is in production in several PSA passenger cars, however additive systems are not seen as a basis for future DPF applications due to ash build-up problems. Beside bare traps, catalysed DPFs offer a more promising solution.

**Figure 6.2-15 Diesel Particulate Filter System**

![Diagram of Diesel Particulate Filter System]

**Underfloor Catalytic Diesel Particulate Filter**

**Reduction Potential:**

$\eta_{PM} > 90\%$

**System Requirements:**

- flexible FIE
- post injection
- multiple injection
- variable injection pressure
- dynamic EGR control
- boost pressure control
- intake throttle
- charge air cooler bypass
- intake air heater
- activation of auxiliaries
  - air conditioning
  - heated windshield, rear window
  - etc.
- CC DOC
- Underfloor CDPF

**Challenge:**

Regeneration under all vehicle operating conditions
Selective Catalytic NOx Reduction (SCR)

The reduction of the engine-out NOx emission on a base metal catalyst by adding Urea water solution from Ammonia upstream of the catalyst is a well known technology used at power plants to reduce NOx emissions effectively. Clear statements from the European automotive industry make the introduction of this technology in series production firstly for heavy duty application very likely. However, SCR with aqueous Urea solution reduces NOx emission in the NEDC approximately by 70% (passenger car application).

NOx Adsorber Catalysts

A NOx adsorber stores nitrogen oxides from the engine exhaust during lean engine operation ($\lambda < 1.0$). After reaching a certain storage level or NOx breakthrough, the stored NOx has to be removed and reduced using a reducing atmosphere ($\lambda > 1.0$). With the state of the art of NOx adsorber development this reducing atmosphere is achieved, either within the combustion chamber, or by injecting fuel into the exhaust system before the adsorber. The first solution requires a highly sophisticated fuel injection system capable of injecting a minimum three times per cycle, additional intake air control (e.g. by an intake throttle) and an EMS function architecture capable of controlling the transitions between the different engine operation modes. However, this is an enormously complex approach, although no additional hardware is needed and consequently this solution is preferred for Light Duty application. This system (see Figure 6.2-17) is capable of a NOx conversion rate of about 65% in the NEDC under fresh catalyst conditions.
6 TECHNOLOGY EVALUATION POWERTRAIN

4-Way Catalyst
To further reduce emission after the engine the next obvious step is the combination of different technologies to achieve simultaneous reduction of all four limited emissions - CO, HC, NOx and PM.

Figure 6.2-17 NOx-Adsorber system configurations

Figure 6.2-18 NOx Adsorber upstream DPF during NEDC (Passenger Car~1700 kg ITW)
As Figure 6.2-18 shows, the combination of DPF (fuel additive supported regeneration) with an upstream located NOx adsorber catalyst offers a reduction efficiency for NOx of ~50%, while PM is more than 90% reduced. Generally, packaging constrains will hinder the integration of two different catalyst substrates into the exhaust line. Consequently the addition of NOx adsorber coating on the DPF substrate is the logical next step. Toyota developed such a system\(^{10}\) (see Figure 6.2-19) which is currently in the phase of pre-series field testing with about 60 passenger cars all over Europe. Toyota claims a reduction of about 50% of the EURO IV limits for PM as well as NOx also with an aged system.

Future Trends Light Duty Diesel

Several new technologies to reduce emission outside the combustion chamber are currently under research. On the one hand, new technologies to simultaneously reduce PM and NOx are under investigation. Activities to find new catalyst materials having the ability to use carbon soot directly as a reducing agent for NOx are showing first results\(^{11}\). On the other hand, several technologies are under investigation to adapt exhaust gas composition to the need of the particular exhaust aftertreatment type. In particular:

- Plasma technology

In the non thermal plasma (NTP) reactor, high-energy electrons and free radicals are created to collide with stable molecules in the exhaust gas stream. Due to the content of excess oxygen, the subsequent chemical reactions result in the oxidation of NO into NO\(_2\), which is subsequently reduced to nitrogen in the DeNOx catalyst. Approximately 65% of the NO emitted during the NEDC cycle is oxidised to NO\(_2\) resulting in 15% NOx reduction in the NEDC. A portion of the NO\(_2\) which is not reduced in the catalyst can enhance the regeneration of the particulate filter\(^{12}\). The potential advantages of NTP technology include tolerance to fuel sulphur and a wide operating temperature window. Additional potential exhaust gas aftertreatment applications of plasma technology are\(^{13}\).
- As a part of a reformer to convert Diesel fuel into hydrogen-rich gas (H₂ + CO) to support e.g. regeneration of NOx adsorber catalysts
- Production of light hydrocarbons for HC-DeNOx catalysts
- On-board ammonia manufacturing as reductant for an SCR catalyst.

Finally it has to be stated that the plasma technology is still in basic research and an introduction in series production is not expected within the next ten years.

- Molecular sieves
  Using the effect of molecular diffusion, the composition of a gas flow can be influenced, such as adding CO₂ from the exhaust gas to the intake air - a particulate-free exhaust gas recirculation.

- Catalytic reductant production
  The idea is the development of a new source for ammonia required for the SCR reaction with NOx. This in-situ ammonia production uses NO as a reactant for the dynamic production of ammonia over a catalyst under reducing conditions. The reducing conditions are created by the injection of metered amounts of Diesel fuel into the exhaust gas upstream of the ammonia-generating catalyst. This procedure worked very well using simulated (particulate free) Diesel exhaust gas. The Ammonia production was sufficient to achieve a NOx reduction over the SCR catalyst up to 90%. However, the observed fuel consumption penalty under these conditions was approximately 25%, but significant potential for improvement is seen.

**Utilisation of the fuel “emission potential”**

Significant emission reductions can be achieved by choice of suitable fuels which enable high engine efficiencies. Although Diesel fuel with lowest sulphur content, low aromatics and with high cetane number will be the continuing major fuel, other types of fuel featuring high H₂/low C contents will be used in much higher extent. Natural gas is obviously a good candidate for such a fuel option.

Several aspects have to be taken into account if the effect of current and possibly future fuels is discussed. Firstly, the primary energy source is the most important parameter in view of GHG contribution. Obviously, fuels completely based on renewable energy, such as direct or indirect sun light (water, wind, photovoltaic, bio-mass), will be CO₂-neutral by all means, if the energy needed for fuel conversion, preparation and distribution would also be based on renewable energy. However, if the efficiency of such a closed-loop fuel supply system were low (e.g. if a large amount of energy is needed for fuel preparation e.g. like H₂-liquefaction), the price for such fuel will be unacceptably high due to the large amount of “hidden” energy needed in the fuel cycle.

### 6.2.1.4 Heavy-Duty Diesel Engines

#### 6.2.1.4.1 Design Trends and Combustion Technologies

The challenges for the heavy duty engine are similar, with greater emphasis on emission control but a stronger market desire for fuel efficiency and reliability in order to reduce operating cost. Fuel consumption and NOx/PM emission will be addressed by combustion process improvements, including application of flexible high pressure injection, four valves per cylinder, improved boosting, electronic control and low oil consumption. There are a variety of combustion process philosophies with corresponding emission control needs. Exhaust gas recirculation (EGR), particulate traps, Lean NOx traps and Selective Catalytic Reduction (SCR) based on urea in combination with oxidation catalyst will be used.
**Downsizing with Variable Turbine / Compressor Technology**

Similar to passenger car-engines downsizing, combined with supercharging, is an effective way to reduce fuel consumption and exhaust gas emissions, and to increase ICE torque and power output, see chapter 6.2.1.2.1. Especially for Heavy Duty Vehicles HDV and coaches the poor responsiveness at low engine speed is critical. This is even more essential than for passenger cars because of the critical drive-off behaviour at hills or with heavy loads and requires improved turbo- or compressor-charging efficiency; see also variable turbine geometry chapter 6.2.1.2.1. The same problem occurs for an application in city buses, where especially for the drive-off phase a high acceleration capability is needed.

**Injection Technology**

The injection system on Diesel engines has a high influence on the emission and noise formation. Particulates and NOx-emission can be reduced with high-pressure fuel injection, rate-shaping multistage injection systems, see also chapter 6.2.1.3.1. A further improvement is required to reach future emission and noise legislation.

**Variable Valvetrain**

Variable valve train technologies have also potential for improvements on HDV Diesel-powertrains. The benefit of a fully variable mechanical valve train is different for Diesel engines than for SI engines. In Diesel engines, this technology is mainly needed to control exhaust gas recirculation for reduction of NOx-emissions and enabling cylinder deactivation while running at constant speed. It can also significantly improve the low-end torque characteristics by speed-dependent adjustment of the valve timing and increase the combustion efficiency by reducing the effective compression ratio with the adaptable intake closing event. Currently, the residual gas fraction is controlled by external recirculation back into the intake manifold. But for cycle-synchronous engine operation, a more advanced control strategy is necessary.

**Material Improvement**

The overall efficiency can also be improved by reducing the heat losses due to restricted heat radiation of the combustion chamber, engine block, cooling and exhaust systems. New materials with respect to low heat storage, heat storage devices or new designs could achieve this. The engine friction, also parasitic power loss, could be reduced when the dimension of the cooling system can be diminished. Furthermore the lubrication system could be eliminated if using oil-free components.

Further challenges for material structures are given in combination with the peak pressure firing.

**Parasitic Losses**

The enlarged number of auxiliaries and complexity of belt drive systems especially on HDV influence the engine friction disadvantageously. Reducing the engine friction is directly convertible to fuel consumption improvement and GHG reduction. Decoupling auxiliary systems of the crank train e.g. driving with Auxiliary Power Units APU’s improves the overall efficiency of the powertrain.

**6.2.1.4.2 Emission Reduction Technology Options**

Also for the Heavy Duty application, the reduction of engine-out emissions is very important as this can be a major prerequisite for the functionality of aftertreatment systems, especially particulate filters.
**Improvement measures:**

**New developments in combustion for emission reduction**

- Improvement of current combustion processes for low PM. This includes:
  - improved fuel injection systems (HPFI, fully flexible CR systems)
  - new air management system including fully flexible valve trains
  - cylinder deactivation systems
- Introduction of advanced low temperature combustion, as described in the following

The many state of the art methods to minimise the engine-out emissions by improving mixture formation and combustion in the well established Diesel cycle and Otto cycle engines and, additionally, by applying exhaust gas aftertreatment devices have proven to be successful to cope with mid term emission legislation.

However, the cost for adequate hardware solutions including expensive aftertreatment systems have been increasing at the same time. Therefore, investigations were started in a third direction by abandoning the state of the art Diesel and Otto processes in favour of a mixed process based on homogeneous charge and compression ignition (HCCI), where combustion takes place simultaneously in the whole cylinder charge. In order to avoid a too steep cylinder pressure rise, a considerable amount of additional inert gas, i.e. recirculated exhaust gas (EGR) has to be mixed to the cylinder charge.

For a number of reasons this process is actually favourable with regard to minimising NOx and particulate emissions regardless of the fuel type, i.e. Diesel fuel, gasoline or gas. NOx emission is low because of the significant charge dilution and the distributed heat release, both leading to lower local combustion temperatures as in the case of the Otto cycle engine where combustion takes place only locally in the flame front or in the case of the Diesel engine where combustion occurs in a thin layer around the Diesel spray. Obviously, one reason for low soot emission is the homogeneous charge, another one is charge dilution, which may lower the combustion temperature even below the soot formation threshold.

Additional to very low engine-out emissions, the following emission control systems in the order of their probability of introduction to the market need to be taken in consideration:

- Exhaust Gas Recirculation (cooled EGR) systems
- Diesel Particulate Filters (DPF, various types)
- NOx Selective Catalytic Reduction (SCR)
- NOx Adsorber Catalyst
- The Combination of DPF either with SCR or NOx adsorber catalyst

Basically, all main emission reduction strategies are building on combustion optimization to reduce engine-out emissions before applying exhaust aftertreatment for NOx or PM, or for both in case of most severe emission standards. Taking the above technologies and applying them in a combination, four major strategies can be defined:
Emission Reduction Strategy 1: PM reduction by engine internal means and oxidation catalyst, NOx reduction by cooled EGR.

Emission Reduction Strategy 2: NOx reduction by cooled exhaust gas recirculation (EGR), PM reduction by Diesel particulate filter (DPF).

Figure 6.2-20 Strategy 1: PM reduction combustion optimisation & oxidation catalyst, plus cooled EGR.

Figure 6.2-21 Strategy 2: Combination cooled EGR and DPF.
Emission Reduction Strategy 3: PM reduction by engine internal means (combustion optimisation), NOx reduction by exhaust aftertreatment (selective catalytic reduction = SCR)

Emission Reduction Strategy 4: Combination of all technologies, i.e. combustion optimisation + cooled EGR + DeNOx and PM aftertreatment

Figure 6.2- 22 Strategy 3: PM reduction by combustion optimisation plus SCR

Figure 6.2- 23 Strategy 4: Combination of all technologies, i.e. combustion optimisation + cooled EGR + DeNOx and PM aftertreatment
In all 4 strategies, the fuel consumption/NOx trade-off could be maintained or improved relative to today’s technology (EURO III technology without EGR), though best fuel consumption is achievable with SCR (Strategy No. 2). However, cost-wise this advantage would be diminished depending on the SCR-system cost and on the price of the reductant (urea-water solution) which has to be carried on-board and refilled regularly as a “secondary fuel” by the operator. In the following section, technology needs will be discussed in more detail.

Short overview on current emission reduction systems (in serial production or in prototype status)

### Diesel Particulate Filters

Operation and regeneration principles are already described above. However, application specific requirements as e.g. a duration of more than 500,000 km mileage has to be considered.

The most common DPF system (in use today on heavy-duty Diesel vehicles e.g. retrofit programs in Scandinavia, United Kingdom, Germany, USA etc.) utilizes NO2 for soot regeneration. Figure 6.2-24 shows a DPF system consisting of an oxidation catalyst to force NO to NO2 oxidation upstream of an uncoated wall flow filter. However, there are several concerns with this kind of filter system.

Firstly, if exhaust temperatures are below about 250°C, the NOx/Carbon reaction is no longer possible, even if the DPF is catalysed and a huge surplus of NOx is available. As a consequence, the filter would plug with soot very quickly if no active regeneration is initiated.

Secondly, the NO2 formation in the oxidation catalyst is inhibited by too high fuel sulphur level. Consequently the CR-DPF is only feasible with low sulphur fuel (< 10 ppm wt) which will not be available until the year 2009 according to latest EU commitments.

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**Figure 6.2-24**: Continuously regenerating trap (CRT™) of Johnson Matthey: Schematic of system configuration and mechanisms involved

Source: Johnson Matthey
Still another concern is ash accumulation in the DPF; for achieving acceptable maintenance intervals both LOC and OAC had to be reduced. Developments in this direction are on-going and will be hopefully successful.

Figure 6.2-25 shows - as an example - two possible EGR arrangements.

**NOx Reduction by EGR**

Cooled EGR is a key technology for in-cylinder NOx reduction.

**Selective Catalytic Reduction**

Within the Selective Catalytic Reduction Catalyst NOx is reduced continuously with a reduction agent. As a reductant, liquid ammonia, solid urea or a urea/water solution has to be introduced before the SCR catalyst. Currently, liquid urea/water solution seems to be the most preferred reductant (one European HD OEM will put this technology into production 2003) and will therefore be further considered.

SCR is most advanced for truck Diesel applications, and a number of studies\(^6\)\(^7\)\(^8\) have proven the viability of this system for EURO IV and EURO V. As shown by figure 16, urea-water solution is injected into the exhaust stream ahead of the SCR-catalyst as a function of the exhaust temperature level and the incoming NOx mass flow, the latter being determined by a NOx-concentration sensor and an air mass flow sensor\(^9\). Typically, with an SCR system NOx reduction > 80 % is achievable in ESC as well as ETC testing without ammonia slip. Higher reduction rates are possible but require an additional oxidation catalyst downstream of the SCR catalyst to prevent NH3 slip. In combination with a PM-optimised combustion, EURO V emission standards can be demonstrated with best fuel consumption without a DPF\(^10\). However, additional operating cost caused by the urea/water solution consumption which, depending on raw emissions is around 5 - 8% of fuel consumption, has to be considered. This technology route is most favoured in Europe for EURO IV and V.
**NOx-Adsorber**

The NOx-Adsorber technology is originally developed and favored as aftertreatment technology for light duty Diesel engines. As already described in Chapter 1.3.2.2, a prerequisite to operate a NOx adsorber is the frequent admission with a reducing atmosphere. Running the Diesel engine at low air fuel ratios at high load, as well as optimising the additional fuel quantity needed and preventing significant oil dilution, is really challenging. Thus, out-of-cylinder rich mixture formation (i.e. to "generate a lack of oxygen" environment) is pursued with heavy duty Diesel engines. However, latest results show that generally rich exhaust gas composition is achievable in most of the engine map within the combustion chamber too.

Consequently two different system configurations are possible as shown in Figure 6.2- 27. To achieve NOx conversion rates in the ESC and ETC above 80 %, a total adsorber catalyst volume of about 4.5 times the engine displacement is required, independent of the chosen system configuration.

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**Figure 6.2- 26 Schematic of SCR system and its control for EURO V emission level**

**Reference: Haldor Topsoe A/S**
A combination of NOx adsorber and catalysed DPF was firstly demonstrated by US/EPA, see Figure 6.2- 28. In this approach the exhaust is split into a dual system. While the one path is adsorbing NOx the other is regenerating, in that only a small portion of exhaust is diverted into that path, and the rich mixture is generated by secondary fuel injection into that path. Thus, NOx conversions as high as 95% at about 3% fuel penalty have been demonstrated, though with an extremely bulky system (71 litre total catalyst volume, including catalysed Diesel particulate filters (CDPF)) and a complex control system with a variety of sensors for NOx and O2, temperatures and pressures.

Figure 6.2- 27 Different NOx adsorber catalyst application variants

Figure 6.2- 28 Schematic representation of US-EPA NOx adsorber concept for a HD Diesel engine achieving US2007/2010 emissions
Compared to the SCR technology, the NOx adsorber has its benefits at low temperature because of its ability to adsorb NOx at temperatures as low as 100°C and regenerate at temperatures > 250°C, whereas SCR is active only above 200°C, see Figure 6.2-29 for NOx reduction efficiencies of the two systems. Applying these efficiency curves to engine-out NOx-emissions of a 12-litre engine which is operated in the US HD Diesel transient cycle, shows that the NOx-Adsorber would achieve 89% NOx reduction, whereas SCR only 74%, see Figure 6.2-30.

Figure 6.2-29 NOx reduction potential of NOx-adsorber and SCR within exhaust temperature range of the US HD Diesel Transient Cycle

Figure 6.2-30 Cumulative NOx emission in US HD Diesel Transient Cycle of a 12l HD Diesel engine vs. exhaust temperature and calculated NOx reduction by NOx-adsorber or SCR, based on the NOx reduction potential of these systems in this exhaust temperature range
However, there are a number of Pros and Cons for either system, a detailed analysis of the pros and cons is given in 6.2.4.2: Hurdles and barriers for future emission and aftertreatment technologies

**Future Trends in Heavy Duty Diesel**

Generally the considered technology is the same as described in 6.2.1.3.2. The investigated technique is more or less in the state of research and application-specific characteristics are not taken into account so far.

**Utilisation of the fuel “emission potential”**

A very big influencing factor on emissions will be the type of fuel which will be dominant by the year 2020. According to all experts' opinion and also in all serious studies, Diesel fuel will still be the major fuel especially for long haul transportation.

For long haul application the energy storage problems for alternative fuels such as CNG or hydrogen will still be the major obstacle for introduction.

To achieve best possible emissions, reformulated Diesel fuels such as oxygenated fuels, gas to liquid fuels etc, practically sulphur free, with high cetane numbers and low aromatics are required. Bio fuels will be added to the standard blend. For more details see chapter 6.1.

For delivery trucks and especially for buses the situation will be much more heterogeneous. DME, CNG, hydrogen and other potential and “cleaner” fuels will be used in much higher extent.

**6.2.1.5 Transmission and Driveline**

Torque and speed output of an internal combustion engine are transformed by a transmission to the vehicle wheels. The desire for CO₂ reduction, combined with a market demand for driving enjoyment, will drive significant change in the European transmission market. Adaptable Systems to driving condition and driver's command have a higher potential to reduce GHG-emission than today's common manual transmissions and will replace them. Depending on cost and scope of application future transmission systems can be subdivided into:

- automatic
- automated manual
- Continuously Variable Transmission (CVT)

**Automatic Transmission**

Automatic transmissions, very popular in North America and Japan, are becoming increasingly popular in Europe as well. Owing to their fuel economy penalty though, the adoption of six or more ratios will be introduced. Normally a torque converter automatically helps to change the gears. The development of continuously variable transmissions has motivated some gearbox manufacturers to develop new 6-speed automatic transmissions. These transmissions can be easily extended to seven- or even up to nine-speed transmissions that can operate over a large range of ratios. This concept makes it possible to start a vehicle with a clutch instead of a torque converter. A small electric starter generator, placed in the space of the torque converter, provides additional functions, such as comfortable engine starts and stops, energy recuperation, or a CVT mode. Currently, the first 6-speed automatic transmission has entered mass production. It is controlled by a mechatronic module with a combination of a hydraulic selector unit and electronic components. The
quality of automatic transmissions is highly dependent on the control unit. The driver can choose between economical or performance-oriented shifting programs.

The challenge for design especially for HDV and coaches is the high starting torque on hills or with heavy loads. Regarding the high mileage, durability and reliability are a stringent requirement for future transmissions.

**Automated Manual Transmission (automatic gearing)**

Newly developed automatic transmissions combine the advantages of manual and automatic transmissions. Robotised transmissions (Automated-manual, AMT) offer significant fuel economy benefits (typically 5%) but the driving experience will remain compromised by the interruption of torque during shifting; developments are ongoing to avoid this disadvantage. Gear selection is performed as usual, clutching and gear engagement are automatic. The precise and optimally harmonised shifting process, “shift by wire,” guarantees a long service life, shift control and reduced fuel consumption. Short shifting times permit fast acceleration. Operating comfort is raised by the omission of the clutch pedal. Moreover, these transmissions are more efficient than traditional transmissions. In addition, the transmission control unit adapts to the driver’s behaviour by adjusting the shifting points. Another reason for the development of automatic gearing is cheaper production costs compared to automatic transmissions. Market penetration will be significant, but limited to smaller vehicles.

**Continuously Variable Automatic Transmission**

The Continuously Variable automatic Transmission (CVT) competes directly with state of the art stepped automatic transmissions. Continuously or infinitely variable types (CVT, IVT) offer improved efficiency, at best equalling manual types in the NEDC test.

The most significant features of CVT drive trains are low fuel consumption and low emissions, good driving performance, including smooth shifting, the ability to withstand high torque, a high level of driving comfort and low weight. In contrast to state of the art gear shifting, the CVT changes the transmission ratio using a variator: a thrust belt or a plate link chain transfers the propulsion power from primary to secondary tapered pulleys (Figure 6.2-31). The greatest advantage of the CVT transmission is that the engine always runs at optimal load conditions. As a consequence, fuel consumption is reduced by as much as 5 percent compared to 5-speed automatic transmissions.
**Dual Clutch Transmission (DCT)**

The twin clutch transmission provides a special type of automatic gearing. It offers comparable benefits as AMTs but with seamless shift quality under most conditions. This technology could achieve very significant penetration of the market if manufacturing costs prove competitive in high volumes.

The use of the twin clutch reduces shifting time without requiring substantial additional manufacturing effort. The input shaft of the transmission is divided into two separate shafts. One shaft switches the gears 1, 3 and 5, the other one the gears 2, 4 and 6. The clutch is electrically activated. By engaging and declutching simultaneously, each gearshift can be performed without shifting delay.

**4 Wheel Drive**

The popularity of four wheel drive will continue to increase in the envisaged timeframe, particularly in lifestyle-orientated vehicles based on front-wheel-drive platforms. Premium vehicles will adopt increasingly sophisticated technologies for distributing drive torque between the wheels in a safe manner.

**6.2.1.6 General Trends**

One of the mentioned technologies only cannot be defined as the key technology to fulfil the defined objectives for state of the art powertrains, but a useful combination can be, e.g. improved combustion engine with intelligent transmission.

Due to the necessity of more flexible and variable engine sub-systems in almost every engine type, engine costs will grow significantly. The rising degree of freedom and variability extends the application effort and sensitivity of failure operation. The fail safe operation requires redundant systems especially concerning the high mileage and reliability of HDVs and coaches. Necessary maintenance efforts must be as low as possible by improving durability or enlarging maintenance intervals. Besides pure technology solutions this is an additional challenge to solve before start of production introduction.

There will be a challenge to reduce costs by detailed improvement of engine components and consolidation of product ranges to obtain various outputs from common units.

In this field of trade off between engine costs and fuel consumption benefit, the new improved gasoline engine concepts will have a very important position in comparison to the increasingly successful but costly Diesel engines. So, for state of the art powertrains there will be a special research demand in a detailed optimisation of variability and materials for the engine, the exhaust gas aftertreatment and the combustion. With the growing degree of variability, the engine management system together with special sensor concepts (cylinder pressure, ion sensing, position sensors, etc.) and actuators will be more and more important to reduce the fuel consumption and the emissions.

**6.2.2 Advanced Powertrain up to 2020**

Internal combustion engines will continue to dominate the market until 2020 and are expected to have a relevant market share still in the year 2020. But many new technologies for gasoline and Diesel engines will replace the existing systems. The future powertrain is related to enhanced and upgraded technologies based on the internal combustion engine. These are mechanical solutions as well as new combustion processes.
6 TECHNOLOGY EVALUATION POWERTRAIN

6.2.2.1 Emissions Standards

In this timeframe it is Diesel engines which present the greatest aftertreatment challenge. Key technologies for most stringent NOx and PM control are cooled EGR, high pressure fuel injection, Diesel oxidation catalyst, Diesel particulate filter, catalytic reduction of NOx by SCR or NOx-adsorber, and combinations of these depending on needs of market and exhaust emission regulation for world-wide emission development strategies.

System integration including electronic on board diagnostics (EOBD) is an absolute must, i.e. combustion systems, mechanical systems, control systems, aftertreatment systems, and measurement systems have to be optimised as a whole to meet market demands and legislation requirements.

Durability and reliability of the various systems still need to be proven before production release. The time for this is very short. This applies particularly to aftertreatment systems for NOx and PM, since NOx-adsorbers and Diesel particulate filters for heavy-duty Diesel engines are still in the laboratory development phase.

The combination of NOx trap and particle trap in one system offers cost and fuel consumption advantages. Improved SCR technology with improved reduction agents can reduce the cost for NOx aftertreatment systems. Non-precious metal aftertreatment systems are the hope for the future out of cost and resources reasons. However, the pollutant transformation efficiency still needs intensive research work.

