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Sustainability Assessment of Road Transport Technologies

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Sustainability assessment of road transport technologies

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Executive Summary

Road transportation is one of the main energy consumers in Europe with subsequent effects in greenhouse gas (GHG) and air pollutants (AP) production. Significant regulatory, and research and technology efforts are concentrated on improving its sustainability, i.e. reducing its impacts to energy resources and the environment. At the same time, mobility of goods and people is a cornerstone of today's economy and should be further promoted while transportation becomes more efficient. The propulsion technologies that will be promoted in the future and the improvements that they can bring along are therefore the decisive factors of whether sustainability targets can be met.

A number of propulsion technologies are assessed in this report regarding their potential to improve the road transport sustainability. These technologies are distinguished into internal combustion, hybrid, and electric vehicle propulsion systems. Each category is further distinguished into more technologies, which are expected to appear in variable degrees as road transport propulsion systems. Table ES.1 presents all vehicle technologies selected for evaluation.

Table ES.1. Vehicle technologies evaluated

Tier 1	Tier 2
Internal Combustion Engine	Spark-ignition
	Compression ignition
	Low-T combustion
Hybrid	Mild
	Full
	Plug-In
Electric	Battery
	Fuel Cell
	Electric vehicle with internal combustion engine range extender
	Electric vehicle with fuel cell range extender

All technologies have been evaluated following a structured group of criteria, which are summarized in Table ES.2. These criteria are assumed to offer a holistic view of the sustainability of each technology. All technologies have been evaluated in an unbiased manner using information from published studies, and engineering assessments where information has not been available.

Key technological characteristics for each propulsion system are described. Also, their applicability to different vehicle types (power-two-wheelers, passenger cars, light commercial vehicles, busses, and heavy duty trucks) is assessed based on the cost, space requirements and performance of each technology. Biofuelling possibilities, using first and second generation biofuels, are considered an asset and the potential of each technology is examined.

An effort has been made to provide quantified information o efficiency, GHG emissions and costs (including externalities) for each technology. Where exact information has not been available, at least order of magnitude and relative differences over conventional technologies are given. Both the current trends and the expected situation are outlined, in an effort to accurately reflect the current status and the potential of each technology.

A number of key conclusions can be drawn from this evaluation:

1. There is no technology available today that can score higher than already used (conventional) technologies in all sustainability criteria established. In other words, there is no "silver-bullet" technology to replace existing ones, at least in the near future.

2. The potential of conventional ICE vehicles is still substantial as they will continue to offer high cost-effectiveness and driving performance which can be hardly matched by alternative technologies. Technology breakthroughs lead to continuous fuel economy improvements. However, the relatively low thermodynamic efficiency limits and strong dependence on fossil fuels means that conventional technologies will have to be gradually phased out and replaced by more efficient alternative technologies, at least for small to medium sized vehicles.

3. Road freight transportation, which is currently heavily depended on compression ignition (diesel) engines, is one sector for which only few alternatives can be found to improve sustainability. Increase of the biofuel share and combination of second generation biofuels

Table ES.2. Sustainability criteria used for the evaluation of each technology

Criterion	Explanation
Energy	
Energy efficiency	Efficiency of converting the on-board fuel energy content to vehicle displacement
Energy security	Use of political inert and/or domestic energy resources
Lifecycle Impacts	
GHG	Total GHG production, including fuel production, fuel use, vehicle manufacturing and end-of-life processes
Materials	Need for materials for vehicle manufacturing and recycling
Air Pollutants	
Regulated	NOx, HC, CO and PM emissions produced by the vehicle's propulsion
Non-regulated	Other pollutants produced during the vehicle operation
Infrastructure	
General	Needs to develop refuelling or communication systems
ICT	Opportunities to achieve additional benefits with the use of information and communication technologies (ICT)
Costs	
Technology	Research, development and production costs
Externalities	Environmental and health costs induced by the use of the particular technology
Customer perception	
	Assessment of the people's response to particular technology

with new combustion concepts (low temperature combustion) may offer significant benefits for a simultaneous improvement in efficiency and reduction of AP and GHG.

4. Electric vehicles have the potential to offer substantial GHG and AP reductions over conventional technologies. However cost, infrastructure needs, and battery capacity are still significant obstacles in their widespread penetration. While technology rapidly improves, there are still no definitive answers as to whether and how much the cost-efficiency of batteries can improve. In addition, the availability and cost of materials for large volume battery and motor production is still in question.

5. Fuel cell technologies based on hydrogen or other fuels also offer significant benefits in terms of AP and GHG. Combined with medium sized batteries, fuel cell electric vehicles may already offer similar or better performance than today's conventional vehicles in terms of performance and range with the potential for zero GHG and AP emissions. This cannot be yet matched by neat electric vehicles. However, this technology is limited by the need to efficiently produce and distribute hydrogen, which basically means developing new infrastructure from scratch. Cost of fuel cell production is also a limiting factor.

6. Hybrid vehicles offer some benefits compared to conventional cars in terms of GHG and AP emissions. However, these cannot be seen as a long-term solution because of their significant dependence on fossil fuels. Also material and R&D cost will continue to suppress their cost-effectiveness compared to the best of the conventional vehicles of today.