Light Duty vehicle

Based on the results of a workshop held among European experts in the field of automotive engineering, the following emissions limitations were considered as the most likely scenario:

- Post 2008 - equal emission limits for Gasoline as well as Diesel Light Duty.
- **CO₂ Emission (NEDC Baseline: 150 g/km CO₂ with average vehicle 1300-1400 kg):**
  - 2020: 95 g/km
  - 2030: 80 g/km
- PM emission will not be further reduced (basis is EURO V proposal UBA). Generally a consideration of PM emission limitation especially for direct injection gasoline engines is depending on their market penetration and as a consequence the share of particulate emission initiated by Gasoline engines.
- NOx emission reduction by 50% of the EURO IV gasoline limit or more. The final reduction is depending on the assessment of the NOx emission initiator. The main focus of the legislation may be the adaptation of the regulations for other emission sources like industrial and off-road engines.
- CO and HC emission will not be further reduced
- Limitations for some special, currently not regulated hydrocarbons but especially for nano-particles
- Limitation of exhaust gas species generated as a by-product of the aftertreatment system, e.g. Ammonia slip in case of SCR technology, NO₂ in case of coated DPF or metals especially in case of fuel borne additives for DPF regeneration.

In addition, a modification of the current test procedure and test cycle is expected. However, today it is not clear if either a new or supplementary test cycle to represent real world driving will be introduced. But additional testing to check emission compliance over the whole engine map (off-cycle effects) is most probable.
**Heavy Duty Vehicle**

From today’s standpoint it is anticipated that by the year 2020 and beyond, the emission problem must be practically solved or in other words the impact on the environment must be reduced by an extent that a “zero-impact” level has been achieved, especially in urban areas.

Nevertheless, lifetime conformity, durability and reliability of the systems will still be an item to be taken care of, especially with sophisticated aftertreatment systems.

- **Greenhouse gas emission targets**
  
  In the respective workshop the realistic fuel consumption (CO2) reduction potential has been estimated by the experts in the range of:
  
  Truck Diesel engines: -10% less than EU II-level
  
  Bus engines (probably in hybrid configuration with electric drives): - 40% (from EU II)

- **Local emissions**
  
  It is assumed that for Diesel propelled vehicles the application of a particulate filter is a must for all categories of commercial vehicles by that time. Especially for buses, zero or “zero-impact” emission in urban areas will be required.

  Based on EUV emission standards (proposed for introduction in 2008) and the outcome of the power train workshop the limit scenario in 2020 could look like:

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>HC</th>
<th>NOx</th>
<th>PM&lt;sup&gt;1)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU x --- 2020</td>
<td>0.5?</td>
<td>0.1?</td>
<td>0.2</td>
<td>0.01 -0.002?</td>
</tr>
</tbody>
</table>

For transient test cycle:

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>NMHC</th>
<th>CH₄</th>
<th>NOx</th>
<th>PM&lt;sup&gt;1)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU x --- 2020</td>
<td>1.0?</td>
<td>0.14?</td>
<td>0.8?</td>
<td>0.2</td>
<td>0.01 - 0.003?</td>
</tr>
</tbody>
</table>

<sup>1)</sup> Legislators will have enforced the use of particulate filters, even when it is almost impossible to measure these ultra low levels. It is furthermore possible that instead of particulate mass, the size and number of small lung creeping particles is limited by that time.

Table 6.2- 6 Possible exhaust emission minit scenario for HD Engines by 2020

Most likely also, other toxic emissions will be considered by the legislation (H₂S, N₂O, NH₃, Aldehydes).
Possibly also odour might be considered, currently odour is regarded to be too difficult to be measured and evaluated.
It can also be foreseen that besides EU- or worldwide and common standards, local authorities might establish more stringent local emission limits. This might refer to inner city areas, residential and recreational areas and for special usages of vehicles (inside buildings etc.)

For public transport and delivery trucks and vans - as they can make efficient use of hybrid powertrain technology - much lower emission targets can be set. It needs to be noted that these vehicles represent niche markets.

### 6.2.2.2 Spark Ignition Engines

By 2020 it is likely that most spark ignited engines will use combinations of the previously described improving technologies - down-sizing with boosting, lean-burn with direct injection, variable valve actuation (including cylinder deactivation and multi-stroke load control) and variable compression ratio - and will feature advanced, adaptive control of these flexible sub-systems, most likely using new sensor technologies. In combination with variable valve timing and/or variable compression ratio, controlled auto-ignition with very low engine out emissions can be realised in a wide engine map area and without full load penalties. Some evolution of fuel properties may support this new combustion philosophy.

Spark ignition engine technology is fully compatible with both Natural Gas and Hydrogen, and if energy policy promotes these fuels into the marketplace, combustion systems tailored to these fuels will emerge. Extreme-charged lean burn spark ignited combustion processes are promising in this respect. This combustion technology only needs oxidation and a three way catalyst (no further NOx aftertreatment systems), if extremely low NOx emissions can be achieved.

#### Controlled Auto Ignition CAI

A new combustion process for gasoline engines is the Controlled Auto Ignition (CAI). The auto ignition is realized by hot residual gases in the cylinder that ignite the air/fuel mixture without spark ignition assistance at the top dead centre of the compression phase, and result in simultaneous combustion throughout the combustion chamber. To avoid intake air heating, it is useful to run the engine with a compression ratio higher than $\varepsilon = 11$.

NOx emissions are reduced by up to 99 percent, compared to stoichiometric SI operating gasoline engines. The process is furthermore accompanied by a reduction in fuel consumption from 10 percent to 20 percent, according to engine operating conditions. This concept solves the NOx/fuel consumption dilemma during lean operation. The CAI combustion provides a less sulphur-sensitive and emission-robust alternative to the stratified DI strategy with sophisticated DeNOx aftertreatment. Due to the near zero NOx emissions levels, lean operation can be used in CAI mode for best efficiency. Nevertheless, it remains necessary to switch to the more state of the art stoichiometric SI mode at higher loads, which is outside the map range, where CAI is possible.

Auto ignition has to be controlled by managing the temperature and pressure history of the in-cylinder mixture during compression to ensure auto-inflammation at the desired time close to top dead centre. To this end there are different control mechanisms available.

- recirculation of exhaust gas into the cylinder
- heating of the intake air
- changing the ignition characteristic of the fuel

Figure 6.2- 32 presents the results achieved under naturally aspirated conditions, when the valve lift configuration is optimised around 2.9 bar indicated mean effective pressure (IMEP) at 1500 rpm engine speed.
A precise cycle-control strategy is required that monitors the concentration of the trapped residual gases, their respective temperature level, and the extent to which they mix with the fresh air charge. With a fully variable valve train, the EGR quantity and the overall temperature in the combustion chamber can be controlled.

### 6.2.2.3 Diesel Engines

To obtain further reductions in emissions and fuel consumption, sub-system variabilities will increase for both heavy duty and light duty Diesel engines. Variable valve timing (including cam-less systems in heavy duty applications), possibly variable compression ratio, and variable injection timing with rate shaping and increased fuel injection pressure, are all likely to feature, again enabled by advanced control systems. To increase the degree of down sizing, in-cylinder peak pressure will increase. For this, new improved materials and engine design concepts are necessary including new high boosting devices. With single cycle control, emission will decrease further. A greater step in NOx emission reduction in a wide mapping area will be expected for the homogeneous charge compression ignition (HCCI) in the part load range without full load penalties.

**Homogeneous Charge Compression Ignition HCCI**

Analogous to the gasoline CAI process, the Diesel HCCI combustion process is seen as a promising way to meet the environmental challenges of future powertrains used in the automotive sector, which will have to achieve lower emissions of CO2 by lowering fuel consumption and keeping emissions of other pollutants low.

Homogenous charge compression ignition (HCCI) is a relatively new combustion technology. Many different ways to achieve homogeneity for this process are currently being discussed. One form of a hybrid concept of the homogeneous operating state of the art spark ignition (SI) and the compression ignition process, as it occurs in Diesel engines, is shown in Figure 6.2- 33. HCCI engines are being developed to reduce emissions and make power generation more efficient.
Unlike a state of the art SI or Diesel engine, HCCI combustion works spontaneously and homogeneously without flame propagation. Heterogeneous air/fuel mixture regions are eliminated. In addition, the HCCI is a lean combustion process. As a result, these engines run at lower local flame temperatures, which reduces the amount of NOx formed during the combustion process. Different approaches to achieve homogenisation are shown in Figure 6.2- 34.

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Difficulties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Injection Timing (around BDC)</td>
<td><strong>High Grade of Homogenization</strong>&lt;br&gt;<strong>Best theoretically pre-conditions for low NOx-emissions</strong></td>
</tr>
<tr>
<td>Late Injection Timing (around TDC)</td>
<td><strong>Well-known combustion process control: injection timing remains as major parameter</strong>&lt;br&gt;<strong>Advantageous Fuel Economy</strong>&lt;br&gt;<strong>State-of-the-Art Injection Equipment</strong></td>
</tr>
</tbody>
</table>

The challenge of realising an HCCI Diesel engine is to phase and control auto ignition in order to create a proper air/fuel mixture and to extend the possible load range.

A major problem is the very fast rate of combustion, which starts simultaneously throughout the whole combustion chamber and causes a high pressure increase and hence, a loud noise.
The HCCI engine runs unthrottled, like a Diesel engine, in a range up to 6 bars indicated mean effective pressure. Because of low NOx emissions in the partial load range, no NOx reduction is necessary and therefore an oxidation catalyst is sufficient for these engines, in contrast to direct injection gasoline engines.

As a result, additional particulate traps and nitrogen exhaust gas aftertreatment systems may not be necessary to fulfill legislative requirements. The increased hydrocarbon and carbon monoxide emissions can be reduced with an oxidation catalyst, though the challenge to reach the catalyst light-off temperature in time remains for the vehicle application.

**Peak firing**

Peak firing with cylinder maximum pressure higher than 200 bar and high BMEP increases the combustion efficiency and power output. Consequently this increases the stress in the engine structure. New materials and designs will have to be developed for block, cylinder head and cranktrain to resist the amplified force distribution. The engine weight must not be negatively influenced.

**6.2.2.4 Hybrids and Auxiliary Power Units**

The environmental political discussion on the role of the individual transport, especially for passenger cars, is open and increasingly controversial. On the one hand, our modern community requires the mobility of the individual, and, on the other hand, the negative effects of environmental contamination and noise pollution are harmful to the health of the population. In the United States, very early strict emission regulations for vehicles were introduced. California has taken a leadership role in this area, in that, they have required that a proportion of 10% of the new cars need to be Zero-Emissions-Vehicles (ZEV) or partial ZEVs by the year 2003. In Europe no regulations of this type are existing.

With the drastic increase in road traffic, there is a corresponding increase in the negative side effects, which overlap with other essential basic conditions, for example the availability of crude oil. The future development of road traffic and vehicles will be increasingly determined by the following goals:

- Reducing the energy consumption;
- Replacement of crude oil with other primary energy carriers;
- Reducing the exhaust and noise emissions;
- Increased comfort through automation of powertrain functions.

The legislation in the USA, which demands ZEVs and extremely low pollutant vehicles (Ultra Low Emission Vehicle, ULEV), has clearly categorised and considered alternative powertrains. The actual LEV legislation in California for 2004 designates special requirements for hybrid vehicles. The LEV II legislation allows hybrid vehicles under certain conditions to achieve ZEV status (i.e. equivalent ZEV or EZEVs). This category allows to reduce the number of pure electric vehicle sales in an OEMs fleet. The hybrid concept and the components thereof, have been developed and tested in the USA since 1993 in the DoE (Department of Energy) sponsored ‘Hybrid Propulsion System Program’. In the year 1994 the ‘Partnership for a New Generation of Vehicles (PNGV)’ has been initiated. In January of 2002 the DOE, DaimlerChrysler, Ford and General Motors announced the FreedomCAR partnership. FreedomCAR focuses on the high-risk research needed to develop the necessary technologies, such as fuel cells and hydrogen from domestic renewable sources, to provide a full range of affordable cars and light trucks that are free of foreign oil and harmful emissions, without sacrificing freedom of mobility and freedom of vehicle choice.
Next to appropriate performance and environmental influences, the evaluation and choice of a powertrain system is another deciding aspect, especially in terms of the operating conditions and the fuel economy. In the following (Figure 6.2-35), the evaluation criteria for evaluating and selecting a powertrain are outlined.

### Figure 6.2-35 Evaluation criteria for powertrains

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>Environmental Influences</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Torque characteristic</td>
<td>• Emissions</td>
</tr>
<tr>
<td>• Control responses</td>
<td>• Noise vibration and harshness (NVH)</td>
</tr>
<tr>
<td>• Start-up behaviour</td>
<td>• Vibration behaviour</td>
</tr>
<tr>
<td>• Driveability</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Economic Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Specific energy and fuel costs</td>
</tr>
<tr>
<td>• Specific manufacturing costs</td>
</tr>
<tr>
<td>• Power density</td>
</tr>
<tr>
<td>• Power requirements</td>
</tr>
<tr>
<td>• Maintenance costs</td>
</tr>
<tr>
<td>• Multi-fuel ability</td>
</tr>
<tr>
<td>• Life expectance and reliability</td>
</tr>
</tbody>
</table>

Increasing on-board electric power requirements, together with a desire for powertrain efficiency improvement, creates a need for hybrid-electric technology and auxiliary power units.

**Hybrid Powertrains**

An interesting alternative is hybrid powertrains. By definition, a hybrid powertrain consists of two different powertrain systems, i.e. at least two different energy converters and storage devices. This definition shows that the term "hybrid powertrain", in principal, allows several different possible variations for a hybrid powertrain. With a few exceptions, an electrical powertrain, preferentially, is combined with a combustion engine.

A hybrid electric vehicle (HEV) is a vehicle, where at least two different energy storage devices (e.g. fuel tank, battery, flywheel, super capacitor, pressure tank etc.) and two conversion devices (e.g. ICE, gas turbine, Stirling engine, electric motor, hydraulic motor, fuel cell) are combined in one driveline. Additionally, at least one of the storage/conversion device combinations should be bi-directional, thus enabling the recharge of the storage device during operation of the car.

Hybrid systems can be roughly divided into the two basic structures of parallel and series hybrid systems. Each of them has different potentials and problems. Besides this, there are several mixed forms of the parallel and the series structure. An overview of the hybrid structures is given in Figure 6.2-36.
In the parallel hybrid structure the internal combustion engine (ICE) and the electric motor are linked mechanically to the wheels (Figure 6.2- 37). Besides the two driving engines and storage systems, these concepts consist of one or even more transmissions, clutches and freewheels. Both systems can be used separately or together to drive the vehicle. During acceleration phases the power of both engines can be added. Because of this, both can be dimensioned relatively small without harming the acceleration ability and the climbing performance of the vehicle. Usually the electric system is dimensioned to meet the requirements of urban traffic (limited operation, zero emissions), while the more powerful combustion engine is used for overland transport and motorway driving. The delivered power of both engines can be added by means of speed addition (e.g. with a planetary gear), by torque addition (e.g. with a spur gear or a chain drive) or traction force addition (combustion engine and electric motor drive different axles). The ratio of the torques in the torque addition solution is free, while the ratio of the speed is fixed. A decoupling of the combustion and the electric system can be realised with the help of freewheel or a coupling unit. The following picture shows the rough structure of a parallel hybrid (Figure 6.2- 37).
The distinguishing feature of series hybrid systems is the series connection of the energy converters without direct linking of the combustion engine to the driving wheels. The combustion engine is driving an alternator, which supplies the electric driving unit and an accumulator (in general a battery) arranged in an intermediate electric circuit (Figure 6.2-38).

Unfavourable in a series hybrid system is the double energy conversion, mechanical to electric and vice versa, maybe in conjunction with storage and the involved long and adverse efficiency chain.

By the combination of two powertrain systems a hybrid offers special advantages. In a driving cycle, the IC engine runs through its complete ‘load’ and ‘revolutions per minute’ fields, which include, in the most cases, many sections that are not close to optimal operation values. A second powertrain can smooth the load of the internal combustion engine by adding some power to the drivetrain and therefore permitting a lower energy consumption and emission output of the combustion engine. E.g. the fuel consumption of an optimised B-class demonstrator hybrid vehicle for European market is below 4 litres/100 km\textsuperscript{9}.

A further advantage of a hybrid vehicle is the recuperation of kinetic energy during phases of deceleration. This is especially interesting when the cyclic nature of city driving is considered. Another advantage of a special hybrid powertrain concept are reduced emissions in highly populated areas. In emission critical areas, i.e. the city, the hybrid powertrain can operate emission-free, using the energy from the energy accumulator, and when outside the emission critical areas it can be operated through the combustion engine, which will also recharge the accumulator.

Considering the disadvantages of a battery powered electric vehicles, the combination of a combustion engine and an electric machine appears to be the best compromise, because it is combining the advantages of both powertrain types such as higher range, faster refuelling, recapturing of the braking energy (recuperation), use of regenerative energy sources, and emission free operation.

A hybrid powertrain cannot simply be the addition of a second powertrain to a vehicle. Through appropriate selection of combinations and dimensioning, the advantages of the single powertrain must be retained and the disadvantages avoided. Through this, it gives the opportunity to reduce the consumption and emissions of the vehicle, as well as the possibility to provide local emission-free driving. For every intended application a different solution can be selected. Furthermore, the vehicle must feature a low weight and a low operating resistance (road and air resistance). Only in combination with a low energy demand, can an extremely efficient powertrain obtain very low consumption values.
Mild hybrids/ISG vehicles (integrated starter generator systems)

The term mild hybrid is not defined very well and is normally used for a hybrid powertrain in which the power of the electrical part is small in comparison to the power of the internal combustion engine. This is clearly the case with the so-called integrated starter generator (IGS).

The powertrain integration of a starter generator is a further variant of a parallel hybrid. The Integrated Starter-Generator (ISG) is especially able to deliver a considerable power into the 42V board net and even meet increasing power demands, required by future new applications.

The advantages and functions of an ISG are:

● higher generator power
● high generator efficiency
● recuperation of braking energy
● low starting noise
● possibility of start/stop operation
● possibility to boost ICE
● reduction of start-up emissions of the ICE

The requirements for ISG systems are:

● 12 - 42V system voltage
● 3 - 10 kW of generator power
● efficiency > 80%
● 200 - 400 Nm start-up torque
● high current storage 200 to 1000 A
● lifetime up to 500,000 start-ups
● cooling media up to 130°C
● very low required space
● low weight
● low costs

The boost function can be used in two ways. The first operational strategy is to add the ISG’s torque to the combustion engine’s torque. This strategy allows, for example, a downsizing or the support of the combustion engine. However, a high state-of-charge (SOC) of the boost storage device must be ensured, as this function has to be available at almost any time when driving.

In the second operational strategy, the efficiency of the total system can be optimised. In this case the ISG assists the combustion engine with additional power. The power will be taken from the energy storage system, previously recharged by regenerative braking. As the combustion engine will be supported by the ISG at low rpm, the working point of the combustion engine can be shifted to more efficient areas.

There are various possibilities to integrate a starter generator into the drivetrain. The different solutions are characterised by the number of clutches used as well as positioning of the ISG and the clutches. The next diagram gives an overview of the different designs (Figure 6.2-39).
The functionality depends on the position and the number of clutches. For example, with a one-clutch solution and the ISG on the crankshaft, pure electrical driving is not possible and the recuperative braking is limited.

**42 V board net voltage**

The technology of the 42 V board net is closely linked to the ISG. The argument for the 42 V board net is the increasing demand for electric power on board. On the one hand the electrical power is needed for comfort, information and safety systems; on the other hand, electrical power can be used to reduce the losses of belt-driven accessories, like the cooling water pump, oil pump, servo pump etc. In most cases these accessories are driven continuously by a mechanical coupling and this leads to a poor efficiency.

A relevant fuel consumption reduction could be realised by driving these accessories only when needed, but today 14 V net would have to carry too much current when all these components are driven electrically. Also the 14 V net limits the start/stop operation of the ICE.

The industry has proposed the adoption of the 42 V level for the board net and it will help to reduce the fuel consumption of state of the art vehicles in the future. The market entry for first systems of this kind is expected to take place between 2006 and 2010. This also opens up the wide use of electrically controlled accelerators, braking and steering systems in the future.

**Auxiliary Power Unit (APU)**

Fuel cells as auxiliary power units (APU) are interesting in vehicles with increased electric power demand. Today, the generation of electrical energy is done by a generator driven by the internal combustion engine. This means the energy is converted in several steps from chemical energy into thermal energy, then into mechanical energy and this mechanical energy is converted into electrical energy. Since losses occur in each of these conversion stages, the overall efficiency of the electricity generation is only about 15 to 20%.

An APU is meant to generate electricity on board of a vehicle with a conventional (small) ICE, especially on those with high electrical energy demand even in standstill such as refrigerator trucks etc. Fuel cells as APU run on the fuel that is used by the vehicle, this means it has to reform gasoline or Diesel. Problems and challenges have to be faced with the
reformer fuel cell vehicles. But the reformer and the fuel cell will be in a small power range and therefore the APU will be less expensive. Also the electrical load profile will probably not be as dynamic as for the fuel cell for propulsion.

**Storage for mechanical energy**

Flywheels were often used for short-term storage, because they have good efficiencies when high powers have to be stored and taken from them in short periods. For reasons of weight, high-speed flywheels are used almost exclusively. But technical and safety problems and also high losses if the energy has to be stored for a longer time, reduced the enthusiasm. Besides the flywheels, which were tested in conjunction with continuous variable transmissions, there are also electro-mechanical flywheels under research. This kind of flywheel has a high inertia and is loaded by the electric energy of an integrated motor. The functionality of the motor can be inverted during discharging so that it acts as a generator that produces electric energy. Flywheels mostly come into operation as niche applications.

**6.2.2.5 Engine Concepts close to State of the Art Combustion Engines**

A lot of research and development has been applied in the past to alternative combustion engine types, including the Stirling engine, micro-turbine, steam engine and free piston engine. Often they offer advantages in terms of low emissions, but these are compensated by low efficiency, high production cost, poor transient behaviour, high weight and reduced durability. Finally, all would require massive change to the existing engine manufacturing and service infrastructure, and are unlikely to succeed outside niche applications unless a technology breakthrough enables significant advantage to be shown.

**Stirling Engine**

The Stirling engine differentiates from the other combustion engines in that working media and heat carrier are separated; it is a combustion engine with external combustion. So the working gas in the Stirling engine is independent from air and exhaust mass flow.

Via an external heat exchanger some exhaust gas energy is fed back to the process via the incoming air, so the total efficiency of a Stirling engine is dependent on the efficiency of this heat exchange. By this it is possible to operate the Stirling engine in a wide operating range which goes far beyond the “rated” operating point, which is the operating point of best total efficiency. Nevertheless, the achievable higher power ratings are only reached with decreasing efficiency. This is also due to the falling efficiency of heat exchangers with higher heat fluxes.

Realised Stirling engines can be characterised in their operating behaviour that the point of maximum power is identical to the rated operating point or they operate already with overload. This explains also the big range of specific fuel consumption which can be found in literature. From this it can be directly concluded that engines which achieve maximum power in rated operating point will have a much worse efficiency in part load condition. On the other hand, by strategically choosing the rated point, very good efficiency can be achieved in part load operation.

For a vehicle, this property means that it will only work efficiently in a relative small operating range, but a big power spread in the range of 1:8 is possible. So for the Stirling engine a layout for a special operating range i.e. city traffic can be chosen and the total efficiency will be acceptable. If this vehicle were used in highway driving then the efficiency will drop considerably compared with the values of state of the art powertrains.

This behaviour makes the Stirling engine an attractive candidate for a hybrid concept, where good efficiency in a restricted operating range can be accepted. In this case the rated point will be placed in part load to cover the mean power...
requirement in city driving as an example. With such a layout, also specific power weights of 5 kg/kW and specific room requirements of 6.5 Lit/kW can be achieved as a maximum. This means for a standard vehicle that it will become relatively heavy.

Regarding other estimated advantages of the Stirling engine such as very smooth running and little noise radiation it can be stated that measurements have shown that the auxiliary drives such as burner blower and compressor for the pressure regulation of the working gas produce noise intensities equal to four stroke Diesel engines. By further development steps these disadvantages might disappear.

Emissions of a Stirling engine are determined predominately by the burner concept. Further it can be estimated that not all optimisation possibilities have been exploited so far and there is still potential for further improvement.

So far the following raw emissions have been reported in literature:

<table>
<thead>
<tr>
<th></th>
<th>NOx (g/kWh)</th>
<th>HC (g/kWh)</th>
<th>CO (g/kWh)</th>
<th>Particulate (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.015-5</td>
<td>0.01-0.34</td>
<td>0 - 1.26</td>
<td>0</td>
</tr>
</tbody>
</table>

Also the load-dependent trends that low NOx is combined with high HC and high CO respectively high NOx with low HC and CO need to be considered.

But in general the Stirling engine is the combustion engine with the best emission reduction potential. Additionally this engine, like the gas turbine, can use many different fuels which, might be an essential advantage in the future.

Concluding, the Stirling engine has the following advantages and disadvantages:

**Advantages:**
- Big power spread (1:8) with good efficiencies only near “rated” power
- Very good emission behaviour
- Potential for low noise

**Disadvantages:**
- High specific weight/power ratio
- Reduced dynamic behaviour
- Big specific space requirement / power
- High development effort up to series production
- High production costs

**Free Piston Engine**

Free piston engines have no real market position at the moment; only a few prototypes have been built.

One example is the free piston engine “Rectilineaire” of Jean Jarret (Automobil Revue No.43 from the 16th Oct. 1980), which is a two stroke, dual piston engine which has got no crank train and produces directly electricity via two linear generators on a push rod. The push rod is directly fixed at the two pistons.

Another example would be the free piston engine from German company Stelzer Motor GmbH in Frankfurt, presented to the public around 1985.

The free piston engines which produce directly electricity in combination with a generator are favourable also for a series hybrid powertrain. In this case the driveline of the vehicle is purely electric, the gen-set is more or less independent. All advantages and disadvantages of a classical big series hybrid system apply, especially the dilemma of power specification, which can be either done for the average power requirement in city or for highway driving.

For all these engines the following properties are valid:
Advantages:
- Compact unit
- Good specific weight/power ratio
- Potential for low vibration and noise

Disadvantages:
- Hard control of engine speed and load
- Critical gas exchange and fuel injection
- Difficult emission behaviour (2 stroke principle)
- High development effort up to series production

Steam Engine
On account of evolution processes in the field of tribology, material, electronics and burner technology, the development of the steam engine improved during the last 10 years. The main system feature is the very low pollutant emission profile. Integral part of the steam engine is a patented ‘Caloric Porous Structure Cell’ (CPS Cell). The CPS Cell can theoretically process any fuel that can be vaporized and pre-mixed with air - liquid or gaseous, fossil or renewable. The result is a clean stream of hot exhaust gas that is used to power a steam drive.

The CPS Cell is made of a highly-developed ceramic foam. While an air/fuel mixture flows through its sponge like structure, the fuel does not burn up as in a conventional burner. In the CPS Cell it oxidizes from pore to pore without open flame - similar to a thermal reactor. The pores have a precisely defined structure and size that prevents the fuel from flaming up and therefore developing thermal pollutant emissions. A simple yet sophisticated heat control system keeps the cell’s temperature at a moderate temperature of around 1200°C. This results in ultra low levels of harmful gases such as NOx, CO and HC and a fuel consumption comparable to a state of the art Diesel engine, see Figure 6.2- 41. The cell’s output power can be accurately controlled and varied within 5% to 100% of its rated power. For highly dynamic applications, the response time for changing the load demand is only a few milliseconds.