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List of Abbreviations

AP	Air pollutant(s)
B2G	Second generation biofuels
BEV	Battery electric vehicle
CAI	Controlled Auto Ignition
CI	Compression ignition
EC	European Commission
EtOH	Ethanol
EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FCREV	Electric vehicle with fuel cell range extender
GHG	Greenhouse gas or gases
HC	Total hydrocarbon emissions
HCCI	Homogenous Charge Compression Ignition
HDV	Heavy duty vehicle(s)
HEV	Hybrid electric vehicle
ICEREV	Electric vehicle with internal combustion engine range extender
ICEV	Internal combustion engine vehicle
ICT	Information and communication technology
LCA	Lifecycle analysis
LCV	Light commercial vehicle(s)
LPG	Liquid petroleum gas
LTC	Low temperature combustion
MtOH	Methanol
NG	Natural gas
PC	Passenger car(s)
PCCI	Premixed Charge Compression Ignition
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
PTW	Power two wheeler(s)
R&D	Research and development
RCCI	Reactivity Controlled Compression Ignition
RES	Renewable energy source(s)
SI	Spark ignition
STTP	Strategic transport technology plan
SWOT	Strengths, weaknesses, opportunities, threats type of analysis
TTW	Tank-to-wheel energy flow
UNECE	United Nations Economic Commission for Europe
V2G	Vehicle to grid communication
WTT	Well-to-tank energy flow
WTW	Well-to-wheel energy flow

1. Introduction

1.1 Background

Combating global warming and climate change is one of the most important challenges currently facing mankind. As a result of its heavy dependence on fossil fuels the transport sector is a significant consumer of energy and a major source of greenhouse gas (GHG) emissions. The transport sector accounted for around 33% of total final energy consumption in the EU27 in 2007, and was responsible for around 20% of GHG emissions, with an increasing future projection. Road transport is the dominant mode, being responsible for 71% of all transport-related GHG emissions [1].

Due to its large contribution, road transport also appears as one of the pillars in reducing total GHG emissions in Europe. A number of policies have been adopted in this respect, which all contribute in meeting the targets of the 20-20-20 policy package, which came into force in 2009. This regulatory framework sets the overarching target of cutting GHG emissions in Europe by 20% over the 1990 levels in 2020. Policies that contribute towards meeting this target include the CO_2 targets for new cars (Regulation 443/2009), the promotion of biofuels in road transport (Directive 2009/30/EC) and the promotion of information and communication technologies (ICT) for the road transport in order to reduce emissions.

The White Paper on Transport [2] clearly shows that current measures are not enough to achieve a sustainable future and that more reductions in GHG will be requested in the long run. A more aspirational target, further to the 20-20-20 regulatory package, has been therefore set, calling for total transport (not just road) GHG emission reductions by 60% over the 1990 levels by 2050. This will have significant repercussions to mobility technologies used, in particular in the road transport sector. For example, the White Paper on Transport foresees that “conventionally fuelled cars” must be halved by 2030 and completely phased out from urban transport by 2050.

In order to support these aspirational targets, the European Commission has put forward a Strategic Transport Technology Plan (STTP), i.e. a set of proposals and a roadmap for the implementation of leading-edge technologies that can and will gradually be implemented in the transport sector [3]. Technologies are not only assessed on the basis of their emission reduction potential but also within their social, environmental and institutional context, since this will largely determine their successful implementation.

At the same time that GHG emission reduction becomes the focus of high level legislation, air pollution continues to be one of the main life threatening factors in cities. Short-term and long-term ozone concentration limits are still exceeded in most EU member states [4]. Particulate Matter is considered responsible for 5 million years of lost life per year in EU alone [5]. In this context, road transport is one of the most important contributor of air emissions at an urban level [6]. Hence, there is still significant scope of action in further reducing air pollutant emissions from road transport.

Further to GHG emission reduction targets and air pollution, the European Union is faced with a number of challenging issues, including availability of resources and materials, energy security, and a daunting economic environment. All these form a unique set of boundary conditions that will largely determine how road transport will shape in the future.

1.2. Objectives

This study aims to assess the main propulsion technologies that are being used or are foreseen for application in road transport. The assessment includes a number of criteria which are relevant in the context of GHG emission reduction, i.e. energy security, air quality impacts, infrastructure needs and societal impacts. In principle, we attempt to offer a holistic view of the opportunities and the main difficulties in promoting different technologies, which have the potential of meeting the long-term environmental and energy targets of the European Union.

In this context, this study aims at identifying the potential of each technology according to the vehicle type, ranging from small mopeds and scooters to heavy duty trucks. The fuel used, with emphasis on biofuels, is also considered and technologies which allow high biofuelling possibilities are positively assessed.

The report is written, to the extent possible, in non-technical language so that it can offer a useful view of the technology possibilities also to the non-experts. Also, a scoring system has been adopted to assess the different technologies. While a scoring system is highly subjective, it also allows to fast identify weak and strong areas of each technology. Hence, it should be rather seen in this respect, and not as an absolute scale for classifying technologies in a particular order.

This work aims at offering useful information in the context of the White Paper for Transport and the Strategic Transport Technology Plan activities. However, this is not officially linked to either of these activities, neither it aims to serve any of the particular targets or pathways identified in those high-level strategic documents. All assessments are based on published technical work and engineering assessment of what technologies are seem to be able to deliver.

1.3. Structure of the report

Further to this introductory section, the report is structured as follows:

- Section 2 describes the methodology used for the assessment of the different technologies. In particular it describes the reasons for the selection of particular indicators and their context. It also groups the technologies studied according to different criteria.

- Section 3 presents details for each technology and its assessment according to the different indicators outlined in Section 2.

- Section 4 summarizes the evaluation and presents the key points for the different technologies.

- Finally, Section 5 provides the main conclusions and an outlook of this work.

2. Methodology

The following sections describe the methodological framework followed for the assessment of each propulsion technology that can be used in road transport. The assessment is mostly based on literature data collected for the various technologies. There is a large number of publications in the area of road transport technology assessment, originating from various parts of the world, but an effort was made to concentrate on European literature data because they are more representative of local circumstances. Studies in US related to technology description have also been used where European data were not available and where equivalencies could be established. Engineering assumptions have been made where more detailed information was not available.

The assessment tries to present all technologies in an unbiased manner. Instead of attempting a detailed description and analysis, an effort is made to deliver the key benefits and limitations of each technology. The situation for the year 2011 is presented and the outlook of each technology in the future is estimated. Key figures related to costs, efficiency, and performance are also presented for each technology.

Each propulsion technology is assessed on the basis of a number of criteria. These criteria are the same for all technology. The following sections of this chapter present the main assessment criteria and explain their content.

2.1. Identity and application range of each technology

2.1.1. Category and type

The different propulsion technologies have been classified in two tiers (section 2.3), based on their characteristics. Tier 1 refers to the main propulsion concept while Tier 2 offers a more detailed technology description.

2.1.2. Technology Description

An outline of the main technological characteristics of the particular propulsion type is given in this section. An effort has been made to use non-technical language so that the operation principle can be made clear even to the non-experts. This has been made on purpose: by understanding the operational principle one can readily assess the potential but also the bottlenecks for the promotion of the technology. This section also delivers some key figures regarding energy consumption, vehicle range with the adoption of this technology, and performs a comparison with other technologies, mainly having in mind to identify strengths and weaknesses. Assessment of the technology according to the different assessment criteria is done in the subsequent sections of the analysis.

2.1.3. Application Range

Each propulsion technology may be better suited for different vehicle types for a number of reasons including space availability, weight limits or even performance applicability depending on typical driving patterns of the different vehicle types.

The first vehicle type considered in this analysis consists of **power-two-wheelers (PTWs)**, i.e. vehicles falling in the L-vehicle categorization according to the UNECE classification and primarily referring to motorcycles and mopeds. Mopeds and motorcycles do not contribute to more than 1% of total road transport GHG emissions [7]. At the same time, technology measures to reduce their CO_2 emissions are generally difficult to introduce, due to their small available space, balance concerns, and weight limitations.

The second category considered is **passenger cars (PCs)**, i.e. vehicles classified as M1 according to UNECE. It is clear that PCs correspond to the vehicle type accounting for most of the GHG emissions of road transport. This is therefore the vehicle category where most mitigation policies have been focused on. The applicability of different technologies to this vehicle type is therefore of particular importance.

Light-Commercial Vehicles (LCVs) is the third vehicle type considered and includes the vehicles termed as N1. In more commercial terms, this includes vans and light duty trucks mostly aiming the transport of goods and professionals with their tools and equipment. CO_2 emission regulations are being planned for N1 vehicles as well, therefore the importance of this vehicle type to meet the Community-wide targets is increasing.

Busses (M2, M3 vehicle types) include urban busses and coaches used for interurban travel. Urban (transit) busses in particular are a special category of a captive fleet which is centrally maintained and operated. This gives the opportunity to apply technologies and fuels much faster and with less infrastructure investments than other vehicle types. A typical example is the electric bus (trolley) which is the only relatively widespread electrified vehicle in European cities today. Hence, the analysis mostly focuses on urban busses while coaches are better covered by technologies mostly appropriate for heavy duty trucks.

Finally, **heavy duty trucks (N2, N3)** include both medium sized and long haul lorries. They are sometimes split to rigid and articulated vehicles, depending on their structure. Heavy duty trucks correspond to a very diverse vehicle category encompassing vehicles travelling at high speeds on motorways and cover long distances daily, down to special vehicles like refuse trucks which operate over a stop-and-go pattern day round. However, as most of the GHGs are emitted by long-haul trucks, emphasis in this report is particularly given to this vehicle category.

A relative score is given in each propulsion technology, depending on its applicability for each vehicle type. The type which best suits the particular technology is assigned a value of 1 while if a technology is not at all suitable for a particular vehicle it is assigned a value of zero. Intermediate values are then given largely on a qualitative basis. An assessment that follows this scoring section justifies the scores selected.

2.1.4. Biofuelling possibility

Promotion of biofuels represents one of the key policies at a Community level to reduce GHG emissions from transport [8]. Today's biofuels are produced by processing vegetable oils as a diesel replacement and by fermentation of sugars for gasoline replacement.

Diesel replacement is referred to as "biodiesel" and is a mix of fatty-acid methylesters produced by the transesterification of vegetable oils. Bioethanol is the replacement for petrol and it is produced by the fermentation of sugars. Those two fuel types are considered as "first-generation" biofuels, i.e. fuels which are manufactured to be usable in today's internal combustion engines. These biofuels are blended with conventional fuels. Use of these biofuels can be made by various propulsion technologies. However, certain technologies offer more opportunities or present limitations in the maximum biofuel use. Hence, the biofuelling possibility for each particular technology is separately presented in the technology assessment.

The assessment is based on the maximum blending ratio that can be used for the two fuel types. A high blending ratio is favourable as this largely leads to higher CO_2 reductions and improves energy security in Europe. However, maximum blending is limited by technical reasons. The assessment is separately done for biodiesel and for bioethanol.

It should be mentioned that "second" generation biofuels are the focus of research today. Second generation biofuels will be produced by advanced processing methods, resulting hopefully in fuels of improved properties with a lower CO_2 footprint. Second generation biofuels, due to their manufactured properties, theoretically offer the opportunity for co-development of advanced energy conversion machines that maximize the benefits of the fuels. For example, one can think of an advanced internal combustion engine-biofuel combination which offers improved efficiency and lower CO_2 emissions than any combination today. Similarly, one could think of a biofuel/fuel cell combination with superior performance than today's combinations. Our assessment in this report mainly refers to first generation biofuels. However, second generation ones are mentioned for these propulsion technologies where a true potential seems to exist.