Plain, purified water can be used as working media. This reflects a good compromise regarding cost efficiency and compliance with environmental criteria. With an electronically controlled injection system a precisely defined amount of steam is injected into the engine’s expansion chambers. The expanding steam’s force pushes down the piston. Higher amounts of injected steam result in a larger force, which directly corresponds to the engine’s torque output. The principal configuration of a steam engine is shown in Figure 6.2- 40.
Due to the fact that lubrication oils are limited in their capabilities to resist high temperatures and could possibly get in contact with the steam and therefore contaminate the drive's feed water, an oil free engine is another important technology option for the realization of steam engines.

**Advantages:**
- high fuel efficiency
- ultra low emissions
6 TECHNOLOGY EVALUATION POWERTRAIN

- high low-end torque
- silent operation
- environment and service friendliness
- fuel flexibility (gasoline, Diesel, natural gas, non-fossil bio fuels, hydrogen etc.)

Disadvantages:
- overall engine efficiency lower than Diesel engine
- operational readiness depending on ambient conditions
- heat-up operation at very cold condition

6.2.3 Alternative Powertrain beyond 2020

It is likely that the “flexible” combustion engine, with highly variable sub-systems under the control of a sophisticated powertrain management system, will continue to evolve in combination with improved, partly renewably sourced, fuels. The Diesel homogeneous charge compression ignition (HCCI) and gasoline controlled auto ignition (CAI) combustion processes, which have many similarities, may merge along with fuel properties into a “Combined Combustion System”. In combination with the improved aftertreatment technologies, zero impact emissions will be reached. If the political will to replace liquid fossil fuels remains in place (and it probably will), gaseous fuelled engines will be highly charged, lean burn and down sized. For all engine types, new materials and design philosophies will enable a specific engine power of 150 kW/litre and weight of 0.5 kg/kW. In combination with advanced transmissions (probably dual-clutch or infinitely variable type) with high efficiency and flexibility, the energy consumption of vehicle power trains will be reduced further. Electric hybridisation may be commonplace beyond 2020, both as an efficiency enabler and provider of power for x-by-wire systems. If there is more CO2-free electrical energy available from renewable or nuclear sources, battery-electric vehicles have to be discussed again. Pure battery vehicles already exist in niche applications and have been under research for decades. For the electric powertrain itself new, more cost-effective production methods for electric motors might be an issue.

Fuel cell vehicles running on hydrogen have the advantage of being real zero-emission vehicles. Technologically, they can be considered as electric vehicles in which the battery has been replaced or supplemented by a fuel cell.

Pure Battery Electric Vehicles

The emission requirements of ZEVs can be satisfied by electric vehicles, however, even after decades of research on battery vehicles it is not possible to fulfil the standard requirements of a vehicle with the current battery technology. Furthermore, when the performance of the electric vehicles is satisfactory for city use, the universal introduction of electric vehicles will not be possible because of limitations in their operational range and top speed. In the future, fuel cell powered electric vehicles will be able to overcome the problems of pure electric vehicles, which are bound to battery technology. There are, however, still many questions and problems to be solved, regarding the complexity of the system, the size, and particularly the system costs. If the battery performance does not improve significantly, pure battery cars are only to be expected in niche vehicles but they may be a building block for other technologies25.

Fuel Cell Vehicles

The fuel cell vehicles together with a pure battery vehicle use the technology most different from the ICE of all the considered technological options. The propulsion is realised electrically with the help of an electric motor just as in a
battery vehicle. The electric energy is not taken exclusively from a battery, but is generated from hydrogen or in the case of a reformer fuel cell vehicle from a hydrogen-rich synthesis gas (e.g. methanol). The fuel cell is a direct conversion of chemical energy into electrical energy with high efficiency.

The potential benefits of the FC technology in the long term are:

- Reductions in local air pollution, groundwater contamination, and greenhouse gases
- Improved public health and safety from reduced exposure to fuel and emissions dangers
- Reduced vehicular urban noise levels and associated stress
- Increased energy security, by diversification of fuels
- Support and acceleration of the long-term trend towards a clean hydrogen and electricity-based economy

These benefits will be essential for the future, but widespread and mature fuel cell technology in vehicles is still far away. Several technological and economical problems have to be overcome on the way to mature and affordable fuel cell vehicles for the end customer.

Fuel cell powertrains for vehicles do not only consist of the fuel cell stack and the electric motor. Altogether they are a very complex system comprising the fuel cell stack, energy storages, compressors, heat exchangers, valves, power electronics and electric motor. In the case of a reformer fuel cell vehicle there are additional components like the reformer, a gas purification unit and a burner. All these components have to fulfill the general requirement for the application in a fuel cell vehicle: low weight and volume, capability of mass fabrication and low costs. Another very relevant issue is an intelligent control of the interaction of all these components to ensure the functionality and a low overall energy consumption of the system.

Research activities worldwide concentrate on the improvement of the efficiency, reducing the costs and increasing the reliability and lifetime of the fuel cell systems. Besides these problems vehicles fuelled directly with hydrogen face the storage of the hydrogen and the missing hydrogen infrastructure as the major obstacles on the way to market introduction. The advantage is that these vehicles can be real ZEV vehicles depending on the method of hydrogen generation, only water is the by-product of the energy conversion on-board.

With the reforming of a hydro-carbon based fuel, the ZEV operation is lost and the overall efficiency is decreased. The decrease in the efficiency in comparison to the hydrogen systems is caused by the additional conversion step and the operation of the fuel cell stack with a gas mixture with only a low hydrogen content. The hydrogen content of the gas produced by the reformer system depends on the applied fuel and reforming technology. The complexity and the costs are increased by the additional components, the warm up time and the transient behaviour of the reformer system. The next picture depicts the different fuel choices with regard to the infrastructure and vehicle expenditure (Figure 6.2-42).
Fuel cell systems can easily be hybridised by the integration of an electrical storage. This is normally done to improve the dynamic behaviour of the powertrain and to store energy recuperated during deceleration phases.

**Truck & Bus Technology Options**

The main objectives for these vehicles with regard to alternative propulsion systems for the desired timeframe are given in this chapter.

- **Reliability and availability**
  In general, as truck and bus powertrains are exposed to very heavy operating conditions, alternative powertrains have to meet more severe reliability and availability requirements than powertrains of passenger cars. In order to be competitive with further developed state of the art powertrain systems, the alternative concepts would need to meet the same reliability and availability as state of the art powertrain systems.

- **Fuel requirements**
  Especially in the field of adequate energy storage for alternative propulsion systems, the fuel needs to be competitive with state of the art Diesel fuel in all aspects. This applies for energy density, operating range, fuel handling and refuelling convenience.

- **Local zero emission concepts**
  Besides these mainstream applications future transport scenarios show the need for special transport vehicle types to protect "vulnerable" regions with respect to noise and exhaust emissions. For these applications special local zero emission concepts could come into operation. Regions to be protected could be on the one hand agglomerations like cities and mega-cities. On the other hand larger environmentally stressed landscapes (e.g. the alps) could be a field of application for these requirements.
Overall fuel consumption

The alternative powertrains have to be integrated into a complete vehicle concept, so provisions for the integration of environmentally friendly systems have to be considered, in a way that reduced energy consumption is obtained in all operation modes (e.g. idle mode) besides the main propulsion goals. Centralized the most important issues are:
- Alternative powertrains have the same reliability and availability as state of the art powertrain systems
- An adequate energy storage for alternative propulsion systems has to be developed
- Special local zero emission concepts have to be created
- Energy consumption has to be reduced in all modes of operation

The technologies offered for the bus and truck alternative powertrain build on experiences made in the passenger car segment.

Electric vehicles

Pure electric vehicles in the heavy load segment seem not to be feasible at all, as they do not offer suitable performance and range due to the huge battery systems needed. Electric vehicles would be possible without electrical storage onboard, taking the electric energy from a trolley line or something similar. This has been realised in the past with trolley buses in cities and could be applied to special routes as well. There has been a proposal to electrify the transit through the Alps. The trucks would then only need a relatively big and powerful electric motor. Electric delivery vans have been in use until the 70s of the last century in milk fleets (UK) and in postal services. These vehicles offer a good relation of curb weight to payload and they usually have very defined routes per day. A maintenance and recharging is possible in well organised garages. So these vehicles offer good noise and emission (CO2) reduction possibilities. New, modernised variants need to be developed. Compared to today, enhanced battery systems are required for a good acceptance.

Hybrid drivetrains

As city buses have a well defined stop and go driving pattern they are ideal candidates for hybridisation. Especially the ability to recover brake energy and to use it for next acceleration allows the introduction of downsizing concepts for the IC engine. Usually medium sized passenger car engines can provide the average power to the drive-train, the electric motor provides the peak power for acceleration. Also here, electrical storage systems need to be optimised.

Dual mode buses with internal combustion engine and overhead electricity supply (trolley bus) would offer a possibility to freely switch between local zero emission policies and non-restricted operating conditions. So these systems enable a normal operation mode up to a certain city boundary and could then be switched to a zero emission mode. These systems would need special infrastructure to incorporate the power demands.

In case of dual mode buses, by substituting the ICE with a fuel cell device, the fuel cell could be used as a fall-back alternative when overhead power is not available. This would lower the requirements for the fuel cell systems in an introduction phase for the technology in heavy load applications. Compared to hybrid systems under research at the moment (Figure 6.2-43), these new systems would not rely on fossil fuel as a main energy source.
Fuel cells in heavy load vehicles offer a large improvement potential on the tank-to-wheel basis concerning CO₂ and regulated emissions. Benefits have to be carefully evaluated concerning operating mode of the individual vehicles, in order to compare the efficiency to state of the art propulsion systems if the hydrogen is not produced from renewable energy. In addition, fuel cells for auxiliary power generation could be used for supplying power while the main engine is not running. Bringing fuel cell systems into several niche applications like Figure 6.2-44 will require large efforts in all aspects of this propulsion system.

It is no coincidence that the first fuel cell applications have been realised on city buses. The available space in a bus (i.e. overhead hydrogen tanks), the standardised driving cycles and the dedicated maintenance and fuel supply in special garages were the reasons. The feasibility of fuel-cell powered buses for public transport is being analysed in several projects at the moment.33
ICE with alternative fuels

Alternative fuels also offer a reduction of pollutant emissions and CO\textsubscript{2}. Favourable applications might be the use of CNG (compressed natural gas) in trucks and buses in high volume applications. A CNG vehicle also imposes less effect on the public, as there is no Diesel smoke or odour. Synthetic fuels offer a wide variety of adjustable parameters. Engines to suite these in the rough everyday operating environment have to be specially developed.

Additional efforts to improve performance

Additional efforts to improve performance account for only a small part of the losses of trucks and buses\textsuperscript{34}. But these systems also offer the possibility to save energy in several operating modes. Regenerative braking devices could offer a saving on the vast amount of energy that is dissipated, especially in urban stop-and-go traffic. Also, accessory drives can be optimised by decoupling them from the engine speed in order to achieve a more efficient operating point (air conditioning, power steering, etc.).

The main foreseen technological options are:
- Electric vehicles
- Hybrid drivetrains
- Fuel cell
- Internal combustion engines (ICE) with alternative fuels
- Additional efforts to improve performance

6.2.4 Hurdles/Barriers and Research Demand

6.2.4.1 Advanced Powertrain

Spark Ignition Engines (SI)

The potential to reduce fuel consumption and emissions is given by some interesting future technologies for SI engines. Lean combustion engines and concepts with fully variable valve train technologies enable an unthrottled engine operation, which results in a higher process efficiency. Downsizing is another technology to lower carbon-dioxide emissions. Especially in combination with variable compression ratio (VCR) it is one of the most promising concepts with a reduction in fuel consumption of up to 25 percent in the NEDC. The development target and the research demand for the SI engine should not be an oversized degree of variability for the engine, especially for engines with small displacements and power output, but to get the highest effect of fuel benefit together with a cost effective solution.

The efficiency of gasoline direct injection engine technologies will be lowered by the necessity to meet the emission legislation standards. The loss in fuel consumption benefit is between 2 and 4 percent in the NEDC cycle, caused by the need to switch from lean to rich operation for NOx trap regeneration. Beside optimising the exhaust gas after treatment, a reduction of the sensitivity against sulphur and nitrate (by the fuel) is necessary for long-life catalysts. Furthermore, another hurdle has to be overcome. The thermal consistency of the absorber catalytic converter is limited to temperatures above 850 °C, which leads to a less efficient light-off behaviour or a limited power output. Optimised engine operation needs new materials and concepts.

In comparison to the gasoline direct injection principle, down-sized engine technology with supercharging and variable compression ratio allows stoichiometric engine operation without additional exhaust gas after treatment for NOx. Because of the complex design, the actuators, engine materials and the control algorithms, there is a research demand
to realise the concept. Using the downsizing with cylinder deactivation leads to a research demand for the valve deactivation system, the engine acoustic and the strategies in the engine control unit for an acceptable transition between cylinder deactivation and all cylinders activated. For the downsized SI engine concepts there is a research demand optimising the level of supercharging and the charger concept (exhaust gas turbocharger or compressor) as well as the optimisation of materials. Also the turbo-compounding (mechanical or electrical) needs to be improved.

Fully variable mechanical valve trains will be very common in the European market in the next decade. They allow the reduction of carbon dioxide emissions up to 10 percent but with increased baseline engine cost. The evolution of valve train systems leads to completely new concepts, like the electromechanical valve train. The maximum degrees of freedom allow valve as well as cylinder deactivation and also multi stroke operations. In addition, several control strategies to improve fuel mixture formation and movement, such as late intake valve opening or valve lift curve shaping and multi lift events, are possible. The result is a reduction in fuel consumption of approximately 18 percent in the NEDC cycle for a 2.0l SI-PFI engine. Concerning the necessity of a high variability of valve timing to realize advanced combustion principles like CAI, the control of the residual gas fraction and a stratified engine operation is possible with the electromechanical valve train. But these concepts also lead to increased costs. Different engine displacements and power output targets define here the variability needed. Further devices which have to be developed are the valve control unit, the actuators for the variable valve train, additional sensors, the 42-volt generator and/or a DC/DC converter for the electromechanical valve train and the vacuum pump and brake assistant systems due to the unthrottled load control.

The more advanced boosted lean burn engine operation or a boosted operation with high EGR in the whole engine map (and the most advanced and discussed technology for SI engines) is Controlled Auto Ignition (CAI). This will be commercially available on the European market beyond 2020. Especially CAI technology makes lean combustion and unthrottled engine operation possible with the lowest nitrogen emissions available from SI technologies. This technology reduces fuel consumption by 10 to 20 percent together with near zero NOX emission levels. For a stable combustion with CAI in a large engine map area, a research demand on the variability of the valve train, combustion chamber design and the combustion itself (degree of boosting, combustion control, engine design, etc.) is necessary. However, this technology faces two technological barriers, which must be eliminated. Combustion control and the increased combustion noise level still pose problems. Research and development work should also focus on these two issues.

Due to a sustainable improvement in emission and fuel consumption reduction, an adaptation of the current test cycle characteristics to a more broad customer usage is necessary.

**Diesel Engines**

The Diesel engine research demand today is much more emission related in comparison to the gasoline engine research work. To meet future legislation standards for Diesel engines it is necessary to develop new engine concepts. The development will be focused on:

- engine modifications
- injection system (unit injector, common rail, fuel)
- number of valves
- electronic control unit (ECU)
- gas exchange (intake system, super charger, EGR, variable valvetrain concepts)
- friction, weight
- oxidation catalyst
Key technologies which have to be optimised are:
- the combustion process
- injection system
- turbo charging with intercooling
- exhaust gas recirculation with exhaust gas after treatment.

The application of variable valve train technologies also enables a decrease of exhaust gas emissions. The requirements for a variable valve train are different for Diesel engines than for SI engines. One main reason for this technology is to control exhaust gas recirculation in Diesel engines, so as to reduce nitrogen emissions. It can also increase efficiency by reducing the effective compression ratio via “Early Intake-Valve Closing”. Currently, the residual gas fraction is controlled by external recirculation back into the intake manifold. For a cycle synchronous engine operation and residual gas control, a more advanced control strategy is necessary. To reduce the additional costs of systems with a higher degree of variability a lot of system development work for the variable train design has to be done.

Analogous to the gasoline CAI process is the HCCI combustion process, one of the most promising technologies for Diesel engines. This technology is seen as an efficient way to meet the environmental challenges of future powertrains. There is a very high research demand for this technology, which allows a reduction of CO₂ emissions and fuel consumption and also cuts associated nitrogen and particulate emissions close to zero. Before successful market introduction can take place, a number of problems must be solved. The challenge of an HCCI Diesel engine is to phase and control the automatic ignition so as to create a proper air/fuel mixture at limited load range. Another major task to be solved is the very rapid combustion, which occurs simultaneously throughout the whole combustion chamber, that results in a dramatic increase in pressure and hence, a loud noise.

Figure 6.2-45 shows technologies for meeting current and future European legislation standards for HDVs. It can be expected that further legislation standards will not be met without more complex exhaust gas aftertreatment technology and also an advanced combustion process.

Regarding passenger cars, there are different strategies to be developed, which depend on the vehicle weight. In Figure 6.2-46 emission technologies to meet the European legislation standards are shown for a 1600 kg vehicle. There are two possibilities, first, an advanced (partly homogeneous) common-rail combustion process (ACCP) in combination with oxidation catalyst and Diesel particulate filter, or second, an improved combustion with common rail, oxidation catalyst, particulate trap and additional DeNOx trap. To optimise the advanced combustion processes as well as the exhaust gas aftertreatment and the system calibration, it is necessary to meet the future legislation standards especially under the cost aspect.
Figure 6.2-45 Technologies for emission reduction for heavy duty engines.

Figure 6.2-46 Technologies to meet further legislation standards.
With the introduction of HCCI and CAI combustion, the combustion principles of Diesel and gasoline engines will merge together more and more. There is a research demand necessary here also to force this trend. A key component of this new combustion process could be a new fuel that has been adapted for vaporization and ignition behaviour.

**Propulsion and fuel concepts**

Transmissions in both passenger and commercial vehicles are evolving so that manual transmissions will be replaced by automatic transmissions, automatic gearing and continuously variable transmissions (CVT). The research demand here is to optimise the automatic transmissions for convenience and driveability using improved electronic control and to replace the torque converter with integrated starter generator.

**Engine Concepts Close to State of the Art Combustion Engines**

- **Stirling Engine**
  Today such engines are not available in series production which is due to the disadvantages listed above. High development efforts are needed to overcome the disadvantages and to reduce costs. Prototypes are produced by the companies Stirling Thermal Motors Inc, Stirling Power Systems Corp., Mechanical Technology Inc. and Aisin Seiki Co. In general Stirling engines are regarded to be good options for stationary remote power supply for houses etc. Due to the weight and specific space requirements resulting from the big heat exchangers a mobile use in vehicle is not seen as very promising. Nevertheless, excellent emission behaviour and efficiency prospects justify further research efforts. Specific topics can be:
    - Lightweight heat exchanger with high efficiency independent from flow
    - Improvements in dynamic load behaviour
    - Reducing leakage of the working gas
    - Optimisation of the auxiliary power systems
    - Catalytic burner systems
    - Cost reduction programmes

- **Free Piston Engine**
  Today such engines are not available in series production which is due to the disadvantages listed above. So far free piston engines are only used or planned to be used as compressors for gas turbines and other exotic applications. High development efforts are needed to overcome the disadvantages for the use in vehicles. In general free piston engines suffer from start-up problems, air management and control problems. Nevertheless the compactness of the unit and the possibility to produce electricity directly electricity justify further research efforts. Specific topics can be:
    - Improvements of gas exchange and injection system
    - Solving starting problems
    - Emission optimisation and aftertreatment
    - Combination with high efficiency linear generators

- **Steam Engine**
  Today such engines are not available in series production because basic research is still ongoing. The good opportunity for solving the trade off between environment friendliness and economy justify further research efforts. Specific topics can be:
- Improvement of materials (oil-free engine operation, high temperature suitability, friction reduction, tolerance to corrosive environment of steam, heat losses etc.)
- Efficiency improvement (higher steam pressures and temperatures, reduction of heat losses etc.)
- Improvement of injection system and control strategies
- Frost-proof operation
- Feed water preparation

6.2.4.2 Aftertreatment

Following the above discussions, hurdles and barriers for these technologies should be briefly analysed again in view of CO2 aspects, powertrain efficiency, fuel effects and exhaust gas aftertreatment techniques themselves.

Combustion technologies

- Improvement of current available combustion technology

In view of next generation combustion systems, it has to be stated that generally lower NOx-levels result in increased fuel consumption. Further, to a minor extent, advanced HCCI combustion systems may result in higher HC and CO emissions which, when oxidized, cause further CO2. However, as long as overall combustion process efficiencies are better than corresponding values of state of the art engines, HC oxidation within the aftertreatment system should be less relevant. In addition, such an improvement will lead to further accumulation of expensive technology elements with the consequence of rising manufacturing cost. Thus, in the light duty area, where the Diesel engine directly competes against the gasoline engine as a power source, the attractiveness of the Diesel engine will decline. It must be mentioned that the Diesel offers also the potential of reducing fleet CO2 emission by increasing the Diesel share in that vehicle segment. In the heavy duty area an increase of purchase price will increase the period of fleet renewal, which has to be compensated by tax incentives to achieve the expected emission reduction, corresponding to more stringent regulations.

- Introduction of alternative combustion (e.g. HCCI)

There is here also a distinct disadvantage in the low combustion and exhaust temperature, in that combustion tends to incompleteness, leading to rather high levels of unburned fuel and CO in the exhaust with a negative effect on thermal efficiency. A rather efficient oxidation catalyst with low light-off temperature will be necessary. Another complication compared to state of the art engine systems is the required rather high exhaust recirculation (EGR) rate and, in the case of Diesel fuel, the effort to cool the recirculated exhaust gas to the required low level. This leads to a more sophisticated but more flexible air management system with higher cost.

A third difficulty is in the fact that compression ignition of a homogeneous charge cannot be timed as in the case of the Otto-cycle engine by the spark or in the case of the Diesel engine by the injection event. For HCCI engines, both the start of combustion and the shape of the heat release curve have to be controlled by the temperature and the composition of the cylinder charge. That means additional provisions for the management of charge temperature and EGR rate. The additional measures include flexible valve timing, variable compression ratio, two-stage or sequential turbo charging, a large EGR cooler and additional sensors as well as an upgraded engine management software to cope with the higher system complexity, both for steady-state and transient conditions. To date, a large variety of different solutions for mixture formation and engine management have been developed to a pre-production or near production status.
Having solved all the problems mentioned before, currently the fact remains that the HCCI system is only suitable for part load. This is mainly because of the rather long time necessary for homogenisation of the cylinder charge leading to an increasing need for higher EGR rates to prevent a too early start of combustion in the case of the Diesel engine and a too steep pressure rise with any fuel at higher loads. The consequence is the need for higher and higher boost pressures with increasing engine load. However, according to the knowledge available to date, the current full load requirement of 22 to 25 bar BMEP will be very hard to achieve. That means either by further intensive research activities the high load problem must be solved or that the potential for lowest NOx and particulate emissions can only be utilised for engine applications with a rather low load factor, i.e. passenger car engines and that there will be the necessity for a combination with a second combustion system suitable for high load.

- Research Demand

The exploitation of the potential of today's combustion technology requires a significant improvement of particular subsystems. Generally the increase of flexibility (e.g. full variable swirl, variable valve actuation etc.) requires new sensors and actuators as well as increased processor power. The state of the art in PC power has to be transferred to embedded systems as used in EMS. Finally, the target is a fully flexible EMS, to be able to operate with various kind of intelligent actuators and sensors. Intelligent means the ability to use sensors (actuators) capable of being connected following the principle - plug and play.

For Diesel engines a further development of high-pressure fuel injection systems (HPFIE) towards 3000 bar, in combination with rate-shaping/multistage injection utilisation seems mandatory. The introduction of new designs and materials will be the consequence.

To introduce advanced combustion, avoiding the problems and difficulties listed in 1.4.1, it would be necessary to create the desired in-cylinder conditions for combustion in a different way. The vision would be to develop a mixture formation device that could perform mixture formation late in the compression stroke and as quickly as needed to thereby control the heat release rate. This desired mixture formation device should be capable of instantaneously preparing i.e. inducing the correct near-to-stoichiometric mixture composition with massive instantaneous recycling and entrainment of combustion products, in order to ensure the necessary charge dilution. This would first of all solve the problem of the steep pressure rise and at the same time remove the difficulties when providing the required dilution rate externally. This approach could be the subject of advanced research and development efforts during the next decades.

**Aftertreatment Systems**

Similarly, as mentioned above, advanced emission control after the engine may result in fuel consumption penalties. Additionally, more sophisticated exhaust gas aftertreatment systems could lead to higher engine back-pressures, which are harmful to overall powertrain efficiency.

Constraints for the development of next generation aftertreatment systems in general will be quite similar, although maybe even more stringent in each of all aspects. Hence, the factors

- durability and reliability (material resistance, effect of lubrication oil)
- weight of catalysts and traps
- space requirements
- sensor and control function integration (OBD)
- costs of advanced after-treatment systems (precious metal)
- cost for maintenance
end user acceptance

secondary emissions (nano particles, NH3, NO2)

have to be taken into account as most critical barriers for successful introduction to mass production.

In detail:

Three Way Catalyst / Oxide Catalyst

Both are established technologies with the main focus for further development of cost reduction respectively reduction of precious metal content without losing effectiveness and durability. Furthermore, improvement of the catalytic coating itself is required as well as the connection between the coating and substrate, to prohibit secondary emission caused by abrasion of precious metal.

Diesel Particulate Filter

Generally, the hurdles for the DPF technology are all more or less connected with the necessity to regenerate the filter after a certain amount of PM is accumulated. On the one hand the material of state of the art wall flow filters is either very costly (e.g. SIC) or susceptible to thermal damage during filter regeneration (e.g. Cordierite). On the other hand the regeneration method itself causes some problems which have to be solved.

Fuel additive supported regeneration is not seen as the future solution, neither for LD nor for HD with the specific requirement of more than 500 000 km maintenance-free mileage, because of the additive ash accumulated in the filter. This causes short maintenance intervals for filter cleaning.

DPFs with catalytic coating, are because of their noble metal content very costly (today approximately 20 $/g noble metal). In addition, the coating durability strongly depends on the maximum temperature (850 °C). However, for light duty application, the catalysed DPF is from today’s point of view the preferred solution.

For the heavy duty application mid term, the bare cordierite filter in combination with an upstream-located oxide cat seems to be the most favourable solution. But this requires on the one hand an active regeneration support and on the other hand a very precise knowledge about the actual filter loading, which requires new EMS function structures (physically based DPF model), new sensors (PM sensor) respectively the combination of both.