2.2. Assessment Criteria (Indicators)

2.2.1. Energy

The first assessment criterion used for each propulsion technology is energy performance. Energy is further split into two subcategories: energy efficiency and energy security.

Energy Efficiency

Energy efficiency primarily refers to the efficiency of the propulsion technology to convert the primary energy stored on the vehicle to useful power to the wheels. This is the so-called tank-to-wheels (TTW) component of energy flow. The higher the efficiency, the lower the energy needs to power the vehicles. However, energy efficiency may also refer to the upstream energy conversion component, i.e the efficiency of the system to convert a primary energy source to useful energy to be stored on board the vehicle. This is known as the well-to-tank (WTT) efficiency component. For example, one can determine the efficiency involved in extracting and processing heavy oil and then delivering oil products for final consumption. However, assessing the efficiency of converting solar power to electricity is not relevant because solar power is a renewable energy while heavy oil is not. This is why we mainly focus on on-board energy conversion efficiency (TTW). The impacts of a propulsion technology to the upstream energy conversion industry are considered in the next section, describing lifecycle impacts of each propulsion technology. In order to conclude the definitions, the sum of TTW and WTT procedures is called well-to-wheels efficiency (WTW), and is a significant criterion for the overall efficiency of a system.

Energy security

Energy security on the other hand refers to the contribution of the particular propulsion technology to utilizing energy sources which are politically inert and energy sources that decrease the European Union dependence on energy imports from third parties. In general, technologies that reduce energy consumption and allow the increase in the contribution of renewable sources are considered to also improve energy security.

2.2.2. Lifecycle impacts

There are two major components of lifecycle impacts of each vehicle propulsion technology: Impacts on greenhouse gases and impacts on materials.

GHG

The assessment of lifecycle GHG impacts of a propulsion technology is of paramount importance in order to correctly assess the potential of this technology to meet the EU's objectives of future GHG reductions. In principle lifecycle assessment means to consider two additional dimensions of GHG emissions further to the consumption of energy on board the vehicle. The first dimension is to take account of the GHG emissions produced in order to deliver the fuel/energy on the vehicle. The second dimension is to include the GHG generation during the production phase and the dismantling (end-of-life) of the vehicle itself. Although this has been considered trivial in the past, several new vehicle technologies are energy intensive to produce, which also results to high CO_2 emissions in the production phase, or present issues at their end-of-life phase.

Materials

The shift from conventional vehicle types to new propulsion technologies, implementing electrical components and subsystems, is in need of new materials. These materials may be expensive, hard to reach or of limited availability. Hence, the large quantities required to build components for an extensive stock of vehicles may be a limiting factor, far more important than technology limitations. The materials which are most important for the manufacturing of each technology are discussed in this section as well as the potential limits these may induce.

2.2.3. Air Pollutants

Regulated pollutants

Air quality protection is one of the criteria that should be assessed when judging the sustainability of a particular technology. New technologies may have a significant contribution in preserving air quality. For example, electric cars produce limited or even zero emissions during their use, hence they have a negligible effect in urban air pollution. This section discusses the impact of different technologies on pollutants which are controlled by regulations, namely carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and particulate matter (PM), including particle number. The section discusses the effect of each technology both in normal operating conditions and also potential effects when malfunctions may occur.

Non-regulated

Several technologies may have a positive impact in the emission of regulated pollutants but may produce pollutants which are not currently regulated but may have a negative effect in health and environment. For example, polyaromatic hydrocarbons (PAHs) are not directly controlled by regulations but several of them are considered as carcinogens. Hence, a technology that leads to an increase of PAHs, despite leading to overall reduction of hydrocarbons, would receive a low score according to this criterion.

2.2.4. Infrastructure

Cars that have to be recharged require large infrastructural developments so that charging can be provided while parked in public space. Moreover, vehicles that require new fuels (e.g. hydrogen) first require that the fuel infrastructure network will be developed before these technologies become popular. Heavy infrastructure investments are a disadvantage when the promotion of a new technology is considered. This can therefore be a limiting factor. The infrastructural needs for the promotion of each technology are included in this criterion.

ICT

Information and communication technologies (ICT) are a rapidly developing sector of informatics with a great potential in the automotive area. ICT refers to all technologies that allow vehicle-to-infrastructure or vehicle-to-vehicle communication and all computer-guided driver aids. ICT offers a great potential in improving transport conditions, reducing fuel consumption and pollutant emissions. Hence, vehicle technologies that enable ICT and the different ICT systems concerned are discussed in this section.

2.2.5. Costs

Technology

Technology costs refer to R&D, material, and manufacturing costs to build a vehicle. In certain cases, technology costs may also include end-of-life costs, i.e. costs for dismantling and recycling vehicle components. In general, technology costs do not include operation costs, which are mostly determined by fuel prices. Fuel prices are a highly volatile component of vehicle operation costs. There is a certain competition between electricity vs. liquid fuel prices, which is usually dependent on the country considered. It is also expected that fuel prices will change more in the future as the shift to renewable electricity production becomes more popular and fossil fuel availability decreases. In order to avoid the uncertainty induced by energy price competition in the future, this has been excluded from the present analysis.