SCR

One significant risk to the SCR technology is the availability of urea water solution over wide areas. Currently an infrastructure to provide any reductant (e.g. Urea water) is not available.

NOx Adsorber Technology

The main penalties are the sulphur sensitivity and the bad durability. Running the Diesel engine at low air fuel ratios at high load, minimizing the additional fuel quantity needed and preventing the lube oil dilution have to be seen as difficulties. Application-dependent systems configuration containing pre-oxide-cat, NOx adsorber and HC clean-up catalyst are extremely voluminous and because of the required amount of noble metal, expensive.

Figure 6.2- 47 compares the pros and cons of the available NOx reducing technology.
Research Demand

Based on suitable technologies and the related hurdles and barriers identified, the research demand is discussed in this chapter in view of CO₂ and GHG aspects, powertrain efficiency and exhaust gas aftertreatment techniques themselves. Research should be carried out in parallel, on the one hand improving the engine process efficiencies by reducing losses such as low temperature heat losses (coolant), mechanical friction and auxiliary losses and, on the other hand, controlling the combustion process (and its related parameters) such that lowest possible NOₓ and PM emissions are achieved. Further, material research has to concentrate on new types of catalysts and traps featuring lower pressure losses. Besides wall flow filter types, more open structures - foam filters - internally coated with catalytically active layers - could be attractive solutions. Thus, reducing exhaust gas backpressure of the engine. Research demand is also identified for new aftertreatment technologies suited for variable fuel blends (based on crude oil and renewable energy sources). In this context, sulphur resistant deNOₓ catalyst systems - with efficiencies > 80% by development of NO selective catalysts - will play a relevant role both during a mid-term transition phase (sulphur from fossil sources) as well as long-term phase when sulphur in fuels from renewable sources has to be processed. In view of best conversion efficiencies in LD driving cycles (legislative and real-world driving cycles with very short durations), research and development has to concentrate on aftertreatment systems (including oxidation catalysts, traps, SCR- and NOₓ-adsorbers) adopted to the temperature and gas composition of the exhaust gases of advanced engine processes (such as gasoline CAI or Diesel HCCI). Finally, further increased importance has to be paid to research on new, non precious metal catalysis and advanced coatings (e.g. for 4-way catalysts for gasoline and Diesel engines) in order to improve the trade-off between costs, durability and efficiency of next generation LD-exhaust gas aftertreatment systems. This should include also concepts for

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**NOₓ reducing Systems**

<table>
<thead>
<tr>
<th>NOₓ Adsorber</th>
<th>Catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Highest NOₓ reducing potential because of its adsorption capability below 250 °C</td>
<td></td>
</tr>
<tr>
<td>+ No additional operation fluid needed</td>
<td></td>
</tr>
<tr>
<td>+ Oxidation catalyst capabilities included</td>
<td></td>
</tr>
<tr>
<td>- Cost (Platinum)</td>
<td></td>
</tr>
<tr>
<td>- Fuel consumption penalty (single branch &gt; 10%, in US-HDTC)</td>
<td></td>
</tr>
<tr>
<td>- Enormous application effort necessary</td>
<td></td>
</tr>
<tr>
<td>- Low space velocity requires high packaging volume (worse case: dual leg system)</td>
<td></td>
</tr>
<tr>
<td>- Durability and sulfur sensitivity</td>
<td></td>
</tr>
<tr>
<td>- HC clean-up catalyst required</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SCR Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Close to series application</td>
</tr>
<tr>
<td>+ Not influencing engine operation</td>
</tr>
<tr>
<td>+ Field test experience regarding durability available (Europe)</td>
</tr>
<tr>
<td>- Additional operation fluid w/o infrastructure</td>
</tr>
<tr>
<td>- Packaging → additional tank and dosing system</td>
</tr>
<tr>
<td>- Status dosing system</td>
</tr>
<tr>
<td>- Low NOₓ efficiency below 200 °C</td>
</tr>
<tr>
<td>- For aqueous Urea solution compressed air supported dosage system required</td>
</tr>
<tr>
<td>- Customer has to refill reductant (comfort ↔ ↔OB D)</td>
</tr>
<tr>
<td>- NH₃ clean-up catalyst required</td>
</tr>
</tbody>
</table>

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Figure 6.2-47 Evaluation of NOₓ reducing technology
new catalytic converters and traps which continuously convert and regenerate themselves under all operating conditions as well as for a variety of fuels and fuel blends used in passenger cars.

**Introduction of new fuels**

Most critical barriers for low CO₂ powertrain systems based on new (renewable) fuels are high supply infra-structure costs. Further, it has to be clarified whether and to what extent low-C content fuels effectively contribute to better well-to-wheels CO₂ balances. Various alternative powertrains show no clear well-to-wheels CO₂ benefit when compared to a modern DI-Diesel engine.

Further, high energy demands during fuel processing (reforming, storage, transport) may either cause increased CO₂ emissions or lower overall efficiencies. Positive effects due to the introduction of new, alternative fuels on engine-out emissions and the performance of the aftertreatment systems may not become effective if production, transport and storage logistics are not economically viable. This is also true if particular positive effects, e.g. reduction of sulphur levels, are overcompensated by other negative effects - e.g. increased CO₂ emission due to this sulphur reduction.

Moreover, fuels in a wider sense, i.e. lubricants significantly affect engine-out emissions already today, particularly PM emissions. Hence, new fuels, new engines and new exhaust gas aftertreatment systems have to be compatible to future lubrication systems and lubricants.

6.2.4.3 Alternative Powertrain

All of the different technological options have specific hurdles and barriers, but due to their pre-market status they all have the cost issue in common. By market introduction and mass manufacturing, the costs of these systems can be reduced, but the cost reduction by mass production has also its limits, as in many cases expensive materials, like noble metals in fuel cells, are required. The costs for these materials will of course not decrease by mass production. In these cases new solutions and manufacturing methods have to be developed to decrease the need for noble metals.

The following table gives an overview of the hurdles and barriers identified during the workshop (Figure 6.2-48):

<table>
<thead>
<tr>
<th>Pure battery vehicles</th>
<th>weight, durability, range, cost, recycling, size, recharge time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid</td>
<td>battery, durability, size, weight, cost</td>
</tr>
<tr>
<td>Mild hybrid/ISG</td>
<td>cost, weight, reliability</td>
</tr>
<tr>
<td>42 V board net voltage</td>
<td>safety, cost</td>
</tr>
<tr>
<td>Fuel cell (H₂ onboard)</td>
<td>infrastructure, cost, H₂-production, storage, reliability, durability, customer acceptance of H₂</td>
</tr>
<tr>
<td>Fuel cell (reformer)</td>
<td>warm up time, efficiency, emissions, CO poisoning, transient operation</td>
</tr>
<tr>
<td>APU</td>
<td>size, weight, safety, durability, reliability, cost, efficiency, cooling</td>
</tr>
<tr>
<td>Storage for mechanical energy</td>
<td>flywheel: safety, weight; hydraulic: noise, cost</td>
</tr>
</tbody>
</table>

Figure 6.2-48 Hurdles and barriers for the application of alternative propulsion systems
The research and demand can directly be derived from the hurdles and barriers of the respective technologies. Not only the integrated systems have to be optimised and tested but in most cases basic research is still required to provide the technologies to meet the targets of costs, reliability, efficiency and performance.

Hurdles and Barriers

The mentioned technologies still face a large number of hurdles and barriers for the technological breakthrough and commercial market application.

- Energy handling of alternative fuels
  Alternative fuels mostly pose great difficulties in handling. Hydrogen needs special handling devices resulting in high costs and handling inconvenience. The storage onboard vehicles has not been resolved to be competitive with Diesel fuels. Other gaseous and liquid fuels also face the problem of adequate storage onboard the vehicle concerning the size of the tank. For trucks and buses, the refuelling times are too long for the amount of fuel to be transferred to the vehicle.

- Energy handling and storage of electricity onboard
  The highest barrier for electrical energy storage onboard is still to achieve sufficient power density with adequate energy availability during the battery life. The reliability at all operating conditions also needs to be improved.

- Cost barrier
  Bringing the alternative propulsion systems to maturity and to market success in the long-term poses the great question of economic competitiveness. Looking at today’s high-volume mainstream applications and their further development, the alternative technologies are from today’s point of view still not competitive for a long time. This represents a very strong demand for the commercial vehicles, with much more focus than in the passenger vehicle segment. In order to have a chance for higher volume applications, the alternative propulsion systems at least need to be at comparable price for the same production volume.

- Operating performance
  Alternative propulsion systems are mostly less reliable than state of the art comparable Diesel-powered systems. The systems need to guarantee operating performance under very harsh environmental conditions. Looking at temperature differences across Europe, which span a large range between north and south, gives an idea of these conditions.

Hurdles and barriers for technological breakthrough can be summarised by:
- Energy handling of alternative fuels
- Energy handling and on board storage of electricity
- Cost barrier
- Operating performance

Research demand

The research demand to address the hurdles and barriers for the identified technologies poses the need for research in several aspects. These are divided into system level and component level topics.

System level:
- Performance optimisation by operating strategy in combination with route information

To overcome the shortcuts of alternative propulsion systems regarding operating range, a combination of future intelligent transport systems and/or driver assistance systems to lower power requirements could be feasible. Using more precise future navigation systems in combination with local road/traffic information, vehicle control strategies could help to make
alternative systems more competitive. Finally these systems could also be used for mainstream propulsion applications to save energy. But the operation of fuel cell vehicles has to account for the typical characteristics. So this technology could be used to keep the propulsion systems in their most efficient operating range (Figure 6.2- 49).

● Bus with integrated ICE + CSG + APU
This concept offers the opportunity to significantly lower emissions on vehicle operation in a city environment with a lot of non-moving time. The APU could be used to supply the energy when switching off the internal combustion engine.

● Adaption of auxiliary systems in buses to new power sources
Due to the shortcomings of new power sources, research has up to now only been focused on the environmental aspects of these systems in little detail. To enable the alternative propulsion technologies, the auxiliary systems need to be customised to these new propulsion systems. The auxiliary systems will need to be adapted to other characteristics in the energy supply. Transferring the systems from a mainly mechanical driven power source to an electric one, that can be more flexibly controlled, offers optimisation potential.

● Auxiliary power generation fuel cell application
Adoption of auxiliary systems (heating, ventilation, air conditioning, coolant pumps, electrification, etc.) can be decoupled from the main propulsion engine for flexible usage. A small fuel cell offers the potential to be the auxiliary power unit (APU). Thereby, the auxiliary systems need to be reengineered to fit fuel cell usage. Transformation of mechanical energy supply for these systems to electrical could also lead to performance optimisation due to possible better control strategies, like in the paragraph mentioned above. APU's could especially help to save fuel in buses when they are running in idle.33

Figure 6.2- 49 Comparison of theoretical fuel cell and internal combustion engine efficiency

Figure 6.2- 49 Comparison of theoretical fuel cell and internal combustion engine efficiency
6 TECHNOLOGY EVALUATION POWERTRAIN

- System reliability optimisation
In order to make the commercial viability possible, small fleets of demonstration vehicles using the proposed technologies will help to build up experience in the new technologies.

Component level:
- Super capacitor applications and battery technology
In order to enhance energy recuperation, storage devices for efficient energy storage from regenerative braking could further improve hybrid and electric vehicle performance in the future. Thereby, the aspects of packaging, safety, energy management and thermal management are predominant for the application in trucks and buses. Together with adequate battery technology, the range and performance of hybrid-electric-vehicles could be optimised. Battery technology research is needed to deliver high-peak and pulse-specific power with sufficient calendar and cycle life (Figure 6.2-50).

![Super capacitor application concepts](image)

Figure 6.2-50 Super capacitor application concepts

- Installation of gas turbine/fuel cell hybrid in trucks
Combination of these systems offers possibility to use a fuel cell and a gas turbine in one energy circuit. Depending on the type of fuel cell, the thermal energy could be used for the gas turbine. Hereby, research is needed to determine the potential of the fuel cell for truck applications, as total operating hours are about 4 to 5 times higher than in passenger vehicle applications. Applications of fuel cells should focus on experiences made with passenger vehicles concerning power and system size. Combinations of several passenger car fuel cells in order to meet truck power requirements should be more promising than developing truck-size fuel cell technology.
- IC engine systems for alternative fuels (e. g. CNG with HCCI or direct injection)
New technologies for combustion processes should be evaluated with regard to alternative fuel. This could lead to emission and GHG reduction due to the fuel and the combustion process.
Sensor system development for engines with alternative fuels

Further usage of alternative fuels could be enhanced by new sensors for alternative fuels. This could help adapt engines to different kinds of fuel, enabling the possibility of flexible fuel usage on a vehicle to a greater extent.

Storage systems for alternative fuels (H₂, CNG, …)

Problems due to storage of alternative fuels have to be solved to achieve a greater level of alternative fuel acceptance for fuels that are non-liquid at room temperature. Basic research considering new materials might provide a breakthrough concerning handling and energy density.

An overview about research demands of alternative powertrain technologies can also be separated in system level and component level:

System level:
- Combination of operating strategy with route information could optimise performance
- Pollutant emissions are lowered by integrated internal combustion engine, crankshaft starter generator and auxiliary power unit (ICE + CSG + APU)
- New power sources could be adopted as auxiliary systems in buses
- Auxiliary power will be generated with fuel cells
- Reliability of powertrain systems has to be optimised

Component level:
- Super capacitor applications and new battery technologies enhance alternative systems
- Gas turbines/fuel cell hybrids will be installed in trucks
- Engines for alternative fuels have to be equipped with new sensor systems
- IC engine systems for alternative fuels (e.g. CNG with HCCI or direct injection) will enter the market
- New storage systems for alternative fuels (H₂, CNG, …) will be developed

Pure battery vehicles

Pure battery vehicles already exist in niche applications and have been under research for decades. The main hurdles are the reliability and costs (mainly for the battery), the recharge time and also the very limited driving range. The main research field is consequently the battery, which has to be improved concerning energy and power density, but mainly with regard to cost reduction. Also hybrids and fuel cell hybrids could benefit from a breakthrough in battery technology. For the powertrain itself, no major technological hurdles can be seen, only new, more cost-effective production methods for electric motors might be an issue.

Due to the long recharge time and the limited energy density, it seems to be very unlikely that the battery vehicle can compete with today’s all-purpose vehicles in a market with free choice of vehicles. But with reasonable costs they could gain a market share as second city cars beside a state of the art car.

Hybrid

Hybrid technology with a high share of electrical power calls for a bigger change to the powertrain of a state of the art vehicle. New transmissions, clutches and big electric motors might be needed. Besides with high electrical power, big batteries are needed and these are still very expensive. Nevertheless, first vehicles as from Toyota and Honda are already on the market.
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Research is needed on the components in a hybrid powertrain, like new transmissions, electric motors and batteries. Also the integration and control of all the components is an important issue. The components themselves have to be optimised, but also they have to fit to each other and the overall powertrain control and energy management has a big influence on the performance and energy consumption of the hybrid vehicle.

Considering the additional complexity and components compared with the state of the art powertrains, hybrids will only slowly penetrate the market. When, in future, the costs for fuel increase further, the higher costs for the increased complexity can be justified and the chances are good that the hybrids can reach a significant market share. But there is also a great dependence on customers’ wishes.

- Mild hybrid/ISG
  Costs, weight and reliability were identified as the hurdles and barriers for this technology. Nevertheless, these hurdles are not as problematic as in the other alternative powertrain technologies. By creating a mild hybrid by adding an ISG to an ICE, there is some complexity added to the system. Costs, weight and reliability have to be optimised for this system. Research has to be done on the electric machines, the integration of the starter generator and system control. Also the batteries that are needed for the ISG, which are a main cost factor, have to be researched. Solutions with belt-driven ISG require the least changes to the state of the art powertrain and will probably be introduced within the next years.

Mild hybrids with an ISG and maybe a downsized engine are seen to become a widespread measure for reducing consumption and emission in the time period 2020 to 2040, especially in city traffic.

- 42 V board net voltage
  The 42 V board net is closely linked to the ISG technology, because it is required for the starter/generators. The identified barriers are linked to the higher voltage level, which requires new components for this voltage level and some concerns exist regarding this voltage (e.g. short-circuit protection). The technology itself will not be a hurdle, but the new components and their introduction have to be developed and this will cause additional cost at component suppliers. Concerning the safety issues, there is still a need for special tests and special precautions have to be implemented in the system to avoid short circuits and contacts with humans. Closely linked to the ISG, the market chances of this technology are good, also because of increasing need of electrical power on board.

- Fuel cell for H₂
  In a fuel cell powertrain the internal combustion engine is totally omitted and the technology is very new for vehicle application. That means that complete new components have to be developed and a new industry has to be created. This is why the costs are the main issue on the side of the fuel cell stack. Research has to be done to decrease the costs of the membranes and catalysts inside the stack and new production processes have to be developed to decrease costs for the bipolar plates. Beside these cost issues, the durability also has to be tested and increased and a lot of research needs to be done to further increase the efficiency. A technology breakthrough is urgently needed to get the system costs down in order to produce the vehicles at reasonable costs\(^{37,32}\).

Fuel cell vehicles running on hydrogen have the advantage of being real zero emission vehicles, but a lot of barriers are linked to hydrogen as fuel. The infrastructure is not available and to be really competitive to state of the art vehicles, new storage methods have to be found. A lot of research is still needed in this field. The only storage technology providing a sufficient energy density is the storage of liquefied hydrogen. But during the process of liquefaction one third of the energy content in the hydrogen is lost. Also linked to the hydrogen as fuel are the safety concerns. Special research and
development efforts have to be spent on the handling and precaution measures for hydrogen. An open question is also the source for hydrogen. Only if hydrogen is generated from regenerative sources is it really CO$_2$-neutral and solutions have to be found to generate hydrogen in sufficient amounts in this way$^{38}$. The market chances of fuel cell vehicles are generally judged very differently today. The judgement of the participants of the workshop was very conservative, foreseeing fuel cells only in niche applications also for the period after 2020. Even to achieve this, a range of fuel cell vehicles has to be offered to make market penetration of 2 - 5 percent possible$^{39}$. The qualitative development of hydrogen applications in the period of 2005 to 2025 is shown in Figure 6.2- 51$^{40}$. Until the market entry of the fuel cell in about 2015, only small test series are expected to use this technology$^{41}$. Another point that prevents an increase in the fuel cells’ market share over 1 percent by 2010 is the fuel delivery infrastructure$^{42}$. 

- Fuel cell with reformer

Fuel cell systems with reformer are developed to solve the problem of hydrogen storage and distribution. An example is NECAR 5 by Daimler Chrysler (Figure 6.2- 52) which solves the infrastructure problem for hydrogen by using a methanol fuel cell$^{43}$. Using fluid fuels and maybe even state of the art gasoline or Diesel, the infrastructure and the distribution is no problem. But the reformer adds complexity and costs to the fuel cell system. Reformers for gasoline and Diesel are in a very early development state and a lot of research is needed to guarantee the hydrogen generation in the transient operation in a vehicle. A big problem is the CO content of the gas produced. On the reformer side the start-up time and the transient behaviour have to be improved and the CO content reduced to a minimum. On the stack side, catalysts which are more resistant to CO have to be developed. With reforming hydrocarbon based fuels for operating a fuel cell, the advantage of CO$_2$ neutrality is lost and from the point of efficiency it will be very hard for such future vehicles to beat improved internal combustion engines.

Figure 6.2- 51 Perspectives for hydrogen as alternative fuel$^{40}$

- Fuel cell with reformer

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The reformer fuel cell technology for propulsion was judged as not relevant in the future. Nevertheless, a possibility mentioned is, that with a breakthrough in technology, fuel cell vehicles with mature reforming technology can create the market for the fuel cell technology in niche applications.

● **APU**

The APU is another possibility to create a market for fuel cells. An APU is an integrated system of reformer and fuel cell stack (high temperature solid oxide fuel cell (SOFC)) and faces consequently similar barriers and hurdles as powertrains with reformer fuel cell systems.

But generating electrical energy for the electronic and electro-mechanic systems on board requires only a small system, which helps to keep the costs for such systems low. Considering the fact that high-class vehicles especially require a high amount of electrical energy on board and that for these vehicles, the economical constrains are not so essential as for smaller cars, high-class vehicles are a possible market for FC-FC-APUs. In these cars a high amount of electricity generated with low noise could provide an added value to the customer, which could justify an increase in costs for the customer.

Another interesting field of application for the APU is the truck application. Some trucks need additional power during vehicle standstill, for air conditioning, heating and especially for refrigerating. Up to now the truck usually had to idle overnight to provide this power. Now, in the US, laws are in preparation to forbid these habits. Then the trucks need to have an extra APU, which preferably can be fuelled by Diesel. SOFCs could be the solution.

● **Storage for mechanical energy**

Vehicles with mechanical energy storage (e.g. flywheels) have been researched for special niche applications, e.g. as an energy storage in a hybrid city bus, which has to accelerate and decelerate frequently. Flywheels have a big safety problem and the problem of a very fast self-discharging. Hydraulic storage systems have a problem of weight, volume and noise. In some special applications with a high stop-and-go driving pattern, such as city buses in Japan, hydraulic storage systems are used.
Both kinds of mechanical energy storage add cost and complexity to the vehicles. For the period of 2020 to 2040 they are not at all seen as a big market player; maybe they will be used in a few niche applications.

The most important research demands are:

- Enhancement of battery technologies with regard to improved power performance (e.g. power density, recharge time, weight) and reduced costs for use in electric and hybrid vehicles
- Research is needed for new transmissions and electric motors for hybrid vehicles
- Improvement of reliability and cost/weight reduction for ICE with ISG
- Research demands in field of 42V board net regarding enhancement of safety standards (e.g. short-circuit protection) and cost reduction
- H₂ fuel cell:
  - Cost reduction for several components
  - Introduction of new production processes with regard to series production (e.g. membranes)
  - Development of storage systems
  - Infrastructure for H₂ is not available yet
- Higher efficiency and reduction of emissions (especially CO poisoning) for fuel cells (with reformer) and APU’s
- Optimisation of flywheels with regard to self-discharging; hydraulic storage systems have to be improved through weight, volume and noise reduction
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In this section technology objectives concerning vehicle structure are given. One of the key features in evaluating the selection of materials used in the production of motor vehicles is the trade-off between weight, strength and user comfort. New vehicle designs have made it possible to decrease fuel consumption by reducing the vehicle's weight, but the history of the automotive market over the past few decades shows that even as many key components have become lighter, consumer demand for more comfort, better safety systems, carrying capacity, and reliability have frequently resulted in the addition of more features, adding to overall vehicle weight.

Vehicle weight has been reduced primarily through changes in design, materials use, and assembly techniques. Manufacturers have been able to decrease weight through stress compatible dimensioning, optimum material usage and optimised welding techniques. Usage of light alloys and metals such as high strength steel, aluminium and magnesium as well as plastics and composite materials will have a great influence on weight reduction. New designs and the use of alternative materials usually go hand-in-hand because component design using light alloys and plastics differs fundamentally from steel construction because of the different characteristics of the materials.

7.1 Technology objectives for 2020 to 2040

The main objectives for these vehicles for the desired timeframe are explained below.

Vehicle weight reduction to improve fuel consumption and to reduce greenhouse gas emissions
The vehicle weight has a tremendous influence on total vehicle power demand, so more than half of the power demand is determined by weight. A weight reduction of 100 kg can save between 0.3 l and 0.4 l of fuel under normal operating conditions [13] [14], and up to 0.8 l fuel per 100 km, depending on vehicle and engine type for the most favourable conditions [6].

Using light-weight materials and light-weight design is seen as more important for reducing fuel consumption than using renewable fuels [8]. Focussing on CO2 in the future and keeping in mind that CO2-neutral propulsion systems still face a number of problems, a reduction in vehicle weight will be necessary.
Increase of passive safety standards

Being already on a very high level for the safety of passengers and pedestrians, the vehicle structure in the future will have to account for compatibility in passive vehicle safety and deal with a wide range in safety requirements. On the other hand, new materials are still expected to improve vehicle impact resistance. [5]. The main challenge is compatibility between passenger cars, passenger cars and vans and finally between passenger cars and vulnerable road users.

Provide enhanced modularity for the total body structure

Satisfying the customer expectations and market needs will lead to enlarged model number, yet at the same time the engineering efforts have to be reduced. Provision of enhanced modularity for the total body structure in order to open up flexibility in vehicle (derivative) design and assembly (care for increasing model range and very different vehicle technologies). [1] Thus a diversification of vehicle types can be foreseen.

The vehicle population can be split up into three general classes:

- All Purpose Vehicles (e.g. mid-size-sedan)
- Long Distance Vehicles and
- Dedicated vehicles (e.g. SUV’s, small urban cars). [8]

Thereby the contingent of compact class cars will increase. [9]

Decreased environmental pollution

Bringing new technologies for body structures into the market will consequently demand adequate recycling methods. Future requirements need to find a balance between maximising reuse and recovery and minimising landfill and thermal recovery. [12]

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### VEHICLE STRUCTURE

#### Fig. 7-1  Fuel economy change for reduced weight with compounding of benefits accounted for [7]

<table>
<thead>
<tr>
<th>Fuel economy change for reduced weight with compounding of benefits accounted for</th>
<th>Weight reduction</th>
<th>Fuel economy improvement at constant performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compared to a current mid-size sedan (City/Highway combined miles per gallon change from VEHSIME model)</td>
<td>2.1%</td>
<td>+1.5%</td>
</tr>
<tr>
<td>Packaging improvements</td>
<td>4.4%</td>
<td>+3.1%</td>
</tr>
<tr>
<td>High-strength steel bodies</td>
<td>1.8%</td>
<td>+1.2%</td>
</tr>
<tr>
<td>Lightweight interior</td>
<td>5.6%</td>
<td>+4.0%</td>
</tr>
<tr>
<td>Lightweight chassis</td>
<td>3.8%</td>
<td>+2.7%</td>
</tr>
<tr>
<td>Aluminum body closures</td>
<td>11.3%</td>
<td>+8.6%</td>
</tr>
<tr>
<td>All-aluminum body</td>
<td>1.0%</td>
<td>+0.7%</td>
</tr>
<tr>
<td>Aluminum engine block</td>
<td>1.8%</td>
<td>+1.2%</td>
</tr>
</tbody>
</table>
Introduction of closed material loops as far as possible
In order to support the decreased environmental pollution, further introduction of closed material loops is essential. This is especially favourable for materials that today offer fuel consumption savings through lightweight applications, but need to be thermally recovered or land filled.

Complete ecological evaluation (life cycle assessment), consideration of environmental effects of production processes for new parts and materials
Bringing new technology into the market will certainly result in sensible recycling concepts for these technologies. The focus has to be put more on an integrated approach at early development stages.

Economic recycling concepts
Enhancement of the recycling process will strongly depend on achieving recovery and reuse at feasible expenditure. This will be needed for several materials to be able to close the material usage loops. Thereby 95 percent of used materials are expected to be recyclable by 2010 [9]. Nevertheless, the processes could still show deficits that should be compensated and eliminated in the future.