Externalities

External costs (or "externalities") refer to the costs that the use of each technology induces to the environment and health, i.e. costs which do not directly contribute to the price of a commodity. In the literature, the total cost, including internal and external costs is sometimes referred to as total societal cost. In the case of cars, environmental damage and impacts of emissions to health are the major components of external costs. The calculation of external costs is tedious and often highly uncertain, as the environmental effects of emissions and impacts to the climate are very difficult to assess and often are not described by linear functions. Despite these limitations, considering external costs (or, as often described, internalizing external costs) offers the possibility to more holistically assess the costs incurred when using cars of different technologies.

2.2.6. Customer perception

New vehicle technologies are not always well accepted by their potential customers for reasons that relate to vehicle performance, drivability, image, cost or other factors. A negative customer perception may be a significant obstacle in promoting a particular technology. Customer perception may not be an independent assessment criterion. It may rather be the combined result of a number of independent criteria, such as performance over cost ratio, or capital vs fuel cost investment. It was decided to lump all these often subjective factors in a criterion summarizing the overall customer perception.

2.3. Technology classification

There are several technological concepts which are today developed and tested as candidates for vehicle propulsion systems. It can sometimes be difficult to identify the key differences between the concepts. To make it even more complicated, these technologies appear with different names in the international literature. In an attempt to streamline vehicle classification, the individual vehicle technologies have been grouped into three main categories, at a Tier 1 level. The main classification criterion is the source of the power to the wheels:

1. Internal combustion engine vehicles (ICEV): Power to the wheels is only provided directly by an internal combustion engine.
2. Electric vehicles (EV): Power to the wheels is provided by one or more electrical motor(s).
3. Hybrid vehicles (HEV): Power to the wheels is provided both by an internal combustion engine and one or more electric motor(s).

Hence, classification at a Tier 1 level is not made according to the fuel used or the exact vehicle configuration, but only according to the source of direct power to the wheels. This avoids some usual confusion in the literature, in particular related to the definition of different hybrid car types.

A more detailed vehicle classification is attempted at a Tier 2 level where the fuel and the configuration of the propulsion system are taken into account:

- ICE vehicles at a Tier 2 level are distinguished into spark ignition, compression ignition, and low-temperature combustion. These differ in respect to the combustion principle and the fuels used in each case.

- Hybrid vehicles are distinguished into mild hybrids, full hybrids (HEV), and plug-in hybrids (PHEV). In all these three configurations power to the wheels is provided by both the motor and the engine.

- Finally, electric vehicles are distinguished into battery ones (BEV), fuel-cell (FCEV), combination of battery with an ICE acting as a range extender (ICEREV), and fuel cell acting as a range extender (FCREV). None of these vehicle types should be considered as a hybrid because in all cases, power to the wheels is provided by the electrical motor(s) only.

The vehicle classification according to the two Tiers is given in Table 1.

Table 1. Vehicle classification according to different Tiers

Tier 1	Tier 2
Internal Combustion Engine	Spark-ignition
	Compression ignition
	Low-T combustion
Hybrid	Mild
	Full
	Plug-In
Electric	Battery
	Fuel Cell
	Electric vehicle with internal combustion engine range extender
	Electric vehicle with fuel cell range extender

Tier 2 should include all major technologies that are currently widely foreseen for road vehicle application.

2.4. Fuels considered

A large number of fuelling possibilities exist today and this number is expected to further increase in the future. The main fuel possibilities are explored in this analysis, in conjunction with the vehicle technology that this fuel is most appropriate on.
The following fuels are considered in this analysis:

Petrol and Diesel: These are the conventional fossil fuels which are available today. Incremental improvements in their properties may be expected in the future but no real fundamental difference compared to today's fuels.

NG: Natural gas that may also include biogas. Natural gas is mainly methane and can be easily combusted using typical spark-ignition engines. NG may be stored on board the vehicle either in liquid or in compressed form which depends on the application and does not lead to any fundamental difference in its usability and vehicle performance.

LPG: Liquid petroleum gas is a mixture of propane and butane and a range of other hydrocarbon traces. LPG can fully replace gasoline on existing engines, with minimum conversions. LPG retrofits are probable the most frequent retrofits today in Europe, as owners try to benefit from the lower prices per unit of energy.

Biodiesel: Biodiesel refers to the blend of fatty methylesters used today in blending with fossil diesel. Biodiesel may be combusted up to a certain proportion in a diesel engine, without any mechanical conversion or other complications. However, due to the complexity of diesel combustion and diesel fuel system, neat biodiesel is not used and is not expected to be used as a diesel replacement.

EtOH: Ethanol (or more exactly: bioethanol) is produced by the fermentation of vegetable sugars and can be used as a replacement of gasoline in spark ignition engines. Ethanol has some advantageous characteristics, such as the high octane number. Blends of 85% bioethanol in normal petrol are already in use today. Higher ratios are not used as the lower vapour pressure of ethanol compared to gasoline makes it hard to start up the engine when ambient temperature drops.

MtOH: (Bio)methanol can be produced with synthesis reactions starting from biogas. Biomethanol is more difficult to handle than ethanol due to the toxic and poisonous nature, hence its use in internal combustion engines is of limited interest. Biomethanol may be more interesting as a fuel in fuel cells.

B2G: Second generation biofuels. This refers to fuels of advanced properties that can be manufactured with a greatest overall carbon benefit than today's fuels. B2Gs may offer better tuning possibilities in order to serve particular needs.

H_2: Hydrogen has been applied as a fuel both in fuel cells and in internal combustion engines. H2 has received large interest in the previous years as a fuel that could fully replace carbon-based fuels. However, the cost-efficiency of this pathway was considered to be less than building electric vehicles and the supporting infrastructure. Hydrogen though still remains as a technical possibility, if the all-electric pathway fails to deliver the desired targets.

3. Technology Assessment

3.1. Internal Combustion Engine vehicles (ICEV)

3.1.1. Spark Ignition (SI)

Technology description

Spark-Ignition engines are the most widespread propulsion systems available in road transport vehicles today. In spark-ignition engines, a fuel with high vapour pressure is mixed with air and the combustible mixture is ignited by a spark plug to produce power. Spark-ignition engines are amongst the highest power density energy converters today. This is the reason they have found a widespread application in a range of vehicle types, from very small scooters to large CNG busses and some trucks. The other main advantages of this type of engine are its rapid response to power demands, its tuneable performance in terms of sound or feeling, and its reliable operation.

Despite their long and successful history, spark-ignition engines have several disadvantages compared to today's and future technology alternatives. Firstly, even the most advanced spark-ignition engines cannot achieve maximum efficiencies above 30-35% in steady state operation. This is a thermodynamic limit which is impossible to overcome with technology improvements. In transient operation and over partial loads this efficiency drops even below than 10%. Secondly, it allows limited fuel flexibility which means that fuel availability can be a real problem, as fossil fuel resources decrease in the future. Thirdly, although significant improvements have been taking place in regards to emission performance, spark ignition engines do produce a number of air pollutants which degrade urban air quality.

Today, significant efforts are concentrated in further improving spark-ignition engines. The main areas of development include direct fuel injection for the combustion, improved air management system with reduced throttling losses, thermal energy recuperation and even better control of the combustion process by means of precise fuelling, lean combustion, and higher compression ratios. For pollution reduction, advances occur both in the engine and the aftertreatment fronts. Engines are equipped with exhaust gas recirculation to decrease combustion temperature and flexible ignition timing to decrease pollutant formation. Catalyst formulations in the exhaust become even more efficient and stroichiometry is closely monitored to achieve optimum conditions for pollutants reduction.

In particular, direct injection becomes a mainstream technology for passenger car engines. Direct injection offers the potential for improved volumetric and thermodynamic efficiencies, in the order of 10-15% compared to conventional port-fuel vehicles. This is due to the cooling effect by in-cylinder fuel evaporation, higher compression ratios allowed by better combustion control and less throttling losses when/if the engine operates in lean mode. On the other hand, direct in-cylinder fuel injection may be the source of higher hydrocarbon and particulate matter emissions. This is because of less time available for fuel evaporation as well as wall-wetting. A new report by JRC shows that meeting particle number emission standards from direct injection petrol vehicles will be a challenge [9].

Some efforts have focussed on using hydrogen as a fuel in spark-ignition engines [10]. Hydrogen can burn at similar conditions to gasoline with tuning of the engine combustion parameters to accommodate its different ignition and flammability properties. The advantage of hydrogen is that its combustion leads to the formation of solely NO_x and water vapour. However, hydrogen can be more efficiently utilized in fuel cells, hence the commercial interest of further developing this technology is rather limited.

LPG and natural gas are also widespread fuels used in SI engines. LPG does not offer any particular environmental or other advantages compared to gasoline. Its use is mostly promoted for cost reasons as its normalized price per unit of energy delivered is much lower than gasoline. Natural gas may offer some advantages in GHG reduction, mostly because this is the hydrocarbon with the highest H:C ratio overall.

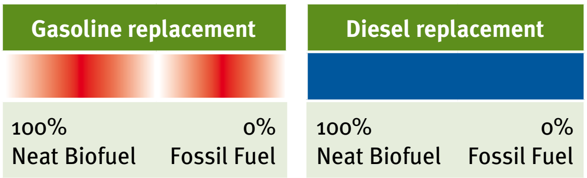
The continuous developments keep spark-ignition engine as the most cost-effective and best performing powertrain for small and medium sized vehicles today. Therefore, industry forecasts and projections foresee that it will remain as the main propulsion technology for such vehicles at least over the next 20 years.

Application range

1.0	0.7	0.5	0.3	0.0
PTWs	Cars	LCVs	Busses	HDTs

Spark-ignition engines are high-speed low-sized engines which are most appropriate for vehicles up to medium size where rapid power changes are required. For larger vehicles, efficiency and power at low speed are more important hence spark ignition engines become less appropriate as the vehicle size increases. For busses, natural gas spark-ignition engines do have some interest as they combine moderate CO_2 emissions and low air pollutant emissions. Also, bioethanol spark-ignition busses are promoted in Sweden.

Biofuelling possibility



Bio-ethanol is the most widespread biofuel used today in spark-ignition engines. Blends of 85% ethanol and 15% gasoline are commercially available in several countries, with Sweden demonstrating the highest share in their road transport fuel consumption. Such high blends of ethanol require engine combustion adjustments and engine materials that can withstand the higher toxicity of ethanol compared to fossil gasoline. Ethanol can also be added to normal fuel up to 10% according to Directive 2009/30/EC and is offered to the pump for use by normal vehicles. For natural-gas spark-ignition vehicles, biogas can be used as a 100% replacement and such examples are widespread in several cities around Europe.

Energy

Efficiency

Spark-ignition engine efficiency improves with technology evolution but still remains one of the least efficient energy conversion systems used for vehicle propulsion. Thermodynamic (theoretical) limits cannot be exceeded by technology improvements. Energy conversion efficiency of spark-ignition engines in current road vehicles is in the order of 18-20%. Engines in principle can reach up to 35% over full load and optimum combustion conditions, in particular with direct in-cylinder fuel injection. Almost equal amounts of energy are dissipated with heat both through the radiator and the exhaust gases of the engine.

Security

Spark-ignition engines generally operate on petroleum products (gasoline, natural gas) and hence are an obstacle in improving energy security in Europe.