So the main objectives for these vehicles for the desired timeframe are:

- Vehicle weight reduction to improve fuel consumption and reduce greenhouse gas emissions
- Increase of passive safety standards
- Provision of enhanced modularity for the total body structure
- Decreased environmental pollution
- Introduction of closed material loops as far as possible
- Complete ecological evaluation (life cycle assessment), consideration of environmental effects of production processes for new parts and materials (e.g. fuel cell systems)
- Economic recycling concepts

7.2 Technologies
In order to realise the objectives for 2020 to 2040, several technological options are identified.

Realisation of smaller flexible vehicle concepts with comfort and safety of large cars
Achievement of new vehicle structures, that incorporate the flexibility to scale the car to the needs of user.

Downsizing of all possible vehicle equipment in order to save weight
Comparable to engine downsizing and miniaturisation of electrical equipment, other parts of the vehicle structure need to be analysed for the potential to minimise them and save weight and package space. One alternative for the future could be a body structure being a high strength cage with energy absorbing parts covered by a minimum weight corrosion resistant film. [4]
X-by-wire systems without mechanical backup to optimise package and weight

X-by-wire systems are only yet in their first phase in market application. The consequent use of these systems therefore offers more flexible use for the vehicle structural design, as several mechanical and hydraulic components will be substituted. The elimination of operating fluids will also enhance recycling and improve maintenance. [16]

Connection and joining technologies in order to support body modules and multi material design

To support new flexible (Fig. 7-2) body concepts to adapt vehicles to market and society requirements, new and flexible joining technologies are needed. These technologies should support joining after the painting process during assembly. Thus, the surface treatment of the structural material has to be considered. Part sharing strategies will be applied in order to manufacture different cars, e.g. sedans, estate cars or coupes out of standardised modules. [6] Efficient multi-material joining technologies will help to adopt the usage of different materials for structural vehicle applications in one vehicle in the future.

Cost-efficient body structure to provide basis for high volume multi material application

Lightweight materials for structural applications face cost penalties compared to steel. Multi material applications in the near future will still be focused on niche and low volume production models (Fig.7-3). For the transfer of these promising weight-saving technologies into high volume applications, low cost technologies for lightweight materials are needed. The application of new materials as well as new manufacturing methods will have a severe influence on the production costs. [9]
Structures: frame structures to support high modularity
Frame structures claim to be as efficient in weight as a conventional unibody. [15] Adopting these frame structures for modularised flexible body concepts offers the potential to save weight and increase the manufacturing flexibility.

Development of painted and pre-assembled body-modules
Further improvements towards a more flexible manufacturing strategy and lowering purchase costs for customers are expected by establishing a modularised setup of the complete vehicle (Fig. 7-2). This will change the current process of body framing, painting and final assembly. These techniques will require new joining and coating technologies. By further enhancement of the surface-coat of the lacquer and on the windows, dirt will glide off ‘like from the leaf of a lotus’. [6] Nanotechnologies will be used, for example for coating plastic windshields to make them scratch-proof. Also weight reduction could be achieved by using this technology.

Optimisation of design process with early consideration of recycling
Design for recycling in early development phases offers the opportunity to facilitate recycling. This enables easier dismantling of components before shredding the vehicle and more successful post-processing of the automotive shredder residue for future vehicles. These requirements need to be considered at a very early design stage and facilitate reuse and recovery.

Improved dismantling technology
Improved dismantling technology can contribute to recycling efforts by designing the vehicle and its modules, systems and components in a way that materials can easily be separated. The fastening concepts therefore need to be reduced in the number of fastening points and need to be easily broken apart during dismantling.

Post-processing for automotive shredder residue, adequate separation of different material types
Despite the fast improvements already made in shredder post processing, new separation technologies are required to process multi-material vehicle structures in a more efficient way while minimising landfill and thermal recovery. These
processes need to be adjusted specifically to the material types that can be handled in the recovery processes. Supplying the recovery companies with sufficient material quantities on one hand and sufficient material quality on the other hand will raise the recycled materials quality and at the same time reduce the costs.

**Easy to recycle material families with different properties**

Up to now, material families with different properties, that are still easy to recycle, do not cover the total span of material properties. Facilitating components that make up structural and functional requirements from one general material family can contribute to this. For example, if it would be possible to engineer the vehicle seat structure, the cushion and the lining from one basis material family, the complete seat could be handled by a dedicated recycling process.

**Quality of recycled materials (comparable properties to new materials)**

The properties of material obtained in the recycling processes are mostly of inferior quality compared to genuine material. To achieve the same mechanical properties of the component, further process developments must contribute to reducing these deficits.

This shows that the following technology options are of high importance:

- Realisation of smaller and more flexible vehicle concepts
- Downsizing of all possible vehicle equipment in order to save weight
- X-by-wire systems without mechanical backup to optimise package and weight
- Connection and joining technologies in order to support body modules and multi material design
- Cost efficient body structure to provide basis for high volume multi material application
- Structures: frame structures to support high modularity
- Development of painted and pre-assembled body-modules
- Optimisation of design process with early consideration of recycling
- Improved dismantling technology
- Post-processing for automotive shredder residue, adequate separation of different material types
- Easy to recycle material families with different properties
- Quality of recycled materials (comparable properties to new materials)
- Production methods

**7.3 Hurdles and Barriers**

To realise the objectives for 2020 to 2040 some hurdles and barriers exist.

**Costs of lightweight solutions for mass production (e.g. manufacturing process, material)**

Hurdles are seen in the aspect of cost efficiency. Especially in the vehicle segments with the highest market volumes, (compact class, e.g. Ford Focus, VW Golf), only a very small share of lightweight materials are used compared to larger vehicle classes. This accounts for light metals (aluminium, magnesium, etc.) as well as for high performance composites (e.g. carbon fibre reinforced plastics)
Performance of joining technologies (cost, strength, stiffness, durability, capability simulation) to connect different materials (metals, composite plastics, ...)
The different joining technologies for multi-material and modular concepts still have disadvantages with regard to general high volume application and modular vehicle concepts.

Non-destructive testing for connections needed
Focussing on joining and connection technology further shows that suitable non-destructive testing methods are missing and that this matter poses a fundamental hurdle for the application of new joining technologies. Monitoring the performance of the joints leads to destruction of the components or subassembly. This is a very negative aspect when focussing on safety-critical joints or innovative connections whose characteristics have to be monitored.

Recycling of high performance materials more complicated than established metallic materials (especially reinforced plastics / multi material build-ups)
Vehicle designs with a high amount of lightweight materials are far more difficult to recycle, especially when looking at the EU Directive for future recycling quotas. This can lead to the conclusion that, during the vehicle lifetime, more energy will be used to move heavier vehicle parts than is necessary. [12]

Fig. 7-4: Conflict of goals: Recycling quota versus reduced fuel consumption and CO₂ emissions [11]

Detailed material know-how (e.g. simulation technologies, failure, fatigue, durability) needed for development process; especially to achieve weight-optimised structures
Lightweight optimisation of vehicles still imposes big hurdles in the development process as material and structural performance lacks simulation predictability.
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**Customer acceptance of smaller vehicle designs, safety standards of very light vehicles**
Reports in the US have shown that smaller vehicles involved in crashes account for an uneven high share of injured passengers and fatalities. The same tendency could evolve in Europe with the introduction of lighter cars. Safety standards and safety features, that are not made known to the public, explicitly might hinder the introduction of new lightweight, ecologically-favoured vehicle concepts.

**Customer acceptance for recycled materials**
Bringing recycled materials into the market for dedicated applications, which might even be related to safety issues, still causes big problems. For example, only a very small number of remanufactured tires are used on cars, despite the fact they are standard on aviation applications.

**Contradiction between safety and light weight due to worse properties of recycled material quality**
Recycled materials face problems to achieve the performance targets with regard to light weight, unlike original materials. Further imposed light weight goals can lead to less usage of recycled materials compared to new materials to lower the total vehicle weight.

**No large scale recycling technologies for critical materials proven**
No adequate recycling processes are available for the automotive shredder residue at the moment to cover high volume material streams at high material quality grades [10]. New technologies are still under development.

**Contamination of materials during vehicle life**
The materials originally installed at the manufacturing stage in the car are very often exposed to various liquids and sediments during the vehicle life. These contaminants cause increased recycling efforts and lower the properties of the recycled material grades.

**Complicated or impossible dismantling of multi-material vehicles**
For complex lightweight fuel efficient multi-material structures, adequate recycling processes are still necessary. The lack of these processes will hinder the market introduction of these emission-friendly design techniques.

Recapitulating the most important existing hurdles and barriers:

- Minimizing the high costs of lightweight solutions for mass production (e.g. during the manufacturing process, material, ...)
- Better performance of joining technologies for connecting different materials (e.g. metals, composite plastics) concerning cost, strength, stiffness, durability and capability of simulation
- Non destructive testing for these connections
- Detailed material know-how (e.g. simulation technologies, failure, fatigue, durability...) needed for development process; especially to achieve weight-optimised structures
- Form higher customer acceptance for smaller vehicle designs and increasing safety standards of very light vehicles
- Recycling of high performance materials is more complicated than established metallic materials (especially reinforced plastics / multi material build-ups)
Enhancement of customers’ acceptance for recycled materials
Contradiction between safety and lightweight due to worse material properties of recycled qualities
No large scale recycling technologies for critical materials proven
Lowering the contamination of materials during vehicle life
Complicated or impossible dismantling of multi-material vehicles

7.4 Research demand

Based on these hurdles and barriers, several research demands can be identified.

Basic research on lightweight materials (e.g. new combination of several materials)
New lightweight materials should be incorporated with more intelligence. This would offer new lightweight design opportunities. This process on the material side can be compared to bringing mechanics and electronics together to create for example mechatronic systems.

Lightweight vehicle concepts analysis (not only focussing on lightweight components or certain vehicle parts): early identification of conflicting interests
The new innovative lightweight materials must be developed with the focus on the usage within the vehicle, thus keeping the complete application boundary conditions in mind. Tailoring materials for vehicle applications will then lead to the possibility of new and innovative vehicle concepts that are lighter and therefore more fuel efficient (Fig.7-5).

Enhanced simulation technologies (material models, optimisation, combination of technologies...)
To support these new materials in vehicle design, adequate simulation tools are needed. Especially, the description of the materials in structural analysis needs to be improved to be precise enough to support the design process. Modelling of the material properties and failure criteria for static, crash and durability analysis will make vehicles more sustainable through optimised material usage.

Fig.7-5: Space Frame Structure concepts [3]
Testing methods for materials and structures, favourable non destructive testing methods applicable in development and production

Further on in the development and manufacturing process, the advanced lightweight materials need to be tested for their structural capabilities. Especially, non-destructive testing procedures have to be developed to assure the integrity of the material during the production process. Also, when servicing the vehicle after an accident, the structures have to be checked for integrity to assure full future performance.

Research on new production technologies (mass production for today’s „high tech” materials, assembly and handling of „fully modularised” vehicles)

Bringing the lightweight materials to market needs significant elaboration on the high volume processes. Many materials capable of reducing the vehicle weight are not feasible for high volume production.

Recycling technologies for advanced lightweight materials and structures

The technologies offering lightweight vehicle design need processes to contribute to closed loop material usage. Research on processes to acquire recycled materials with material properties close to genuine materials offers further application potential of lightweight materials.

Better knowledge of influence of future technologies (e.g. fuel cell) on recycling process

Forthcoming vehicle technologies will have significant impact on vehicle recycling. In order to bring greenhouse gas-friendly technical solutions to market, recycling concepts for these vehicle systems need to be elaborated, especially for technologies which are supposed to become mainstream applications in the future.

Recycling methods: better separation technologies; better alternatives to shredding

To improve recycling on a broad scale basis, processes to dismantle multi material structures and recycling technologies for electronic equipment in particular are needed.

The most important research demands are:

- More intensive basic research on lightweight materials (e.g. new combination of several materials)
- Earlier identification of conflicting interests to improve lightweight vehicle concepts analysis with a high spectrum (not only focussing on lightweight components or certain vehicle parts)
- Enhancement of simulation technologies (e.g. material models, optimisation, combination of technologies)
- Further development of testing methods for materials and structures, especially for favourable non destructive testing methods applicable in development and production
- Research on new production technologies (mass production for today’s „high tech” materials, assembly and handling of „fully modularised” vehicles)
- Creating recycling technologies for advanced lightweight materials and structures
- Better knowledge of the influence of future technologies (e.g. fuel cell) on recycling process
- Optimising recycling methods in consideration of high volume and automated recycling methods to achieve better separation technologies as well as better alternatives to shredding
In contrast to the personal automobile market, where regulation demands pressures for improved fuel economy rather than consumers having driven reductions in weight, buyers of commercial vehicles have sought vehicles with lower weight. For regulatory and financial reasons, a key purchase criterion for purchasers of commercial vehicles is load capacity, which is directly dependent on the net weight of the vehicle. Thus, lightweight construction technologies have been very important for manufacturers of commercial vehicles.

### Technology objectives for 2020 to 2040

Several objectives for 2020 to 2040 exist. These are based on the commercial factors on the one hand and society needs on the other.

#### Vehicle weight reduction to accomplish higher payloads

Due to the primary aim of commercial vehicles to move passengers and goods, a reduced unladen weight of the vehicle accounts for an increased payload. Supporting this aim enables the reduction of the number of freight movements due to increased capacity of the vehicles. In the case of vehicles not completely loaded, a reduced vehicle weight still contributes to energy savings and emission reduction. [5]

#### Reduction of aerodynamic losses

Aerodynamic losses still offer a large improvement potential for energy savings especially for trucks. A reduction of aerodynamic losses of 25% results in a fuel saving for constant highway travel of about 10 to 15%. [17] Thereby, the reduction of vehicle drag as well as the reduction of rolling friction could be useful in terms of lowering CO₂ emissions. [5]

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**Fig. 7-6:** Power required to overcome aerodynamic losses on a long haul truck [5]
Reduce road load and wear by vehicle structure
Roads are heavily subjected to wear and suffer from commercial vehicle use. Especially routes that are extremely often exposed to commercial vehicle usage often show typical signs of deterioration and damage. This should be reduced in order to enable longer lifetime for roadways, reduced repair costs and reduced congestion due to roadwork (e.g. different vehicles’ track width).

The main objectives for these vehicles for the desired timeframe are given by:

- Reduce vehicles’ weight to accomplish higher payloads
- Reduction of aerodynamic losses to achieve lower fuel consumption and pollutant emissions
- Reduce road load and wear by vehicle structure
- Improving crash safety performance

Technologies
In order to realise the objectives for 2020 to 2040 several technological options are identified.

Realisation of lightweight vehicle concepts
Lightweight vehicle structures for trucks and buses offer the possibility to increase the payload without increasing the total weight of the vehicles. This aim can be achieved on the one hand by applying lightweight vehicle design and by lightweight material usage or, on the other hand, by application of lightweight concepts (e.g. FRP cabins, aluminium frames).

Integrated aerodynamic concept for trucks and trailers
In order to reduce the aerodynamic losses, the external air flow of the truck and trailer can be optimised by adequate body shaping and / or flow devices. This needs to be combined with an optimisation of the internal air flow of the truck as well as the underbody air flow of the trailers. A technical concept is needed to achieve optimised air flow for different truck-trailer combinations as these combinations tend to be changed very often in use.

Adaptive chassis and suspension systems with variable track width
Suspension systems that realise variable track width offer the possibility to distribute the loads more evenly on the roads. This should result in a larger area of the road covered by the vehicle tires and thus an optimised usage of the total available road surface. The combination of these systems together with today’s lifting axle technology could ensure the ideal loading of the road surface under all operating conditions (with and without payload).

Recapitulating the following options could be identified:

- Realisation of lightweight vehicle concepts
- Integrated aerodynamic concept for trucks and trailers
- Adaptive chassis and suspension systems
**7 VEHICLE STRUCTURE**

**Hurdles and Barriers**

To realise the objectives for 2020 to 2040 some hurdles and barriers exist.

**Costs of lightweight solutions for mass production**

Focussing on the commercial aspects, the vehicles need to be extremely cost efficient. Bringing new technical solutions to the market can increase vehicle cost and hinder the technology introduction. These aspects focus particularly on material costs on the one hand and on manufacturing costs on the other. Operating, maintenance and repair costs also have to be considered.

**Durability of lightweight solutions**

Durability requirements of commercial vehicles are several times higher than for passenger vehicles. An estimated lifetime mileage of 750,000 to 1,000,000 km in rough operating conditions requires a reliable design and proof of all functional requirements within the complete vehicle life. New lightweight vehicle approaches often suffer from a lack of good fatigue and lifetime performance predictions. This hinders market entry and market penetration.

**Trailer configuration swapping**

Changing configurations of trailers and trucks makes it difficult to optimise the truck / trailer combinations with regard to airflow. Optimisation on the truck with regard to a specific trailer shape can cause disadvantages with another kind of trailer. In conjunction with long service lives of vehicles, this will cause severe difficulties in optimising aerodynamic losses.

The following hurdles and barriers have to be overcome:

- **Lowering costs of lightweight solutions for mass production**
- **Improving durability of lightweight solutions**
- **Simplification of trailer configuration swapping**

**Research demand**

Based on these hurdles and barriers, several research demands can be identified.

**Basic research on lightweight materials**

New material systems with intelligent capabilities are needed. Research on the combination of several components to form lighter solutions will pursue this aim (Fig. 7-7). The result is to achieve more “intelligent” materials than those in operation today and in the near future. These material systems will not only fulfil structural tasks in vehicle design, but they will also provide more information about the status of the material and component in order to avoid failure or to combine different functions.
Application of lightweight body structure concepts

New lightweight materials have to be applied to the vehicle concept. When focusing on the vehicle requirements, the advantages of these materials need to be elaborated and the disadvantages minimised. Besides the application of new materials and concepts, manufacturing requirements also need to be investigated in an early research stage.

Repair strategies for lightweight design body structures

Especially for the application of fibre-reinforced-plastics (FRP) as a structural material, optimised repair strategies are still to be developed. Disassembly options that are available for metal structures only exist to a very limited extent for FRPs and need to be further developed to enable vehicle servicing.

For metal-based lightweight concepts, new joining and disassembly technologies are needed that enable a more efficient assembly and at the same time optimise the functional performance of the joints.

Aerodynamic losses

An investigation into the aerodynamic optimisation of different combination of truck / trailer systems offers energy saving potentials. But in order to achieve these, a flexible system probably needs to be developed, in order to adapt to different boundary conditions of the individual trailer systems.

The most important research demands are:

- Deeper basic research on lightweight materials
- Higher application of lightweight body structure concepts
- Developing innovative repair strategies for lightweight design body structures
- Reduction of aerodynamic losses
References


[2] auto motor und sport; no. 20; 2001; p. 100


[8] Smokers, Richard; “Sign posts towards 2050”; TNO Automotive; 1998; T048


[18] European Conference on Smart Structures and Materials, Glasgow, 1994, S. 11 ff
The European Union is the largest car producing area in the world and the largest car market. Research and Technological Development (R&TD) is essential for improving the impact motor vehicles have on our society. Safety and environmental sustainability are the key issues in this respect. In the fifteen Member States of the European Union there are approximately 42,000 reported deaths and 1.5 million casualties as a result of road traffic accidents. The annual costs to the European Society due to these accidents are more than 160 billion Euro.

It is obvious that, in spite of the significant improvements in vehicle safety which were achieved in the past 25 years, the current number of deaths and injuries plus all the associated social and economical costs, must still be regarded as unacceptable. Vehicle safety experts world-wide agree that significant further reductions in fatalities and injuries can be achieved. A prerequisite for the successful introduction by the automotive industry and its suppliers of new technologies for the reduction of casualties is that new knowledge as well as reliable design and evaluation methods become available. Considering that the reduction of time to market and continuous reduction of costs are the main needs to industrial competitiveness, new design methods have to become available to further advance the design process. A particular challenge in the field of vehicle safety is the trend towards smaller and lighter, more fuel-efficient vehicles and the increased usage of electrical vehicles for environmental reasons. An optimal combination of various technologies is required to offer passengers of these lighter vehicles a similar level of protection to that in conventional vehicles.

Road transport safety can be defined in a number of ways, including the official World Health Organisation (WHO) safety definition: ‘freedom from unacceptable risk of harm’. Road safety is however usually defined in a negative way. Safe road traffic is characterised by the absence of crashes, injuries and fatalities. For society and for the individual, the loss of health is the most serious effect of crashes. It leads to huge losses both in monetary terms to society and in personal suffering to the individual. Therefore it is essential to state that loss of health is the main road safety criterion.

All available strategies should be applied in order to reduce the numbers of deaths and injuries on the road:
- Influencing exposure by alternative transport systems;
- Influencing human behaviour by education and (harmonised) penalties;
- Active vehicle safety and crash avoidance measures;
- Passive vehicle safety or crash safety measures;
- Trauma care, for instance through improved rescuer support.

Road safety is not about choosing one or the other: an integrated package is required.

The price paid for mobility in Europe is still far too high. Though the number of deaths in road accidents dropped significantly at the beginning of the 1990's, the trend has been less marked in recent years. The European Union has considerable, even sole responsibility for encouraging the deployment of innovative technologies that should lead to the introduction of safe new vehicles on the market.

The need for a strategy and action plan on a European level to reduce the road casualty problem was recognised fairly recently. In 1997 the European Commission presented “Promoting Road Safety in the European Union: the Programme for 1997-2001”. The Commission advocates a cost-benefit approach in the formulation of future road safety policy: there is economic justification for taking measures costing up to one million Euro in order to save a single life. The more recent “White paper” calls for a reduction in the numbers of deaths on the road by half in the current decade [8.1].
8.1 Passive Safety Aspects

Road transport safety problems and strategies can be organised according to a matrix, which is composed of three time phases of the crash event plus the three areas influencing each of the phases.

<table>
<thead>
<tr>
<th>Pre-Crash</th>
<th>Crash</th>
<th>Post-Crash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human</td>
<td>Vehicle</td>
<td>Environment</td>
</tr>
<tr>
<td></td>
<td>Passive safety</td>
<td></td>
</tr>
</tbody>
</table>

General strategies to improve passive safety aspects are:

- Influencing the crash conditions, for instance by improving the environment (e.g. deformable guide rails);
- Improvement of the vehicle crashworthiness (e.g. energy absorption);
- Influencing the impact motion of the human (e.g. seatbelt);
- Influencing the impact contact between human and vehicle interior (e.g. trim, padding).

Normally several strategies are combined in a passive safety measure.

8.1.1 Objectives

Increase of the level of passive vehicle safety is a very effective strategy to reduce the number of casualties among road users in the European society. There is no doubt that the highest level goal in the field of road traffic safety is to avoid all fatalities and severe injuries. Ideally the whole land transport system should be developed such that no more accidents with severe injuries can occur. This is probably never fully achievable, because human errors (intentional or not) and technical failures will still occur. Nevertheless development and introduction of critical technologies that improve passive safety for all European road users in all relevant accident types and accident severities should be encouraged. This means extending from the current design practice, which focuses on a single or limited set of conditions like a mid-sized male car occupant in a standard accident at medium impact speed. A further reduction in casualties can be achieved by extending the ‘vehicle design envelope’ to all road users in all accidents. The final objective or mission should be to achieve equal levels of passive safety for all road users. This level of protection should be so high, that further development of the vehicle’s structural crashworthiness and passive protection systems would not lead to a significantly different accident outcome.

In fact, research and technology development is required in 3 directions:

- All impact scenarios (so not only frontal and side, also rear and rollover);
- All injuries (so not only life threatening injuries, but also long-term disabling injuries);
- All road users (so not only car occupants, but also pedestrians, not only the adult mid-sized male, but also the small female and child).

Over the past decades a considerable effort has been put into improving and optimising road vehicle safety. Next to structural improvements of the car, attention is turning increasingly to the opportunities offered by advances in sensor
technology and information technology. In the field of active safety there has been a lot of activity resulting in a wide range of safety devices that assist the driver in driving comfortably and safely. Many of them belong to the advanced driver assistance systems (ADAS) and navigation systems categories (see also § 5.1.3.2). The consequences of accidents can be further mitigated by monitoring information of the upcoming crash. Smart safety systems can take real-life crash circumstances and individual occupant features into account. The combination of active and passive safety systems adds a new dimension to vehicle safety: Intelligent Transportation Systems (ITS). ITS comprises all applications of advanced information processing, communications, remote sensing and control technologies in the field of transportation engineering. They are all directed towards a common goal: increasing transportation efficiency and road safety for all kinds of drivers (and other road users) for all kinds of driving situations and for all kinds of crash scenarios.

The introduction of new knowledge and technologies to improve road safety should be accelerated. Besides regulations, consumer testing programmes are a driving force for vehicle manufacturers and a source of information for the consumers. Public awareness campaigns are still necessary, however the message should be short and simple! The topic ‘safety science’ should be taken into schools; young children should form the foundation for a new safety culture.

The objectives in the field of passive safety for 2020 and beyond:

1. Equal level of protection against injuries and fatalities for all road users in all accident situations.
2. Integration of active safety and passive safety measures to avoid crashes and to mitigate the consequences of these crashes.
3. Facilitate quick(er) implementation and use of technical innovations.

### 8.1.2 Technologies

There are currently around 42,000 fatalities and several millions of non-fatal casualties annually reported from road accidents in the European Union. The management and reduction of accidents on such a scale must be based on clear and consistent information. Accident statistics and investigations are very relevant for problem definition and priority setting with respect to policy making, as well as for evaluation of the effect of countermeasures taken on a national or European level.

The basic information and knowledge should be obtained from real-world accident data: assessing injury frequencies and types of accidents causing these injuries. The next step is to study injury mechanisms, define injury risk functions and injury tolerances, and to develop assessment tools (crash dummies, mathematical dummies) to study specific accident types and/or injuries. Accident statistics and biomechanical studies can be considered as the basis for this field, therefore this basis should be ‘strong and reliable’. The following step is to develop test methods based on these real-world accidents, using the tools and associated injury tolerance levels, and implement them in harmonised standards or regulations. New energy-absorbing structures and materials should be developed as well as related production technologies in order to manufacture these materials at a competitive cost level and to be able to integrate these materials into assembly lines and manufacturing processes.

New safety concepts should be developed. An important area in which significant improvements in the future can be expected is the field of so-called ‘intelligent’ or ‘smart’ restraint systems. Current restraint system technologies, like airbag systems, are usually based on the optimal protection of an average car occupant in a standard accident configuration. However, there is a vast range of accident types and there is a large variation in occupant sizes, seating positions and
many other variables that affect the outcome of an accident. Intelligent restraint systems that adapt to the actual accident condition and for the particular occupant shall be able to protect car occupants better than current restraint systems. These systems shall require information obtained from new sensors in the car and shall be able to intelligently manage the levels of restraining forces and how they are applied to the occupant.

The most dominant factor related to the frequency and severity of injuries is the speed of the vehicle(s). New intelligent systems should control the vehicle speed in certain areas.

The further development and application of virtual testing can improve the implementation of new knowledge and technologies into the vehicle. PR/marketing and tax incentives will accelerate the (correct) use of new safety systems.