Lifecycle impacts

GHGs

The gasoline spark-ignition cars registered in Europe in 2010 produced ~143 g/km of CO_2 over the regulated type-approval cycle. Real-world emissions of greenhouse gases however are higher by 10-15% than the levels achieved over the certification test [11]. Tailpipe CO_2 emissions correspond to the most significant component of lifecycle CO_2 emissions. According to the JRC analysis [12], the well-to-tank CO_2 emissions for gasoline production are equal to 12.5 gCO_2/MJ fuel. Assuming a 43 MJ/kg heating value for gasoline and a H:C ratio of 1.85, this leads to 75 gCO_2/MJ (IPCC 2006 proposed value is 69 g CO_2/MJ). By assuming a 140 g/km tailpipe CO_2 emission factor, Vliet et al. [13] estimated 163 g/km WTW emissions for regular gasoline cars. By including production, spare parts and end-of-life estimates, Leduc et al. [14] estimated that a gasoline vehicle producing 208 g/km of CO_2 by on-road tailpipe emissions corresponds to 265.8 g/km when all GHG emitting sources are taken into account.

Significant reductions in total GHG emissions can be achieved by using biofuels. According to Directive 2009/30/EC, ethanol produced by sugar cane equals to a reduction of total GHG by more than 70% while bioethanol from other sources achieve less but also important reductions in total GHGs.

Materials

Spark ignition engines require large quantities of steel and other metals (Al, Mg) to manufacture. A typical medium sized engine weighs approximately 150 kg, 80% of which is metal components. However, economies of scale and the existing business model mean that material availability and cost do not constitute a problem for large volume engine production.

Air pollution

Regulated pollutants

Spark-Ignition engine emissions have significantly decreased over the last years. Current, well-maintained and operating engines emit pollutants at concentrations that are difficult to discern from background urban levels. Cold-start operation, before the engine and the aftertreatment system have reached their normal operation temperature, produce increased emissions compared to hot operation levels. However, current regulations control the emission levels in both hot and cold-start operation. Current regulatory trends shift from requiring more string emission limits to guaranteeing long-term maintenance of low emission levels. This is achieved with the introduction of on-board diagnostic systems, improved durability requirements, in-use compliance regulations and frequent roadworthiness tests. Successful implementation of such control regulations would correspond to minimum contribution of spark-ignition engines to urban air-quality problems.

Non-regulated pollutants

Although regulated pollutant limits are successfully implemented by relevant regulations, spark-ignition engines may lead to the formation of pollutants currently not regulated, such as nanoparticle emissions and polyaromatic hydrocarbons. In case of malfunctioning aftertreatment systems, H_2S and NH_3 emissions may also be produced. Research is currently directed to better understanding emissions and formation of these pollutants in order to inform regulators. Reduction of the emission of such pollutants can be achieved by both introducing engine measures and fuel measures. For example, the decrease of sulphur from fuel is an important measure both because it reduces sulphur containing pollutants but also because it enables the use of more advanced and efficient aftertreatment devices.

Infrastructure

Spark-ignition vehicles are an established technology that requires relatively limited investments in infrastructure, further to maintenance and incremental improvements in the road and refuelling network, as they already have been taking place.

ICT

ICT measures are seen as a new area which can bring substantial reductions of GHG emissions from conventional spark-ignition vehicles. This mainly refers to advanced intelligent transport systems that can be used for traffic management. Examples of such systems include intelligent traffic light control, variable bus priority lanes, etc. The benefits that can be achieved by the introduction of such measures are numerous, including more efficient transport, lower GHG and AP emissions, and improved safety.

Costs

Technology

Spark-ignition engines are amongst the most lightweight power conversion units, when fuel storage is also taken into account. Also, R&D follows established pathways, which means that procedures have been optimized for cost. Due to this reason, spark-ignition is currently the lowest cost solution for road vehicles available. Van Vliet et al. [15] estimated a total cost of ownership of 3690 €/year for a spark-ignition car, which has been the lowest compared to all other alternatives, including diesel, hybrid, and a range of electric technology vehicles.

Externalities

External costs of spark-ignition vehicles are important because of the emission of air pollutants and greenhouse gases. Ogden et al. [16] estimated that total societal costs for a regular gasoline car in US equal ~12.4 thousand dollars, compared to 5.6 thousand dollars of manufacturing and operation costs. Air pollution costs are the most significant contributor to external costs, followed by GHGs and then the insecurity in the oil supply chain. External costs for vehicles should be dropping with technology improvements which reduce both air pollutants and GHG emissions.

Customer perception

Spark-ignition vehicles are a well-established technology and very well perceived by potential customers. Currently, the only true competitor for the large majority of customers are compression ignition (diesel vehicles) and, in some occasions of expensive cars, hybrid vehicles. Current improvements in spark-ignition engine efficiency and performance have greatly revived the interest in gasoline vehicles, which offer the most cost-effective solution for up to the medium size car sector.

3.1.2. Compression Ignition (CI)

Technology description

In a compression ignition engine, fuel is self-ignited after pressure and temperature inside the combustion chamber exceed a certain limit. Compared to a spark-ignition engine, compression ignition ones offer a higher efficiency because of higher compression ratio, unthrottled air intake, lean operation and better utilization of turbocharging. Diesel engines require higher pressures to operate and combustion is slower than spark-ignition ones. Hence, they are better suited to larger applications where inertial forces of large engine components demand lower speed operation, which is best suited for diesel engines. Diesel engines have received significant improvements over the last years, including full electronic fuelling and combustion control and ultra-high fuel injection pressure. Exhaust gas recirculation is also actively adjusted to reduce NO_x emissions.