The technologies to fulfil the objectives in the field of passive safety for 2020 and beyond:

- Accident statistics and investigations
- Biomechanics and improved physical/virtual assessment tools
- Improved and new vehicle test methods
- Energy-absorbing structures and new (lightweight) materials
- New intelligent safety concepts and structures
- Sensor technology and control systems
- Virtual testing
- (Policy measures)

### 8.1.3 Hurdles and barriers

Several hurdles and barriers can be expected before new technologies can be introduced, for instance technical or social hurdles, timing, cost, production or feasibility barriers.

Currently a lack of accident data and biomechanical knowledge exists. Maintaining the privacy of accident data as well as the protection of this data could become a hurdle to developing an international accident database. Biomechanical research using volunteers or human surrogates could become more and more difficult because of ethical acceptance issues.

The time to develop and implement new vehicle test methods into regulations is increasing: for new topics this is already 25 years. National governments more and more protect their car industry rather than their citizens. The commercial interests are very high.

Virtual testing techniques still suffer from a lack of worldwide-accepted validation methods.

New passive safety structures and systems very often increase the vehicle weight, which influences not only the fuel consumption and emissions, but also the protection of the occupant in the other vehicle involved in the crash.

New complex safety systems introduce reliability problems. Intelligent systems that overtake the driver’s action must be failsafe. Moreover, will the public accept these systems?

A general hurdle is the lack of sufficient money to perform the required research in order to develop breakthrough technologies.
8.1.4 Research demands

Interdisciplinary research programmes are required in order to accelerate knowledge development and to integrate technologies. More medical expertise is required in the field of accident investigations and biomechanical research. ICT technologies should be applied in order to enhance the research activities and disseminate the knowledge.

With the variety of issues that remain within the responsibility of the EU, a realistic, flexible, multifaceted approach to accident databases is called for:

- At the base level, there is a need for data that is comprehensive and consistent over the whole region covered by the EU. This would provide counts of accidents, vehicles and casualties using the same categories, common terms and definitions over all the member states.

- At the in-depth level, there is a need for a variety of research groups that are geographically spread, use a variety of techniques and that address issues of both general and special interest. A primary aim would be to have a sample of accidents covered at the in-depth level that could be statistically related to the overall European situation as described in the base level data. Groups that employ retrospective techniques could be used to address car occupant and motorcycle riders issues (passive safety), while those that employ at-scene methods could in addition cover pedestrian and pedal-cycle accidents (vulnerable road users) and accident prevention issues (active safety). In addition, there should be flexibility to address issues of both long-term and short-term interest. Questions of short-term interest could relate to newly introduced technologies, areas where new actions are suggested (e.g. extension of rules to light goods vehicles), or issues of typical public interest (e.g. children in minibuses).

- The intermediate-level databases, over which the EU can exercise influence, are most likely to follow on from direct actions taken at the base and in-depth levels. For the future, the supplementary data required to form an intermediate level database is likely to be sourced from one or more national Member States or to be contributed from the private sector.

Black-boxes should be installed in order to support accident investigation studies.

Further biomechanical research is needed, especially in the area of brain/nerve and neck/spine injuries, injuries resulting in long-term impairment, as well as research in the field of child injury criteria. A large worldwide co-ordinated research programme is needed to study human tolerance in impact situations and to develop a common database. The anthropometry of the next generation of car occupants should be studied as input for tool development. The tools, crash dummies and mathematical human models, should be scaleable in size, weight and stiffness in order to simulate not only the mid-sized male occupant, also the whole population at risk (so including children and elderly).

Vehicle crash test methods should be developed that are based on realworld accidents, in this way taking the changing vehicle fleet population (e.g. SUV) into account. The test methods should include physical as well as virtual tests in order to assess the risk of all occupants in all accident scenarios, as well as to limit the design costs and to increase time-to-market. Worldwide harmonisation of test methods is required in future. The incompatibility of road users is demanding an integral approach, instead of separate test methods optimising only one crash scenario.

Improved cost-benefit models should support the introduction of new legislation. The effect of new legislation or consumer testing programmes should be evaluated by real-world accident investigations.

Material research programmes are required that bring together experts in the field of impact energy management, production processes, recycling and repair techniques. Improved material characteristics are needed with respect to weight
energy-absorption ratio in different environmental conditions. This also calls for a multi-material approach including
new bounding techniques. Research should result in intelligent materials as well as the development of realistic
mathematical material failure models.

Research programmes looking for new safety concepts and structures should be stimulated. The feasibility of a ‘zero-injury-
car’ should be studied. New ways for safe transportation of children should be developed, as well as systems for automatic
restraint of luggage/objects. New structures should make the access to casualties by rescue services easier. Developments
in other areas of the vehicle design, for instance smaller engines and steer-by-wire, offer new possibilities for passive safety
systems to protect the car occupant.

Development of reliable sensor systems to monitor the occupant and the environment is necessary to further optimise the
restraint response. Simulation models should be able to predict the effectiveness of these systems. The development time
and computing time of mathematical models will have to reduce. Better and more realistic models are necessary. First-
time-right predictions are required in the field of virtual testing. Legislation should include more and more virtual testing
techniques in order to assess a larger area of real-world accident scenarios.

Education and training programmes should be developed in order to create public safety awareness.

The research needed to develop the technologies to fulfil the objectives in the field of passive safety for 2020 and
beyond:

- Develop and maintain international accident databases at different levels (base, intermediate, in-depth) based on
  harmonised procedures.
- Evaluate the effect of new legislation and consumer test programmes by real-world accident investigations.
- Biomechanical research in order to study injury mechanisms and tolerances of the whole population at risk.
- Develop and maintain international database with biomechanical data.
- Measure and develop database of anthropometry of next generation of car occupants.
- Develop more realistic, validated assessment tools representing the whole population at risk.
- Develop vehicle crash test methods based on real-world accident data and cost-benefit models, integrating more than
  one accident scenario, as well as integrating virtual testing techniques.
- Develop new lightweight, energy-absorbing materials and intelligent crash structures, including mathematical
  simulation features.
- Study new safety concepts, including zero-injury-car, including interactions with other technologies (e.g. X-by-wire).
- Develop more reliable sensors and control systems.
- Develop virtual testing techniques to integrate active and passive safety features, as well as other technologies (e.g.
  power-/drivetrain).
- Develop education and training programmes.
8.2 Active Safety and Driver Support

Referring again to the matrix presented in the previous section, Active Safety embraces a number of areas from pre-crash warning and prevention to post-crash rescue management. This is illustrated in Figure 8-1 below:

Table: Aspects of Active Safety

<table>
<thead>
<tr>
<th>Pre-Crash</th>
<th>Vehicle</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human</td>
<td>Smart driving – distance to vehicle ahead, lane following, object recognition, automatic avoidance</td>
<td>Transmission to vehicle or warning signs of information on road condition, traffic, weather, hazards ahead</td>
</tr>
<tr>
<td>Warnings &amp; information on road &amp; traffic</td>
<td>Chassis control – brakes, steering, suspension – dynamic stability</td>
<td></td>
</tr>
</tbody>
</table>

Passive safety

<table>
<thead>
<tr>
<th>Crash</th>
<th>Passive safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated monitoring &amp; reporting of casualty condition</td>
<td>Smart restraints &amp; airbags</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Post-Crash</th>
<th>Automated transmission of requests for assistance</th>
<th>Alerting other vehicles to presence of accident</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated transmission of requests for assistance</td>
<td>Alerting other vehicles to presence of accident</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8-1: Aspects of Active Safety

Active safety as a production technology is very much in its infancy, with huge potential to create an impact on the harmful effects of road traffic accidents to occupants, pedestrians and third parties. The ultimate goal is often seen as an “accident proof vehicle”, which informs the driver of hazards and intervenes where necessary to avoid disaster. As discussed below, there are many hurdles to actually achieving this goal, both in terms of technology and public acceptance.

Linked to this topic is the issue of Driver Support. Again this is a complex topic, starting with simple provision of information (navigation, route planning, avoidance of traffic), and then assisting or taking over from the driver (smart cruise control, lane following, road trains, and ultimately full self-driving). Clearly the linkage between these technologies and Active Safety is strong, and equally clearly there will be a major hurdle of public acceptance to overcome - although ultimately a self-driving vehicle could be a highly attractive proposition.

General strategies to improve active safety and driver support are:

- Provision of better information to drivers, road users, police and emergency services regarding road conditions, traffic, weather and hazards
- Monitoring of driver alertness, health and fitness to drive
- Active control of vehicle stability - braking, spring/damper systems, steering - to avoid loss of vehicle control
- Driver assistance, especially in conditions where concentration may be difficult (sustained cruise) or the level of hazard may be high (urban / suburban driving)
- Recognition of hazards in the path of the vehicle (pedestrians, other vehicles, tight corner, road junction), resulting in either a warning to the driver or automatic action by the vehicle (automated braking or swerving)
Intelligent management of an accident (deployment of seat-belt tensioners, air-bags and other devices based on knowledge of collision dynamics) and its aftermath (casualty monitoring, automatic request for emergency assistance, vehicle-vehicle-infrastructure hazard warning). Smart safety systems of this type have been considered in the preceding Passive Safety section.

Ultimately, vehicles with a high degree of self-driving capability which are "accident proof" by design.

State of the Art

Active Safety is a technology in its infancy. However, over the past decade significant advances have been made especially in the fields of vehicle stability and mobile telecommunications:

- Anti-skid Braking Systems (ABS) entered production for cars and trucks in the 1980's, and reduce the risk of losing control during hard braking. They are now virtually universal on new commercial vehicles and medium to large cars. Discussion is underway to make fitment mandatory to most road vehicles. Latest-generation systems use more sophisticated control algorithms such as weight-sensitive electronic brake-force distribution (EBD), and frequently integrate to electronic skid prevention (ESP) and traction control (TCS) systems.

- Traction control systems (TCS) are commonplace on more powerful vehicles, and enable higher performance with front-wheel drive. Their benefit is to reduce the risk of losing control of the vehicle due to wheelspin.

- Electronic stability program / electronic skid prevention (ESP) has been introduced to passenger cars in the 1990s. It operates by a combination of individual wheel braking and powertrain torque control, to counteract the onset of an under-steer or over-steer skid.

- Mobile telecommunications have entered the road vehicle in the form of mobile phones and internet access. Usage today is for information and entertainment rather than active safety. There is very little infrastructure in place for the specific purpose of active safety, although traffic monitoring and driving-offence detection systems are now in common usage in some regions of Europe.

- GPS based satellite navigation systems are available as a fairly high-cost option in any vehicle. Usage in taxis and commercial vehicles is starting to become widespread, with some systems interfacing to "fleet-manager" systems via the Internet. GPS is nominally accurate to a few metres, giving potential to provide information on approaching corners and junctions. However, the first generation map data relies on CD-rom data storage which means updating is manual. It also contains no information on hills, speed limits, junction priorities etc.

These technologies can however provide the foundation for information-enabled systems to improve safety, convenience and efficiency.

8.2.1 Objectives

The objectives presented here are a concensus of EARPA member opinion, but with the benefit of correlation with published national, European and international objectives. As Active Safety and Driver Support is a technology in its infancy, which will continue to develop over coming years, it is appropriate to consider objectives as a function of time.
2010

- **50% reduction in road deaths** relative to year 2001, as per the European White Paper [1]. Naturally, reductions in non fatal injuries, vehicle damage and delays caused by accidents are also desired, but it is believed that these are likely to be achieved if a combination of active and passive safety technologies are used to achieve the simple road deaths target.

- **Reduction in operating costs**, including insurance, as a result of fewer accidents. No specific target has been set, and it should be noted that the beneficial effects of safety technology advances may be partially offset by growth in traffic density and resulting congestion.

- **Measurable beneficial impact from in-vehicle hazard warning systems** based on the fusion of advanced sensor technology and, possibly, first generation vehicle-vehicle-infrastructure communication. Again, no numerical target has been set at this point.

- **Congestion management networks in place** in selected key cities and other sensitive areas - with facility for vehicle-infrastructure communication but not dependent on it to be effective.

- **Limitation of speed and dangerous driving** via self contained intelligent onboard systems, perhaps with the ability to react to the degree of local hazard. This is a logical evolution of the simple, non-intelligent speed-limiting devices fitted to some vehicles today.

- **Customer acceptance of active safety systems**, by ensuring that early technologies are of high quality, publicising their success, and educating the public. Comparison can be made to the compulsory fitment and wearing of seat-belts in most European countries over the last three decades, which has met with some public resistance but has dramatically reduced fatalities.

2020

- **75% reduction in road deaths** relative to year 2001. This would entail a further halving of the fatality rate, and can be considered a logical extension to the European White Paper target. Again, proportionate reductions in non-fatal injuries, vehicle damage and delays caused by accidents are also likely.

- **Congestion free highway driving**, enabling 10% reduction in highway journey time, and significant reduction in highway driving stress. This is an important target in view of projected increases in traffic volumes across Europe, especially in and near accession countries. It is likely that mobility issues will be very much in the public eye at this time, hence the market may be willing to absorb the cost of congestion-reducing technology such as telematics and fully intelligent cruise control. These technologies will also contribute to safety gains.

- **Highway lane-control and truck road-trains enabled** in key target areas, with a view to more widespread usage in following years. Technology of this type is a key enabler for the fatality and congestion reductions sought, hence it is worthy of being considered an Objective in its own right.

- **Other key technologies enabled**, including “black box” accident recorders, intelligent traffic management, vehicle-vehicle-infrastructure communications, on a basis limited to key vehicle types or target sensitive locations.
2030+

- **Zero fatal accidents by 2050** - again, an ambitious target which will require almost total penetration of intelligent vehicle technology with a high degree of self-driving. Legacy vehicle issues (older vehicles, including classic cars) will need to be addressed. Again, proportionate reductions in non fatal injuries, vehicle damage and delays caused by accidents are also likely

- **Smart driver assistance and autonomous driving enabled** in selected conditions by 2030, and virtually all conditions by 2050. This collection of technologies is the key to achieving accident-free road transport as described above

These objectives in the field of active safety and driver assistance can be summarised as:

- A progressive reduction in fatal and other accidents and consequential human and financial costs, equating to approximately a halving of accident rates every decade, to create virtually accident-free road transport by 2050

- A significant effort to counterbalance and overcome the effects of traffic growth, by using the new technologies to reduce and eliminate congestion

- A parallel set of targets or milestones for the introduction of key enabling technologies which will facilitate not only safety improvements but also reductions in congestion and improved enjoyment of travel

- Integration of active safety and passive safety measures to avoid crashes and to mitigate the consequences of these crashes, while creating spin-off benefits in terms of reduced journey times and improved efficiency

- Facilitation of quicker implementation and use of technical innovations by addressing hurdles and barriers

### 8.2.2 Technologies

A Technology Roadmap for the introduction of active safety and driver assistance technologies (see chapter 4, page 57), has been developed based on EARPA member expert opinion and a review of relevant literature [8.1, 8.2, 8.3, 8.4, 8.5, 8.6, 8.7, 8.8, 8.9]. Again, in reviewing the technologies in detail, it is appropriate to look at different future time periods.

#### 2010

In this relatively near-term period, principle advances will be those which are:

- **Stand-alone**, thereby avoiding dependence on infrastructures which are not yet developed, and / or

- **Synergistic** with existing systems, sensors and infrastructures, thereby allowing low cost and easy introduction

Key technologies for this period are:

- **Sensors**, especially those to detect distance to vehicle in front, obstructions in the path of the vehicle, position of the vehicle in its road lane. These technologies already exist in the form of smart cruise control (distance following) and park assistance devices. As their market penetration increases, they can be adopted either as input to **driver warning devices** or (once suitably dependable) to trigger emergency braking if appropriate. This technology is applicable to all vehicle classes, but will probably enter via the luxury car market first, then to trucks (possibly encouraged by legislation) and smaller cars (as the cost reduces with volume)

- **Smart limitation of speed** or dangerous driving, possibly driven by speed-limit data on GPS/map systems and
control-system analysis of aggressive or unreasonable driver behaviour. Currently trucks and commercial vehicles are required to have speed limiting and recording devices; it is speculated that this market would be the first to adopt such a system, possibly encouraged by legislation. Fleet operators would see a benefit in terms of improved driver behaviour, although drivers may be more reluctant to accept such intrusive devices

- Second generation active chassis dynamics, including “supervisory vehicle vectoring” which distributes torque to each driven wheel under electronic control. Unlike first generation systems, this maintains an enjoyable driving feel, thereby discouraging the driver from switching the system off

- First X-by-wire applications, the principle one being full brake-by-wire systems which are feasible in this period. Steering systems will remain mechanically based but with greater emphasis on electrical assistance, including smart variable ratio systems [10]. Availability of 42v electrical networks is a key enabling technology, and the need for mild-hybrid systems as a contributor to CO2 reduction may also assist in incentivising 42v penetration at this time

- High speed data buses will be required to link sensors, telematics, GPS/map and vehicle control systems. There is already massive growth in the complexity of powertrain and vehicle control, and by 2010 it will be necessary to adopt new standards and methodologies to ensure that control inputs and information are robust and used effectively. Costly sensors will be easier to justify if many systems can make use of the information they provide (“sensor fusion”). One possible spin-off is the use of active safety / driver assistance information (especially GPS/map, Telematics and key external sensors) in more efficient management of the powertrain - for example hybrid vehicle energy storage. This powertrain application is less safety critical than active safety, and is a good way of introducing “integrated vehicle management”. This issue is pertinent to any vehicle type, but the heightened attraction of even small efficiency or operating cost gains may mean that the commercial vehicle (truck, bus) market becomes the first point of application

- Wireless car-car-infrastructure communication will arrive in this timeframe, although infrastructure information will be market-led rather than oriented towards specific safety or mobility goals. Commercial vehicle fleet management and luxury car infotainment are most likely applications in this time

- GPS enabled systems (or Galileo once available from 2008) are already available as an aid to navigation, although high costs are preventing market penetration into the private-user arena. However, if costs fall, these systems can become more universal and provide useful information for the control of chassis and powertrain systems (including warning of approaching junctions or corners too fast), based on accurate knowledge of upcoming road topography. The costs of this technology are again likely to be justified first in commercial vehicles and luxury cars

- Image enhancement and night vision systems based on “head-up display” technology are currently used in military applications and can be applied to road transport if costs are dramatically reduced and fail-safe performance established. In this timeframe, systems which highlight dangers ahead are said to be possible. It is unlikely that a system which over-rides normal vision would be acceptable for some time. It can be suggested that emergency service vehicles will benefit from this technology before it becomes widely available

- Driver Alertness Monitoring, using sensors to detect drowsiness from eye movement and other body functions, has been demonstrated by suppliers. Commercial vehicles, especially long-haul trucks, appear to be a logical first application of this technology
2020

This time period offers potential for more extensive use of more sophisticated systems, for a number of reasons:

- More widespread uptake of enabling technologies like 42v powernet, high speed data buses, integrated vehicle management controllers, GPS/map systems and vehicle-vehicle-infrastructure communication capability
- Time for the development of infrastructure, provided that there is a political commitment to ensure that it is funded and implemented
- Time for growing public acceptance of new technologies (especially partial self-driving) and possibly changes in legislation to facilitate its use

Key technologies for this period are:

- **First use of partial self-driving systems** on the highway, including lane-following cruise control (possibly introduced for long-haul trucks before this time, applicable to most vehicles by 2020, and requiring a degree of driver involvement), and the first fully automated road-trains for long-haul trucks. These technologies will require provision of suitable highway facilities including either dedicated lanes for enabled vehicles, or a combination of legacy-proof systems and driver education. Hence their usage is likely to be limited to a small number of key routes at this time
- **Full steer-by-wire** may be in service by 2020, although a part-mechanical system is probably suitable for the applications above. Full steer-by-wire will be an enabler for future partial self-drive including lane-following, auto-avoidance, skid control and full self-driving over the following years. Improvements in packaging, ease of assembly, refinement and passive safety may also be realised. Premium cars and heavy trucks are likely first recipients of this technology
- **Driver health monitoring** will have evolved from basic alertness systems via the application of more sophisticated sensors. Again, long-haul commercial vehicles (trucks, inter-city buses) are the obvious first recipient of this technology
- **Sensor technology** will develop more sophisticated capabilities, especially in the field of image recognition. Recognition of pedestrians in the path of the vehicle, and recognition of traffic dynamics leading to impending loss of control / collision, will be key applications
- **Active distress systems** will have the capability to use information about the accident and its surrounding circumstances, and driver / occupant monitoring, to notify the emergency services, road infrastructure and other vehicles. Basic systems may be in use earlier than this time; by 2020 a significant amount of useful information should be available. This information may also be used in “black box” recorders for the purpose of accident investigation, although this is likely to meet substantial resistance from the public
- **Traffic management**, using intelligent processing of traffic density and telematics information, is feasible today but dependent on infrastructure development hence it is not likely to be in widespread use until 2020. First target applications will be cities, however highway control will assume growing importance and may offer greater potential in conjunction with the lane-guidance and road-train systems which facilitate dense highway traffic. **Inter-modal networking**, linking road to rail, air and sea, and private cars to public transport, is another possible development of this technology
- **New driver information and human-machine interface technologies** may be required by this time to prioritise information and ease the burden on the driver at times of peak load
2030+

Prediction of the precise nature of technology in this timeframe is difficult. However, it is possible to suggest that the general trend will be towards technologies which enable an accident-free, and possibly self-driving vehicle. Such technologies could include:

- **Intelligent intervention and avoidance**, including automated swerving, skid control and cornering, building on the automated braking and lane-following systems which will be in reasonably widespread use by this time. Interaction with older “legacy” vehicles, having less or no automated avoidance capability, will require careful study. These systems may also be able to detect poor driver health and carry out a safe manoeuvre to the roadside.

- **Extension of lane-following and road trains** to all vehicle classes and a wider selection of roads. Again, legacy vehicles will be a major issue which must be addressed.

- **Full self-driving vehicles** can be envisaged, but are not likely to reach production before 2050 due to the need for robust validation over every possible part of the envelope. The societal implications of a vehicle which completely drives itself (requiring no more than an instruction of where to go) are enormous - not just in terms of safety but also in making road transport accessible to a wider cross-section of people.

8.2.3 Hurdles and Barriers

The technology roadmap indicates how a major change in the functioning of a vehicle is possible with active safety and driver support technologies. Such major change can result in a number of significant hurdles and barriers.

2010

In the early years - circa 2010 - the technologies involved are essentially evolutionary extensions to existing systems. Barriers can be classified as:

- **Technical**: Reliability, weight (especially of redundant systems), electrical power requirement, electronic network capability, developing new protocols, security and privacy of information. Addressing these issues to produce robust solutions is essential to avoid a public “technology backlash”.

- **Financial**: Cost of onboard systems (especially for mass-produced cars and light vans), and provision of funding for infrastructure. Successful systems will be those which maximise synergy with existing sensors or actuators, and provide improvements in many aspects of vehicle functionality. Although safety is highly saleable today, there is a risk that consumers may start to perceive diminishing value if the costs are high. Legislation may be required to mandate some systems. **Infrastructure funding** requires a political will to deliver the infrastructure, backed up by a unified global choice of the best, flexible and future-proof technology. The question of **who pays for telematics information** will be starting to become an issue - it is probable that the best information will not be free.

- **Legal**: Standards and codes for new systems must be agreed and accepted.

- **Psychology**: Drivers must accept and demand new systems rather than have them imposed. Systems which appear to assist good driving, as opposed to restricting or reporting bad driving and dictating driver behaviour, are likely to be most accepted. However there is a risk that congestion-charging systems and speed-limiting devices may create an adverse “big brother” reaction amongst drivers.
In the mid part of the evolution - circa 2020 - the issues are similar but their order of priority changes:

- **Customer / social / legal acceptance** is likely to become a dominating factor, with the arrival of partial self-driving and greater intervention by the vehicle. This can be divided into a number of sub-issues:
  - Drivers feeling that their freedom or rights are being restricted by intervention systems. Some drivers may be attracted by the benefits of safer, stress-free semi-automated driving; those of a more old-fashioned outlook may feel challenged or threatened
  - Drivers feeling that their privacy is being compromised by systems which exchange information on the location and speed of their vehicles. “Black box” systems which record information and make it available for prosecution for driving offences will be especially unpopular - systems which help and encourage positive driving behaviour appear preferable
  - Legal implications if a system fails causing an accident. Even if an active safety technology saves a hundred lives, public outcry is a strong possibility if a single life is lost due to failure. It may be necessary to provide a degree of legal protection to vehicle manufacturers to facilitate the introduction of systems which offer a large net benefit to the fatality rate but with a small possibility of fatal failure
- **Missing infrastructure** could restrict further gains by this time. While much can be achieved from vehicle-to-vehicle communication alone (including improved journey planning for individual and mutual benefit, as well as warning of safety hazards), it may be necessary to achieve a consistent degree of infrastructure development (telematics beacons, intelligent infrastructure, inter-modal networking and roads suitable for road-trains) in order to achieve required safety and mobility goals
- **Cost of information** will become a major issue - for example, if the best safety-enhancing information is sold on a commercial basis, this raises a question of social responsibility versus commercial practise
- **System reliability and robustness** must be 100% assured by this time, with rising dependence of human safety on these systems. Bad publicity from an unreliable system could set back progress by a decade or more, with a consequent failure to reduce long-term fatality rates
- **Conflict of active safety technologies with environmental issues**, taking a number of forms:
  - Increased weight, leading to increased CO₂, especially in passenger cars where the weight is most significant
  - Power consumption of X-by-wire systems, leading to increased CO₂
  - Recycling of electronics, sensors and actuators placing extra burden on recycling infrastructure
  - “E-smog”, particularly the impact of electromagnetic signals (both within the vehicle and in telematic systems) on vehicle users - similar in nature to current concerns about the health effect of mobile phones
2030+

Looking to the long term - beyond 2030 - issues are once again similar but with a different order of priority:

- **E-pollution and its health effects** have the potential to be a major issue, with the possibility of wireless electronic technologies dominating the workplace, home and transport. The responsible technologies will have been in existence for some time, but it may take some years before any health effect becomes apparent. It is suggested that well targeted early research can pre-emptively address this issue.

- **Legal issues** will remain very much in the public eye, with issues such as who is responsible for a self-driving vehicle needing to be addressed.

- **User acceptance of self-driving**, and the perception of “big brother” controlling the roads, will remain a concern although major benefits should be demonstrable by this time.

- **Human error** could remain an issue despite increasing automation and intervention by the vehicle - the key issue being human misinterpretation of a sequence of automated events, leading to a disastrous human decision. With large quantities of semi-automated vehicles mixed with older, manually-driven ones the scope for catastrophe is significant.

- **Integration of legacy vehicles** in general will be a major issue - historically, it is not acceptable either to ban older vehicles or require them to be upgraded, and this is a right which both classic car owners, and less wealthy drivers of older vehicles, will wish to see retained.

8.2.4 Research demands

Research demands have been suggested based on the objectives, technology roadmap and likely hurdles / barriers. Again it is appropriate to identify certain research activities with each time period of the roadmap. However it is not correct to assume that the most distant part of the roadmap requires no research now, as some long-term or preparatory research may be required.

**Short Term - For 2010**

Research needs in this timeframe are generally aimed at making the first active safety technologies robust, affordable and desirable. They include:

- Definition of advanced vehicle **power requirements** (hybridisation plus X-by-wire) and strategies for efficient **power management**

- Development of better, cheaper **sensor and actuator** technology - especially new **materials**

- Creation of **design rules, methodologies, codes of practise and protocols** for physical systems, information networking, control algorithms and human-machine interfaces

- **Exploration of synergies** between on-board active safety, improved powertrain control, and road network based congestion and pollution management systems

- Assessment and improvement of system **reliability and fault tolerance**

- Development of **simulation tools** for physical and electronic systems as an aid to virtual development

- Development of **manufacturing technology** for the components and systems above

- **Market research** and legal studies to facilitate successful technology uptake
Medium Term - For 2020

Medium term research needs are aimed at the introduction of desirable and affordable partially-autonomous vehicles with a high degree of integrated on-board intelligence. Despite the longer time horizon, it is appropriate to initiate or continue research in these areas now:

- **Second-generation sensor technology** (object recognition etc) - reliability, accuracy, cost
- **Strategy development** - communications standards, fail-safe methodologies, complete vehicle communication, sensor fusion and control integration
- **Human impacts of E-smog** - health effects of electromagnetic transmissions, psychological impacts of information overload
- **System test and validation** methods - safety, compatibility, e-smog & EMC
- **Traffic management** - vehicle interfacing, infrastructure needs, intelligent road technology, central or distributed control

Long Term - For 2030+

Here, the focus is on a successful transition to autonomous systems. The enormity of this task is such that it remains appropriate to initiate research now:

- **Autonomous systems** - reliability, compatibility with legacy vehicles and their drivers, cost reduction
- **Long term health effects** of electromagnetic pollution
- **Mobility research** - intermodality, mobility management, new concepts

These needs can be summarised as follows:

- **Development of each element of the technology roadmap** - building block technologies and materials, integration, development of high robustness and low cost
- **Systems integration** - communication protocols, sensor and actuator fusion, strategies for vehicle and road network, integrated vehicle management and holistic optimisation
- **Impacts of change** - health effects, public acceptance, human-machine interface, setting standards and legal frameworks to enable change
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9.1 Exterior Noise Aspects

9.1.1 Exterior Noise Aspects Passenger Car

The noise emission from road vehicles is limited by legislation in order to protect the environment against high noise emission. In the EU, the essential noise emission limits are defined by the directive 70/157/EEC and its numerous amendments which have been established up to today. The related noise limits were significantly reduced over the last thirty years as shown in Fig. 9.1.

![Pass-by noise limits since 1975](image)

Fig. 9-1: Pass-by noise limits since 1975

However, the experience shows that large reductions in legislative limits have only relatively small effects in real-world situations. The noise pollution arising from road transport is still one of the big environmental problems affecting many people. For example, nearly every second person in Germany feels seriously annoyed by road traffic noise and in the EU it is nearly every third person (Fig. 9.2). There is even a relatively high percentage of population suffering from health effects caused by road traffic noise. For comparison, the percentages are significantly lower for the rail traffic noise effects. Fig. 9.2 describes the current situation of noise exposure which is already unsatisfactory. But the traffic volumes on the roads will further increase. Comparing the traffic of the year 1998 and the prediction for 2010, an increase of up to 40 % is expected (Fig. 9.3). Such an increase of the traffic volume will lead also to an increase of the road traffic noise emission by 1.5 dBA. This means that the measures for future reduction of road traffic noise must compensate also for this noise increase.
All these facts illustrate the high importance of further efficient control of road traffic noise.

9.1.1.1 State of the Art

The current legislative limit for the noise emission of passenger cars is 74 dBA according to 92/97/EEC which is the latest amendment of 70/157/EEC establishing limits. In order to fulfill this limit, technologies were developed to reduce the powertrain noise, the noise emission from exhaust and intake systems, the rolling noise and the overall noise emission from the vehicles [9.2]. Typical technologies for the current status of vehicle exterior noise are:
● Triple exhaust muffler systems
● Intake systems with various resonators
● Optimised combustion conditions (particularly for Diesel engines)
● Precise tuning of running clearances
● Stiffness optimisation of load carrying structures and attached components
● Acoustic partial shielding (like engine top covers, “styling covers”)
● Noise damping materials (like laminated sheet steel, sound absorbing linings etc.)
● Improved tyre tread pattern
● Improved sound attenuation of vehicle body (by undershield etc.)

Nowadays, in many driving conditions of state-of-the-art cars, the rolling noise is the predominant noise contribution. This is valid not only for highways, but also for urban main streets. A typical noise source distribution of a state-of-the-art vehicle is shown in Fig. 9.4. Besides the predominant tyre noise, further essential noise contributions arise from the exhaust system (tail pipe), the intake system and the engine. Of course, not included in Fig. 9.4, but also important is the noise reduction potential arising from the vehicle driving condition.

This ranking of noise sources influences the priorities for future noise reduction and the related technologies.

9.1.1.2 Objectives

Before pointing out future technologies, the objectives for the future treatment of road transport noise have to be defined.

As described in 9.3, the general objective concerning environmental noise is to half the perceived noise emission in residential areas with a mid-term time scale of 2020 and beyond. This means that - roughly - all contributions to the

Fig. 9-4: Noise source distribution of a 74 dB vehicle in pass-by test [9.2]
perceived noise emission have to be halved too. Halving the perceived noise corresponds - again roughly - to a noise level reduction by 10 dB.

Of course, the noise emission contribution arising from road transport is determined not only by the noise source “vehicle”, but also by the traffic situation, the noise propagation conditions, i.e. the road infrastructure and building situation towards the residential area, and by other boundary conditions.

From this point of view, the mid-term goal for the reduction of the vehicle noise emission shall be in the range of 3 dBA. This refers strictly to the vehicle-related matters and does include the tyres, but does not include the noise reduction potential of the road surface.

9.1.1.3 Technologies

The main technologies for future vehicle noise reduction have to reflect the priority ranking of the noise reduction topics as outlined above: tyres, engine, exhaust and intake system and vehicle driving condition.

For the further development of quieter tyres, a still deeper understanding of the noise generation mechanism is required despite the existing knowledge and the ongoing research activities in this field. Based on that, new simulation models with increased accuracy have to be established as powerful development tools.

For the reduction of engine noise, one approach will be the full encapsulation of the engine (and transmission) itself or the engine bay of the vehicle. In both cases, an improved sophisticated thermal management of the encapsulated volume will be required to overcome any heat balancing problems. An alternative approach will be improved engine noise control without secondary measures like encapsulation or local noise shielding. In this field, an outstanding breakthrough technology would be a highly damped material of such high strength that it can be used for high load carrying structures like engine block, crankshaft, gears etc. Also other noise relevant vehicle components like gearbox, engine mount brackets and certain chassis parts can gain big acoustic benefits from such materials. Today, highly damped materials such as laminated sheet steel can be used only for non-load-carrying parts like covers, oilpan etc.

Another important aspect of engine noise is the combustion, particularly with Diesel engines. Although big progress has been made in the development of quieter combustion systems, Diesel engine combustion suffers still from high noise excitation under certain critical operating conditions such as cold start and warm-up phase, low idle, part load conditions and high load accelerations. The future demands for higher efficiency and lower exhaust emissions will lead to sharper and noisier combustion processes. Therefore, sophisticated technologies will be required to counteract this noise-increasing trend and to better control combustion noise also under the critical operating conditions as mentioned above. Current gasoline combustion is clearly quieter than Diesel combustion. However, significantly higher combustion noise must be expected with future advanced direct injection combustion systems of gasoline engines so that improved combustion technologies are required also for future gasoline engines.

If the internal combustion engine in a vehicle is replaced by any alternative system like fuel cells or others, essential effects on the noise emission will occur. In most cases, the noise emission is expected to be significantly lower (probably with
very different noise characteristics). Hence, alternative powertrain systems have to be taken into account, when future vehicle noise reduction is to be discussed.

Basically, active noise cancellation is a well-known technique for noise control and applied already in certain fields like aircraft. Within the field of vehicle exterior noise, the orifice noise of the exhaust and intake system is suitable for active noise control. It might be possible that active noise control is also applicable to tyre noise. However, technologies providing efficient, reliable, production feasible and low cost solutions for this field of application, are still missing.

The noise emission of vehicles depends on the driving conditions and therefore, it depends also on the driving behaviour of the drivers. Very evident examples are the audible differences in the driving style of motorcyclists. The quiet driving of a vehicle might be supported by an intelligent management of the engine and the transmission considering, for example, not only the vehicle, road and weather conditions, but also the actual traffic situation.

In sum, the technologies to fulfil the objectives in the field of vehicle noise emission for 2020 and beyond are:

- New simulation tools with increased accuracy for the development of quieter tyres leading to further improved solutions for low-noise tyres
- New combustion systems (more quiet & more clean & more efficient & no acceleration noise)
- Highly damped materials for load carrying structures of engines, gearboxes and other vehicle components
- Full encapsulation of powertrains with improved thermal management
- Alternative powertrain systems (without internal combustion engine)
- Active noise control for intake and exhaust systems, maybe also for tyre noise
- Intelligent management of engine and transmission for optimum (quiet) vehicle operation

9.1.1.4 Hurdles and Barriers

Besides general cost hurdles - most new technologies are connected with increased costs - there are also some technical hurdles.

The most severe technical hurdle is expected with the development of new highly damped materials of high strength. This is considered as a big challenge to the material scientists. As can be seen in Fig. 9.5, a damping increase by a factor of about 100, compared with the typical metallic materials, would be required for sufficient acoustic effects. However, if such a development could be successfully completed, this would result in a big progress in the noise control at source. In addition, this would be applicable not only in the automotive section, but also in many other fields like construction machinery and other kinds of outdoor equipment, maritime components, household appliances etc.

Other essential technical hurdles are expected in the fields of low-noise tyres and quiet combustion systems. The development towards quieter tyres is faced with the other numerous development targets connected mostly with safety relevant features. Progress in tyre noise reduction must not be achieved at the expense of safety features. Concerning combustion systems, the noise excitation by the combustion is physically in an opposite behaviour compared to most of
the other development criteria such as high efficiency for low fuel consumption and low CO\textsubscript{2} emission, low exhaust raw emissions and high torque and power performance. Therefore, it is a big challenge to find solutions which meet these contradictory requirements to a high degree.

A rather general technical hurdle is that most noise control measures, in particular secondary "add-on" measures, imply weight increase, which is against the trend towards lower weight. In addition, the increasing use of light materials in the automotive sector - mainly for fuel saving reasons - leads often to unexpected and unwanted noise problems. This aspect gives rise to a further special research demand.

### 9.1.1.5 Research Demands

Research is required to establish the basic and detail knowledge which is needed for the development of new technologies. An important role is played here by computer simulation. Powerful simulation tools enable the “straight” development of complex and sophisticated solutions leading to the new technologies. Therefore, the further development of simulation techniques has also to be part of future research activities in order to simulate physical processes more precisely and to increase the accuracy of predicted results.

Such improved simulation approaches are needed for the noise emission behaviour of the whole vehicle, but in addition also for the noise and vibration behaviour of individual vehicle components. This leads to the following research demands in the fields of simulation:

- Improved modelling of the road/tyre/vehicle interaction leading to simulation tools with higher accuracy (when the interaction is investigated, vehicle and tyre cannot be considered without road)
- Modelling of the relevant vehicle noise sources with increased accuracy
Simulation of air flow and temperature within encapsulations
Modelling of relevant noise sources of alternative powertrain systems

The other research demands are directly related to the new technologies as listed on the previous page. These research demands are to be summarised as follows:

- Deeper investigation of the road/tyre contact for better understanding of the interactions;
- Development of flat track test benches for the research and development of low-noise tyres
- Advanced research on DI Diesel and DI gasoline combustion to make it more clean, more efficient and more quiet without “acceleration noise”
- Enhanced research on high strength materials for significantly higher damping with producibility on an economic cost level
- Specific research on the noise behaviour of alternative powertrain systems and their relevance for the future road transport noise
- Further research on active noise control technologies for intake and exhaust orifice noise to provide efficient, reliable and production-feasible solutions on a economic cost base
- Research in further application fields for active noise and vibration control in the automotive section (e.g. for tyre noise control?)
- Development of intelligent management systems for quieter powertrain (vehicle) operation
- Research into improved acoustic properties of light-weight materials used in the automotive sector

Finally, it must not be forgotten that the legislative limitations of the vehicle noise emissions which have the purpose to protect the environment, should be efficient for noise reduction in the real world of road traffic. As known (9.4), this is not sufficiently the case today. Therefore, many research activities are in hand to develop new or improved test methods for the vehicle noise emission which reflect the real traffic situations in a much better way. Such research activities must be continued.

9.1.2 Exterior Noise Aspects Heavy Duty Vehicles

9.1.2.1 State of the Art

According to 92/97/EEC, the maximum of the current legislative limit for the noise emission of trucks and buses is 78 dBA for the power class up to 150 kW and 80 dBA for the power class over 150 kW. The main noise sources of today’s vehicles are the engine, the transmission, the exhaust system and the tyres [9.6]. Typical technologies for the current status of vehicle exterior noise are:

- Lower rated speed of engines
- Engines with common rail injection system
- Stiff engine structure
- Stiff transmission structure
- Acoustic partial shieldings at engines and transmissions
Improved sound attenuation of vehicle chassis by further acoustic shieldings at the vehicle

- Use of noise damping materials (like laminated sheet steel, sound absorbing linings etc.)
- Enhanced exhaust muffler systems
- Intake systems with various resonators

The major noise-critical driving conditions of trucks and buses in real traffic are mid and high speed cruising (rolling noise) as well as acceleration and full load driving (e.g. uphill) at lower speeds (powertrain noise, exhaust noise).

9.1.2.2 Objectives

The general objective concerning environmental noise is to halve the perceived noise emission in residential areas with a mid-term time scale of 2020 and beyond. This means that - roughly - all contributions to the perceived noise emission have to be halved too corresponding to a noise level reduction by about 10 dB.

Of course, the noise emission contribution arising from road transport is determined not only by the noise source “vehicle”, but also by the traffic situation, the noise propagation conditions, i.e. the road infrastructure and building situation towards the residential area, and by other boundary conditions.

From this point of view, the mid-term goal for the reduction of the noise emission from trucks and buses shall be in the range of 3 dBA. This refers strictly to the vehicle related matters: it includes the tyres, but does not include the noise reduction potential of the road surface.

9.1.2.3 Technologies

The main technologies for future vehicle noise reduction have to reflect the priorities of the noise reduction topics which are the engine, the transmission, the exhaust system and the tyres. Other topics not to be neglected are the vehicle driving condition (driving behaviour of driver), the intake system and the cooling system.

For the further reduction of engine noise, one approach will be a rigorous acoustic shielding or even the full encapsulation of the engine (and transmission) either at the powertrain or at the vehicle chassis or split at both parts. In any case, an improved sophisticated thermal management of the shielded or encapsulated volume will be required to overcome any heat balancing problems. Similar to the car situation, an alternative approach will be improved powertrain noise control without secondary measures like encapsulation or local noise shielding. In this field, an outstanding break-through technology would be a highly damped material of such high strength that it can be used for high load carrying structures like engine block, crankshaft, gears, transmissions etc. Also other noise relevant vehicle components like drivetrain axles, engine mount brackets and certain chassis parts can gain big acoustic benefits from such materials. Today, highly damped materials such as laminated sheet steel can be used only for non-load-carrying parts like covers, oilpan etc.

Another important aspect of engine noise is the combustion of the Diesel engines. Although big progress has been made in the development of quieter combustion systems, Diesel engine combustion suffers still from high noise excitation under certain critical operating conditions such as cold start and warm-up phase, low idle, part load conditions and high load...
accelerations. Especially the full load accelerations of heavily laden trucks in urban traffic are the origin of annoying noise. The future demands for higher efficiency and lower exhaust emissions will lead to sharper and noisier combustion processes. Therefore, sophisticated technologies will be required to counteract this noise increasing trend and to better control combustion noise also under the critical operating conditions as mentioned above.

If the internal combustion engine in a vehicle is replaced by any alternative system like fuel cells or others, essential effects on the noise emission will occur. In most cases, the noise emission is expected to be significantly lower (probably with very different noise characteristics). Hence, alternative powertrain systems have to be taken into account, when future vehicle noise reduction is to be discussed. In particular, such alternatives might be promising for city buses and urban delivery trucks [9.7].

For the further development of quieter tyres, the situation is similar to that of cars, but with probably more severe boundary conditions due to the much higher traction forces. In any case, a still deeper understanding of the noise generation mechanism is required despite the existing knowledge and the ongoing research activities in this field. New simulation tools with increased accuracy are required, but will be the same as for car tyres. However, the technologies for realising quieter tyres will probably differ for cars and trucks/buses.

Basically, active noise cancellation is a well-known technique for noise control and applied already in certain fields such as aircraft. Within the field of vehicle exterior noise, the orifice noise of the exhaust and intake system is suitable for active noise control. It might be possible that active noise control is also applicable to tyre noise. However, technologies providing efficient, reliable, production feasible and low cost solutions for this field of application are still missing.

Another item which will become more important when the main noise sources are treated is the cooling system. Its performance requirement will increase because of further increasing engine performance and further extended shielding, but the noise emission has to be decreased. This demands, from new technologies, for more efficient and quieter cooling systems with the same or even less space requirements.

In addition, for noise simulation of all noise sources, paths and operating conditions, appropriate parametric noise path models are required. Only in this way will a balanced combination of noise control measures be achieved.

The noise emission of vehicles depends on the driving conditions and, therefore, it depends also on the driving behaviour of the drivers. For example, the gear selection plays an important role for the noise emission of trucks [9.6]. The quieter driving of a vehicle might be supported by intelligent management systems of the engine and the transmission (driver assistance systems) considering, for example, vehicle, road, weather and traffic conditions.

In sum, the technologies to fulfill the objectives in the field of noise emission from trucks and buses for the year 2020 and beyond are:

- Extensive shielding or even full encapsulation of powertrains with improved thermal management
- Parametric modelling of whole vehicle noise for all noise generation mechanisms, transmission paths and operating conditions (noise path modelling)
- Highly damped materials for load carrying structures of engines, transmissions and other vehicle components
9 NOISE, VIBRATION AND COMFORT

- New combustion systems (more quiet & more clean & more efficient & no acceleration noise)
- Alternative powertrain systems (without internal combustion engine), especially for city buses and urban delivery trucks
- New experimental methods, facilities and simulation tools with increased accuracy for the development of quieter tyres leading to further improved solutions for low-noise tyres
- Active noise control for intake and exhaust systems, maybe also for tyre noise
- Intelligent management of engine and transmission for optimum (quiet) operation of vehicle (driver assistance system)

9.1.2.4 Hurdles and Barriers

Besides general cost hurdles - most new technologies are connected with increased costs - there are also some technical hurdles, which are basically the same as for passenger cars.

The most severe technical hurdle is expected with the development of new highly damped materials of high strength, as it is considered as a big challenge to the material scientists. A damping increase by a factor of about 100, compared with the typical metallic materials, would be required for sufficient acoustic effects. However, if such a development could be successfully completed, this would result in a big progress in the noise control at source, not only in the automotive section, but also in many other fields of mechanical engineering.

Another essential technical hurdle is expected in the fields of low-noise tyres. The development towards quieter tyres is faced with the other numerous development targets connected mostly with safety relevant features. The progress in tyre noise reduction must not be achieved at the expense of safety features.

Concerning technical hurdles with the further development of Diesel combustion systems, the noise excitation by the combustion is physically in an opposite behaviour compared to most of the other development criteria such as high efficiency for low fuel consumption and low CO₂ emission, low exhaust raw emissions and high torque and power performance. Therefore, it is a big challenge to find solutions which meet these contradictory requirements to a high degree.

A rather general technical hurdle is that most noise control measures, in particular secondary "add-on" measures, imply weight increase, which is against the trend towards lower weight. In addition, the increasing use of light materials in the automotive sector - mainly for fuel saving reasons - leads often to unexpected and unwanted noise problems. This aspect gives rise to a further special research demand.

9.1.2.5 Research Demands

Research is required to establish the basic and detail knowledge which is needed for the development of new technologies. An important role is played here by computer simulation. Powerful simulation tools enable the "straight" development of complex and sophisticated solutions leading to the new technologies. Therefore, the further development of simulation techniques has also to be part of future research activities in order to simulate physical processes more precisely and to increase the accuracy of predicted results.
Such improved simulation approaches are needed for the noise emission behaviour of the whole vehicle, but in addition also for the noise and vibration behaviour of individual vehicle components. This leads to the following research demands in the fields of simulation (which are similar to those of the passenger cars):

- Improved modelling of the road/tyre/vehicle interaction leading to simulation tools with higher accuracy (when the interaction is investigated, vehicle and tyre cannot be considered without road)
- Modelling of the relevant vehicle noise sources with increased accuracy
- Simulation of air flow and temperature within encapsulations
- Modelling of relevant noise sources of alternative powertrain systems

The other research demands are directly related to the new technologies as listed on the previous page. These research demands are to be summarised as follows:

- Enhanced research on high strength materials for significantly higher damping with producibility at an economic cost level
- Advanced research on DI Diesel combustion to make it more clean, more efficient and more quiet without “acceleration noise”
- Deeper investigation of the road/tyre contact for better understanding of the interactions
- Development of flat track or other test benches for the research and development of low-noise tyres
- Specific research on the noise behaviour of alternative powertrain systems and their relevance for the future road transport noise
- Further research on active noise control technologies for intake and exhaust orifice noise to provide efficient, reliable and production feasible solutions on a economic cost base
- Research on further application fields for active noise and vibration control in the automotive section (e.g. for tyre noise control?)
- Development of intelligent management systems for quieter powertrain (vehicle) operation
- Research on improved acoustic properties of light-weight materials used in the automotive sector

Finally, it has to be kept in mind that the legislative limitations of the vehicle noise emissions which have the purpose of protecting the environment, should be efficient for noise reduction in the real world of road traffic. As known [9.5, 9.8, 9.9], this is not sufficiently the case up to today. Therefore, many research activities are in hand to develop new or improved test methods for the vehicle noise emission which reflect the real traffic situations in a much better way [9.5, 9.10]. Such research activities must be continued.

### 9.2 Interior Noise Aspects

The interior noise (and vibration comfort) problem in road vehicles is very different from that of exterior noise in the sense that the main driving forces are not coming from legislation but from customer as well as manufacturer requirements. While customers do not often select a vehicle only because of noise comfort, they do expect an ever better noise comfort in their purchased vehicle. If this proves not to be the case, customers are dissatisfied and will likely change vehicle and brand.
When looking at noise sources and potential solutions for interior noise, a number of components, technologies and hurdles are very similar to those for exterior noise, for example in relation to engine, tyre and exhaust noise. But there are also significant differences, related to structure-borne noise transmission, body structure, trimming and sealing. These are optimised in great detail because of interior noise while exterior noise is hardly affected. Also the subjective perception (“sound quality”) aspects are much more important for interior noise than for exterior noise.

Furthermore, the implementation of interior noise abatement measures cannot be seen independently from other critical vehicle performances such as fuel consumption, passive safety, vehicle handling, thermal comfort, durability, communication & entertainment. Even packaging and vehicle assembly aspects have to be evaluated as constraints. For some parameters, there exists a positive spin-off towards noise behaviour (e.g. increased body stiffness), for other parameters, this leads to conflicting design requirements. Mastering the multi-attribute compromise and pushing the global performance envelope hence imposes very difficult design challenges.

Since almost all components and systems affect interior noise quality, low interior noise development is critical in introducing novel technologies into vehicles. For example, novel powering systems (electric, hybrid, hydrogen) could in the long term allow lower interior noise levels, but such systems also pose new challenges on the level of subjective perception, transient operation, secondary noises, support structures etc. Novel lightweight structures tend to be highly critical for noise. More efficient combustion processes may impose a noise penalty.

This determines that interior noise is in the critical path of the vehicle development. Fast and reliable analysis of NVH, in relation with the other performances, is hence essential for vehicle innovation and competitiveness.

9.2.1 State-of-the-Art

An introductory remark should be made regarding the importance of interior noise for the customer. For a large segment of potential car buyers, acoustics are maybe not directly seen as a key purchasing motivation like styling, power, fuel consumption, roominess and budget. But after some driving, good NVH very much influences customer satisfaction and loyalty. Bad NVH experiences may move customers away since they will be linked to the perception of poor quality or lack of refinement [9.11]. Furthermore, professional assessment such as in specialised press increasingly takes up NVH behaviour as one of the pro/con elements. And noise problems take up an important part of customer complaints and warranty problems.

As main contributors to interior noise, one typically distinguishes powertrain, rolling and aerodynamic noise. Significant advancements have taken place on controlling these noise sources, especially for engine noise and more recently also for rolling noise. These are due to improved intake and exhaust systems, improved engine design and engine concepts (balancing shafts...), better airborne isolation (between engine and cabin), improved vibration and acoustic absorption, improved mount materials and principles (hydro-mounts, semi-active mounts) and to improved structural design. Examples of the latter are the improved body stiffness optimisation (in view of other attributes), component radiation reduction, the use of better (and more temperature invariant) damping materials and the use of multi-level isolation systems such as sub-frames. Also the tighter manufacturing processes, working with less components and new connection techniques (improved welding processes, bonding and riveting techniques, glued windows etc.) and allowing lower tolerances have contributed to the NVH improvement.
As a consequence, a gradual decrease of interior noise levels is noted over the last decades, which, per class of vehicles, is in the order of 2 to 3 dB per 10 years [9.11] for a given operational condition. Absolute levels are hard to give and compare, as they depend significantly on the testing conditions and procedures, which are, contrary to those for exterior noise, not standardized. Hence procedures are very company specific and comparable “benchmark” values are only available within the companies individually. Still, [9.11] shows the following two relevant comparisons for resp. road and engine booming noise.

In Figure 9.6, the A-weighted interior noise at the driver’s ear position is shown for subsequent generations of high-line (S1 segment) automobiles at a constant speed of 60 km/h on a (severe) reference gravel road (without engine noise taking part).

![Figure 9-6: Evolution of interior road noise dBA levels in the S1 segment [9.11]](image)

In Figure 9.7, the boom noise in high-end cars is compared over different generations. The figure represents linear dB values at the driver’s ear, obtained as a mixture from different throttle position (light throttle to WOT), averaged in the 3000-4000 RPM range.

![Figure 9-7: Evolution of booming noise dB levels in high-end cars [9.11]](image)
Related to the overall reduction of the interior noise, more emphasis is currently put on reducing noise coming from secondary sources such as HVAC and electro-mechanical and hydraulic auxiliary systems (power steering, seat control,...) or noises unrelated to vehicle functions, such as dashboard squeaks, rattles (from seat, seatbelts, doors, windows...) [9.12]. Also gear noise (rattle, whines) has an important impact on the powertrain design (double flywheel, torsion dampers, active dampers, ...).

It is important to note that these improvements have to a large extent become possible due to important advances made on the level of testing methods and physical-prototype based design modification predictions. This includes data analysis and diagnosis methods, noise source identification and contribution analysis methods etc, leading to extensive benchmark testing and to formal target definition on vehicle as well as subsystem level [9.12]. But these investments have also led to a significant increase of the NVH part of the total effort, cost and time required to develop new vehicle models. Many solutions lead to significant cost and weight penalties. And still, they do not guarantee the absence of undesirable levels of NVH near/after vehicle launch and the related launch delays. The result is that the NVH design process itself is under a huge pressure to become more effective and efficient in order to meet the current vehicle design standards.

The main approach thereby emerging over the last years is that of “virtual prototyping”, extensively making use of numerical simulation models to predict the component, subsystem and even full vehicle performance. While for specific applications or attributes significant successes are reported, important limitations remain on the level of model building efforts, modelling accuracy, calculation speed and the seamless integration in the complete vehicle design process. Particular challenges for NVH virtual prototyping exist in relation to performing “system-level” simulations (and not only of component behaviour) and in making the step from doing mere forward calculations to providing insight into the design behaviour, requiring a much more design-centred simulation approach.

Another important factor that emerged over the last decade is the importance of Sound Quality. Whilst in the past it was sufficient to make cars more silent, over the last years an increasing effort has been made in achieving a pleasant sound character and a vehicle-specific acoustic feedback [9.13]. The vehicle noise behaviour has to be optimised in terms of subjective perception characteristics and has to match the other vehicle performance. This is leading to the introduction of “Brand Sound” development [9.14, 9.15], aiming to make the vehicle sound part of the overall vehicle image. It is imperative that this “brand sound” is maintained even when the overall noise level is reduced. For NVH virtual prototyping, this requires “customer-oriented simulations”, taking into account these sound quality aspects in the virtual design stage. At present, these aspects are essentially realised through proper exhaust and intake design.

### 9.2.2 Objectives

With respect to basic interior noise target levels, the extrapolation of the past evolution of 2..3 dB/decade (for a given vehicle class and operating condition) is expected to continue, perhaps with the exception of the highest class vehicles where engine and road noise tend to approach the limits required to perceive a minimal acoustic feedback.

Especially for the lower/middle class vehicles, the trend exists to improve the quality of a new design to that of the last design of the next higher category [9.11]. While, except for the lower-class vehicles, average powertrain noise is already at acceptable levels, road and wind noise will be the major targets for further reduction. Changing driving conditions put
additional constraints on specific problems like idle vibration and noise (congested traffic), but may also differ between markets (e.g. tolerances for bad roads in emerging countries, ageing effects...), requiring market-specific solutions.

An important objective in this context is the establishment of standard testing procedures for interior noise, similar to these existing for exterior noise. This will be important in order to really put forward verifiable target values. Such conditions will have to include measurement parameters (location, measurement functions, ...) as well as test conditions (tyres, road surface, throttle, speed, ...).

The customer tolerance for unwanted or secondary noises is not only expected to lower, also the lower overall levels will provide less masking and make these sounds more perceptible. The increased demands for thermal comfort and hence the more standard use of HVAC systems, also in cheaper vehicles, will require appropriate solutions for the related noise (also with low-cost HVAC systems).

In general, the trend to use vehicle sound as part of the “brand values” will become more firm, contributing to the “personality” of the car. In the long term, this may lead to individualized, customer defined, vehicle sound [9.13]. The “sensation” of the sound becoming more important than the actual noise components will require adding artificial sound components to emphasise the required performance and “brand” qualities.

However, due to the strong interrelation between NVH and the other vehicle performances, the starting point for setting objectives for Interior Noise development is the assessment of the global challenges for vehicle development. It is within this context that the new targets for interior noise will have to be met, perhaps more as constraints than as true targets. These challenges are the following:

- Reduce fuel consumption and emissions. For combustion engine type propulsions, which are expected to remain dominant till after 2020, this will partially be achieved by improved combustion processes for high-efficiency engines. Higher internal forces and increased impulsiveness may be in conflict with the low-noise requirement.
- Improved passive and active safety. Requirements for improving crashworthiness can be consistent with those of NVH (stiffer bodies may also provide good inertness and low noise transfer functions at powertrain and axle attachment points [5.. 1]), but the design evaluation will still have to be made. On the level of vehicle handling, low road-noise is in conflict with improved road behaviour, each manufacturer defining its own compromises in line with the vehicle profiling. The challenge is to push the envelope.
- Improved manufacturability and more integrated construction. The reduction in the number (and increase in complexity) of subsystems, as realised through the use of e.g. high-tensile steels, and the application of novel connection and bonding techniques has led to stiffer constructions, but also with less inherent damping (e.g. in the joints). The multifunctionality of the resulting parts furthermore makes it less obvious to address the NVH issue separately, requiring the support by multi-attribute design optimisation.
- The key requirement for a major breakthrough on consumption however will be the reduction of the vehicle weight. This has to be achieved in part by reducing the add-on materials for damping and sound shielding by at least 50%, shifting the design challenge to improving the structural design and using novel structural materials with higher inherent damping and/or absorption. But this will not be sufficient to reverse the vehicle mass evolution. Further reducing vehicle weight by modified design concepts and light-weight materials will put major challenges on the structure-borne noise.
transmission and the air-borne noise isolation. Next to safety, noise behaviour will become an essential constraint for implementing novel material solutions.

- The faster renewal of models and shorter model enhancement programs essentially put a constraint on the NVH design cost and time. Furthermore, while the base vehicle design is starting from a reduced number of platforms, more and more product variants are required, including multipurpose vehicles, SUV, 4-WD, high-power sports version etc. This trend to personalisation and niche derivatives is expected to increase. Since NVH is typically a system-level performance, each new variant has to go through an NVH refinement phase. Design engineering budgets for guaranteeing proper NVH behaviour of the complete vehicle family will however decrease rather than reflect this increased complexity, requiring robust and performant derivative design engineering capabilities.

- The continued awareness of brand values and the implicit “satisfaction erosion [5..1]” require stability of the NVH performance as a function of time, in its turn requiring robust design solutions. Similarly, on the level of production, control of manufacturing variability (and introducing robustness for production variability in the design) will have to reduce the amount of customer complaints, satisfaction loss and warranty costs.

- The increased introduction of vehicle communication and information systems (essentially for the driver) [9.16], entertainment (for the passengers) [both already within 10 years] and on longer term [2010-2020 and beyond] telematics, driving assistance and automatic driving, will all drastically impact the demands on the car’s acoustic environment. Clear and unequivocal transmission of messages and commands (voice control), high quality infotainment and undisturbed speech in the vehicle will become essential requirements.

- In the longer term, the introduction of vehicles with unconventional drive systems will open new opportunities but also demands. It is foreseeable that electric vehicles and vehicles with hybrid propulsion systems will increasingly gain market share. As these vehicles exhibit a completely different sound character compared to conventional propulsion systems, specific solutions to reach the above design requirements will be needed [9.13]. This will not only include consistent reduction of the noise generated by the auxiliary units, by the electric components or secondary sources (more apparent due to the low noise in ZEV mode), but especially the matching of the “brand values” with the intrinsic vehicle noise, made difficult by the perceptual mismatch between operational conditions and generated/perceived noise.

In summary, the objectives for future interior noise performance are: continued reduction of levels as well as a growing necessity for “brand values” and this in a context of reducing weight, high rate of derivative designs and reduced design engineering budgets and time. In the longer term, specific challenges are presented by electric/hybrid propulsion systems and in-vehicle communication and entertainment.

9.2.3 Technologies

The potential technologies to address these objectives fall into three categories: passive solutions, active solutions and innovative design processes.

Passive solutions:

This involves many of the solutions already discussed with exterior noise, related to the control of transmission (local noise shielding, advanced mount materials, advanced construction materials with high intrinsic damping), as well as the cancellation or reduction at the source (more efficient combustion systems, improved powertrain concepts, quieter tyres...).
An important challenge exists for innovative high-damping, low-weight materials, based on composites (including polymer/metallic/fibre components). It will however be difficult to make major breakthroughs, especially on the level of "brand" sound design, purely with such material solutions.

**Active solutions:**

While active noise technology has been researched and developed for more than a decade, the successful applications in vehicle design remain very limited. Advancements on the level of materials for realising low-cost, high-performance and reliable actuator solutions, or even solutions integrated with the structural material into smart components, have a very large potential. Especially in the context of low-weight designs, active control may be the only solution to reach acceptable noise behaviour. And in view of sound “branding”, active noise control offers a direct solution, allowing adaptable target functions to be implemented.

**Design methods:**

The real challenge however for interior noise design may be a very practical one, related to the design cost and time available for each new vehicle family and variant. This is further amplified because NVH optimisation requires system level and customer-oriented simulation. While the technology to capture and analyse customer expectations, including subjective perception aspects, is evolving rapidly, the capability to realise the required performance in a design cycle of less than 18 or 24 months requires a drastic front-loading of the functional performance engineering process to the earliest design stages. This is at present not yet possible at the required accuracy and speed, requiring major breakthroughs not only on the level of simulation methods and “brute force” calculation capacity, but also on the level of modelling approaches (which type of models, how to model specific components and connections), maximal re-use of experience and predecessor/platform design, introduction of uncertainty and variability in the design, introduction of active control in the design models etc. Key elements to be supported are the fast propagation of vehicle level targets (in the full context of brand values) to the applicable design levels (subsystems and components, for use within the enterprise or at suppliers), and the virtual vehicle level synthesis and validation of design proposals. This is essential to make the current simulation approach truly design-centred.

The inherent design trade-offs, which need to be made between noise behaviour, weight, crashworthiness, durability, handling etc, require a multi-attribute optimisation methodology which has to rely on consistent multi-disciplinary simulation models, forming a true “virtual prototyping” process. Very important in this context is the capability to link this modelling approach to the assessment of the brand values through “virtual car sound” synthesis and assessment.

**9.2.4 Hurdles and Barriers**

Several technical hurdles are related to specific design solutions such as the development of new highly damped materials of sufficient strength, or the development of applicable materials for active noise or vibration actuation in ANVC solutions. Overcoming these barriers is essential to enable novel design solutions.

The key expected hurdle however to the actual deployment of novel solutions, once they are available, is the inability to introduce the actual NVH optimisation early enough in the design process in order to be cost-effective and timely. It is also the only way to verify their deployment in the context of the conflicting demands for the various system level
performances. Essentially, this means doing by (system level) simulation what now is done by testing on physical prototypes.

More specifically, the development of noise reduction solutions (by transmission isolation as well as by damping and absorption) is intrinsically in conflict with the aims for weight (and hence fuel consumption and emission) reduction, requiring an upfront multi-attribute optimisation to come to a solution. The trend towards multifunctional parts poses specific challenges in this context.

Even when appropriate design methods are available, vehicle cost implications may remain a bottleneck. The key question will be what premium value customers will be prepared to pay for low-noise (or brand-value noise) solutions when legislation is imposing drastic reductions on the level of emissions (and hence weight).

Finally, the evolution to more complex parts and materials will lead to new challenges on the level of recycling and material separation (e.g. of high-damping materials). This will conflict with the demand for a larger recycling fraction of the vehicle.

### 9.2.5 Research Demands

Research demands can be formulated on each level of the technologies addressed above:

- Establishment of standard testing procedures for interior noise
- Research on novel designs for advanced materials with low weight, high damping and good acoustic properties
- Research on high-performance but low-noise combustion processes and engine designs
- Research on tyre/road interaction for road noise reduction (leading to improved road surface and tyre design)
- Research on improved intake/exhaust systems
- Research on reducing aeroacoustic noise sources (mirrors, sunroof, HVAC...), including the therefore needed simulation capability.
- Research on the noise behaviour of alternative powertrain systems
- Research on the practical introduction of active noise and vibration control for vehicle interior noise application, with particular emphasis on the development of innovative materials for structural and structural/acoustical actuation
- Research on analysis and engineering methods to capture the human perception of vehicle sounds in view of vehicle brand design, and to link this perception to the actual vehicle design and engineering models
- Research on advanced simulation methods for the vibro-acoustical performance of vehicles in all design stages, including the link to multi-disciplinary optimisation and covering the complete audible spectrum (including the medium and high frequency ranges)
- Research into methods for concept-level (pre-FEM, pre-CAD) vibro-acoustical design evaluation and optimisation
- Research on proper target setting and target deployment at the various vehicle design levels
- Research into mastering the problems of design uncertainty and variability, introducing uncertainty in the virtual prototype models and leading to robust design solutions and improved production control.
References


EU Sixth Framework Research (“FP6”) - Abstract of Calls relevant to Furore

- “Alternative Motor Fuels” (Sustainable Energy Systems) - Large scale integration of fuels into the transport system - resources, production, storage, distribution, use; tools to monitor & stimulate demand; assessment & monitoring of new & alternative fuel research activities
- “Re-balancing and integrating different transport modes” (Sustainable Surface Transport) - Freight transport corridors; city logistics; inter-modality concepts supported by advanced IT systems and offering better functionality; telematics for goods logistics & loading
- “Increasing road (rail & waterborne) safety” (Sustainable Surface Transport) - Accident & Injury Analysis, Road Infrastructure Safety
- “New technologies and concepts for all surface transport modes” (Sustainable Surface Transport) - Future generation of clean and economical engines; virtual institute on advanced combustion to develop clean powertrains for road transport; propulsion technologies and fuel supply/delivery based on alternative and renewable fuels; integrating near-zero emission propulsion systems such as fuel cells; holistic noise abatement solutions; measurement/sensing technologies for optimum vehicle/infrastructure operation; innovative urban transport of persons & goods; analysis of future energy supply & transport scenarios
- “Advanced design & production techniques” (Sustainable Surface Transport) - Product development tools for reduced development time; advanced design & manufacturing techniques for reduced cost & energy consumption; low-mass materials & structures; integration of manufacturing processes; clean maintenance & recycling of vehicles; road construction concepts for high efficiency, low noise and better safety; technologies for inter-modality of transport
- “Micro and Nano Systems” (Information Society Technologies) - Integrating Sensing, Actuating and Processing devices; Improving interaction between person and machine; adding functionality and reducing cost; demonstrate feasibility of large area systems integration (for example telematics)
- “Safety for Road (and Air) Transport” (Information Society Technologies) - Advanced Sensors and Communication Systems; integrating on-board safety systems that assist the driver; distributed intelligent agents, communications, positioning and mapping, and their integration; vehicle information infrastructure for safety and efficiency
- “Embedded Systems” (Information Society Technologies) - Embedded network systems for sensing and control; fault-adaptive control and management

EU member states - summary of policy information

Germany

Germany is making significant progress to meet the EU voluntary reduction in CO2 mainly as a result of improved vehicle fuel efficiency promoted by emissions based taxation and the voluntary commitment from the German Association of Automotive Industry (VDA) to improve technology [3.62]. With a view to further improving fuel efficiency, the VDA is also in discussion with the Federal Government to assess the use of low viscosity oils and low rolling resistance tyres.

Taxation incentives also include an increase in energy tax with potentially an exemption for renewable fuels, a reduction in labour tax and distance tolls for trucks > 12 tonnes due to commence in 2003, part of the funding contributing to an anti-congestion scheme.
The Federal Government have made a commitment to invest in integrated modes of transport and aim to improve infrastructure efficiency with the aid of telematics and integration of various modes of transport. More cycle routes are to be developed and further investment is planned in combined road-rail transport. One example of this is the Brenner Action Plan 2005, developed jointly by Germany, Italy and Austria, which aims to improve trans-alpine rail freight and combined transport in the Germany-Austria-Italy corridor.

The Federal Government also supports the Transport Energy Strategy, an initiative involving vehicle and fuel manufacturers which aims to develop a strategy for the nationwide implementation of one or two renewable, low CO₂, alternative fuels. By the end of 2001 it was agreed to further investigate hydrogen fuel with the Government supporting research into issues associated with a hydrogen infrastructure. To assist in this aim, the Clean Energy Partnership had been launched with a stated goal of promoting and developing the use of renewable fuels. Further details of projects suitable to receive funding are given in the Federal Transport Infrastructure Plan 2003 [3.63].

**United Kingdom**

The UK Government has declared strong intentions to address global warming via a target of 60% reduction in total national CO₂ output by 2050. Policy for road transport and other sectors is outlined in a White Paper [3.60], while more detail on road transport is given in a strategy document [3.61]. National collaborative research programmes are co-ordinated via the “Foresight Technology Roadmap” [3.2], major research targets are given in the Strategic Plan [3.3]. Recently the Low Carbon Vehicle Partnership has been created to bring together stakeholders and promote new technologies.

Safety improvement measures have centred on the controversial usage of cameras to record speeding and traffic-light offences. However, these measures appear to have been effective in reducing accidents. The London Congestion Charge is a pioneering scheme to charge for using city roads at peak times, based on auto-recognition of license plates, and appears to be effective.

A variety of incentive schemes exist for environmentally friendly vehicles including grants for alternative fuel conversions and hybrid vehicles, co-funding of research prototypes, exemption from the London Congestion Charge, and taxation of company-provided cars based strongly on CO₂ emissions.

**France**

French law imposes air quality measurement systems on all cities, and enables local authorities to take action, for example banning cars, when pollution levels reach high levels. Each region has a plan to improve air quality, part of this comprising the Urban Travel Plan [3.64]. This locally developed plan lays out measures to, for example, reduce car transport, develop of less polluting forms of transport and to maintain the effectiveness of the road network. Measures than can be incorporated into the plan are various but examples include the introduction of ‘express lanes’ for low CO₂ emission vehicles and free parking in city centres for ZEVs.

On a national scale, transport policy is focussed towards several key areas in order to reduce emissions: improvement in vehicle technology, goods transport, inter city and urban transport and fiscal measures such as reduced tax on alternative fuels and purchase of CO₂ efficient vehicles [3.65].
Vehicle technology improvements, whilst the responsibility of the manufacturer, is supported by Government funded research programmes, in particular PREDIT 3 (from June 2001) which has the fight against climate change as its main priority. France is also keen to promote implementation of certain technologies across Europe, for example, the adjustable speed regulator, which has benefits in terms of road safety and energy efficiency.

**Italy**

Several measures are in place to reduce transport CO₂ emissions including; a voluntary agreement with Fiat to reduce specific CO₂ emissions, promoting the use of collective passenger transport (car sharing, collective taxis), promotion of low carbon fuels and a more efficient goods transport network reducing the amount of road haulage and increasing the use of rail/sea.

Italy recognises natural gas as having a large unexploited potential in spite of the investment required to update and extend the current infrastructure required to encourage greater use. By means of either agreements or local legislation, schemes are in place to encourage the replacement of old buses with either gas-driven buses or hybrids. Financial incentives are also offered for the purchase of or conversion to LPG passenger cars.

Proposals are in place to shift the tax burden towards fuels deemed to cause more damage to health and the environment and to tax vehicles according to weight as well as horsepower. Plans are also in place to manage urban congestion by introducing charges, restricting access to historic areas based on vehicle emissions levels and to reduce emissions by increasing the environmental awareness of individual drivers [3.66]

Although some road transport infrastructure development is planned in order to bring Italy in line with the rest of the EU, the focus of the General Transport Plan, a ten year plan approved in 2001, is to promote rail over road and to develop sea routes.

**Austria**

Fiscal incentives for CO₂ reduction in Austria include; tax breaks for bio-Diesel, vehicle and registration taxes, which are based on engine power and fuel efficiency, and road tolls. Road tolls introduced in 1996 were time-based but environmental drivers have instigated a change to distance based tolls for trucks from 2004 with passenger car tolls to follow. Vehicle taxes are amongst the highest in the EU and are set to increase, not least as Austria believes pricing should better reflect the actual cost of transport particularly for sensitive areas like the Alps. The use of price differentiation based on time of travel may also be introduced to limit congestion [3.67]

Improvements in rail and local transport, are to be supported with further funding. This in part is provided for by local government which is required to contribute some revenue gained from fuel and energy taxes.

The Ministry of Environment has initiated several Mobility Management projects to support the re-allocation of passenger traffic from private cars to public transport, cycling and walking for three specific areas: large events, business and tourism.

Future proposals include: the promotion of energy efficient / alternative modes of transport, in particular pilot schemes...
Switzerland

Switzerland's policy for CO\(_2\) reduction relies heavily upon fuel and energy taxes as this is seen as an effective measure to influence technological development, choice of transport and transport demand. Pilot projects have been initiated which provide tax relief on alternative biomass fuels, in particular RME and ethanol. Vehicle taxes, differentiated by weight, have not been seen to have an effect on emissions.

Switzerland's environmental policy aims to reduce emissions as much as is feasible and to lobby for international emissions reduction. On an international scale, Switzerland is involved in a joint project with Russia, Poland and the Baltic states to promote renewable energy sources and improved energy efficiency. On a national level, government funding is available for a joint project with the Swedish Automotive Industry and Academia to develop environmentally compatible vehicles whilst maintaining industry long term competitiveness [3.68].

Transport Policy is aimed explicitly towards both safety and minimizing environmental impact. The Swiss National Road Administration (SNRA) is promoting green driving courses which train the individual to drive in an environmentally compatible way. Local investment programmes include developing cycle networks and renewable motor fuel for goods & passenger transport. Local grants are available to projects which develop an environmentally stable society. With regard to road safety, Project Vision Zero aims to eliminate road deaths by improving the transport system and infrastructure to minimize risk [3.69].

Netherlands

The government target is for a 6% reduction of CO\(_2\) compared to 1990 by 2010 and is aiming to achieve a climate-neutral energy provision. To this end, 18m€ is being made available over 10 years to demonstrate the entire process from production to application of climate-neutral gaseous and liquid fuels by 2010 (GAVE programme). Current measures to reduce CO\(_2\) include vehicle taxation to encourage the purchase of fuel-efficient cars and to discourage personal company car use and commuter traffic. National policy also aims to reduce fuel consumption by reducing speeding, increasing tyre pressures and, through driver training and monitoring instrumentation, to encourage environmentally friendly driving styles from the individual. The Netherlands has also been a key player within the EU in experimenting with and developing unpopular yet effective variable road pricing schemes [3.70].

Other nations - summary of policy information

USA

Federal programmes are in place to promote the development of fuel efficient cars and trucks and to produce cleaner fuels and to reduce the number of miles travelled. These range from the voluntary schemes, to promote the use of alternative fuelled vehicles and 'clean' commuting options, to the 'Clean Automotive Technology' program, which aims to...
have a fleet of affordable, ultra low emissions, ultra high fuel economy vehicles on the road by 2010, to the high risk research program ‘Freedom Car’ focussed on developing hydrogen powered fuel cells and relevant infrastructure [3.71]. Other goals and measures are outlined in the Department of Transportation Performance Plan FY 2004 [3.72].

Although central funds are available, the provision of improvements to paths for cyclists and pedestrians, traffic flow improvements (such as ride sharing) and alternative fuel projects are implemented locally.

**California**

A bill was passed in 2002 (Assembly Bill 1493) requiring ARB to legislate to enforce “maximum feasible” greenhouse gas emissions reduction for new vehicles from 2009. The bill explicitly forbids California ARB to ban any specific vehicles or use of new fees or taxes on motor vehicles, fuel or miles travelled. The automotive industry has stated its intention to overrule this decision in the Federal Courts. California has the right to develop its own vehicle emissions standards, hence the outcome of any case is likely to rest on whether the courts decide the Bill is a pollution reduction measure or a regulation covering fuel economy.

A further example of legislation that is unpopular with the auto industry is the new LEV II legislation (from end 2003 - 2010). This now incorporates larger vehicles but the introduction of a ZEV requirement, expected for 2005, is being held up in the Courts.

California has introduced various measures to encourage personal and business ownership. For example, SULEVs and ULEVS are allowed concessions (to end 2003 and end 2007 respectively) to travel in the High Occupancy Vehicle Lanes and all taxis operating at International airport are required to be SULEV standard.

**Canada**

Canada has a high vehicle ownership per household (greater than the UK) and, if no preventative measures are taken, road traffic is predicted to grow by 33% from 1990 to 2010.

Key measures to control this growth include expansion and improvement of public transport such as expansion of SkyTrain and the light railway network. Intelligent Transportation Systems are being developed with Government support to enhance intermodal transport, safety and traffic management both to reduce emissions and improve efficiency.

Canada has targeted a 25% improvement in fuel efficiency by 2010 and negotiations are underway with the U.S. to introduce a voluntary fuel efficiency standard within NAFTA.

Future transport policy is directed towards the use of less GHG intensive fuels and the use of public transport and less fuel intensive modes of passenger transport. The Government are also in discussion with industry and academia to research and understand real transport costs and to develop an appropriate pricing policy [3.73].

Within these measures, the development of fuel cell vehicles (Canadian Transportation Fuel Cell Alliance), alternative fuels (bio-Diesel and ethanol blended gasoline) and intelligent transportation systems are seen as offering great opportunities
APPENDIX: EU AND NATIONAL POLICY INFORMATION

to Canadian businesses. Further details of Canada’s plans are detailed in Straight Ahead - A Vision for Transportation in Canada [3.74].

Japan

CO₂ emissions reduction plans in Japan are broadly similar to those seen in Europe and include the promotion of: public transport; off-peak commuting; telecommuting; an environmentally friendly lifestyle, and longer summer holidays. These activities are led from the front through a range of activities undertaken by the Japanese Government staff, such as the Kasumigaseki No Car Day [3.75].

Technology is to be used to reduced emissions in a number of ways. For example, targets for automobile fuel consumption should be improved by 15% to 20% over 1995 levels by 2010. Increased use of clean energy and low pollution vehicles should be promoted although the need for an improved infrastructure, specifically battery re-charging stations, is recognised. A range of intelligent transport systems, for example to collect tolls and monitor congestion are to be expanded, and will benefit both emissions reductions and safety. Further research is to be carried out into the development and application of more advanced telematics. Further details of Japan’s approach to transport development issues can be found in the White Paper on Land, Infrastructure and Transport in Japan [3.76].

Tax incentives are in place to encourage the purchase of low emissions vehicles and low fuel consumption vehicles. Tax concessions are also available when replacing older, vehicles that do not comply with NOx legislation with new vehicles. Local authorities also have the power to levy automobile tax based on vehicle specification. For example, during 2001-2004 Tokyo Metropolitan Government is charging a higher rate for vehicles > 10yrs old and a lower rate for environmentally friendly vehicles.

India

The development of India’s economy is closely linked to its transport network and has estimated 50% of all petroleum products are attributed to the transport sector. India’s road network is in need of upgrading and revenue from taxes on gasoline are allocated for this purpose.

In 2000, emissions regulations, Bharat I (similar to EURO I) were introduced nationally with local implementation of Bharat II in the Northern Capital Region and extended to other major cities. Other emissions reduction measures include production of battery operated vehicles within India and large scale conversion of petrol and Diesel vehicles to CNG [3.77].

India has ratified the Kyoto protocol on the Containment of Green House Gases (GHG). As a developing country, India is under no obligation to reduce GHG emissions but will benefit from technology transfer and foreign investment in clean technology projects.
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EUCAR/Working Group Powertrain, CONCAWE, International Energy Agency and other companies, research organisations and University institutes dealing with automotive research.