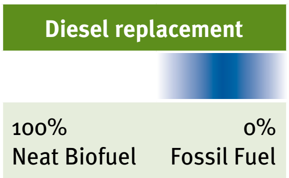
Impressive improvements have been taking place in the aftertreatment front of diesel technology as well. Current light duty diesel engines are all equipped with diesel particle filters which practically eliminate solid particles from the vehicle exhaust. Medium and heavy-duty engines are equipped with selective catalytic reduction devices, which utilize a urea-based reducing agent in the exhaust to reduce NOx emissions. Large R&D efforts are still concentrating on integration, optimization, downsizing and cost reduction of all these devices.

Application range

1.0	0.7	0.8	0.9	1.0
PTWs	Cars	LCVs	Busses	HDTs

Diesel engines are best fit for large vehicles where high power at low operation speed is required. For small vehicles, diesel engines are not well suited because of size and weight concerns but also because they cannot deliver the required power and performance under the driving conditions imposed by the driving patterns of such small vehicles. However, downsizing of diesel engines is currently taking place with the smaller commercial engines to reach capacities of slightly more than 1 l. In fact, even smaller diesel engines are available for L-category four-wheelers, however they are of rather outdated technology.

Biofuelling possibility



Biodiesel is the biofuel with the highest volume consumed in Europe. Biodiesel is produced by the transterification of vegetable oils and is a blend of saturated and unsaturated methylesters. Directive 2009/30EC allows up to 7% blending of biodiesel in conventional fossil diesel. Higher blending ratios are currently not possible for a variety of reasons. Issues with biodiesel include long-term storage stability, corrosion of metal parts, compatibility with engine elastomers, lube oil dilution, and impacts on pollutant emissions. Due to these reasons, the regulations only gradually move towards allowing higher blending ratios. Higher biodiesel blending is currently only allowable in controlled fleets, such as busses, where maintenance intervals and practices as well as engine materials can be adjusted to the fuel properties. Higher biodiesel blending possibility is expected to be possible when the so-called second generation biofuels become available. These are expected to have optimized properties for compression ignition engines, which will allow their higher blending or even use as neat fuels. Such a fuel is currently used in Finland with very positive results [17].

Energy

Efficiency

Compression ignition engines are more efficient than spark ignition ones, for reasons explained in the technology description section. The theoretical thermodynamic efficiency can exceed 50% for typical engine operation in automotive applications. In real-world conditions where partial low operation is frequent, average efficiency drops to around 25-30% on average for cars and 35-40% for heavy duty trucks. In fact, diesel cars compete with gasoline hybrids in terms of fuel economy. Several tests in the media try to reach a conclusion on which of the two technologies is most efficient. However, this is difficult to reach because appropriate selection of vehicle types and driving conditions can largely determine the answer. As a rule of thumb between a diesel and a hybrid spark-ignition vehicle of equivalent size and performance indexes, the hybrid will be more fuel efficient in urban conditions and the diesel will be more efficient in motorway conditions.

Security

Fossil diesel is the main fuel combusted in compression-ignition engines and, as a result, compression ignition engines do not contribute to the energy security. This may be changed by the increasing introduction of biodiesel as a fuel. Biodiesel can be locally produced using vegetation existing in the area of operation of the biodiesel powered vehicle. Second generation biofuels are expected to further assist in this direction.

Lifecycle impacts

GHGs

Diesel cars registered in Europe in 2010 averaged 139 g/km CO_2 emissions over the certification test. This is only marginally lower than the gasoline average value (143 g/km). The reason for the marginal difference, despite the much better efficiency of diesel engines is because the average size of a diesel car is larger than the gasoline one. Similar to gasoline cars, the tailpipe CO_2 emissions is the largest part of lifecycle CO_2 emissions. JRC [12] estimates

14.2 g CO_2/MJ fuel for the upstream GHG emissions which is only a fraction of the 76 g CO_2/MJ which is estimated for the combustion of the fuel (2006 IPCC value is 74 g /MJ). Van Vliet et al. [13] estimated 156 g/km of CO_2 emissions including fuel production, assuming tailpipe emissions of 131 g/km. Leduc et al. [14] estimated 252 g CO_2/km including fuel production, vehicle operation and manufacturing, spare parts and end-of-life procedures. In all analyses, diesel vehicles score better in overall greenhouse gas emissions than spark ignition vehicles do.

Materials

Compression ignition engines require a more robust construction than spark ignition ones in order to withstand the higher forces developed due to the increased operation pressure. They are therefore in need of some 20-25% more metal for their construction while aluminium use is limited to fewer components. However, material availability is not an issue for established vehicle technologies.

Air pollution

Regulated pollutants

Compression ignition engines continue to be the highest individual source of pollution in road transport, despite the significant advances of engine and aftertreatment technology. Currently, NO_x emissions constitute the highest problem as diesel cars even of latest technology are shown to emit several times higher than the corresponding emission standard [18]. In particular, NO_2 – which is much more toxic than NO – is emitted at higher proportion in current diesel NO_x emissions than in the past. The reason for the high NOx emissions is that this is a byproduct of the quest for efficient combustion, since the high temperatures requested for efficiency also lead to increased NO_x emissions. What was not initially expected was the large difference between real-world emissions and emissions over the certification test. This has been the result of electronic engine control, which limits the EGR involvement only in the operation range of the certification cycle. Operation beyond this range is without EGR with subsequent high emissions of NO_x.

PM emissions used to be a problem from diesel engines. They still continue to be for large diesel engines in heavy duty trucks not equipped with particle filters. In the diesel car segment, diesel filters have become mandatory since 2010 with the introduction of the Euro 5 emission step. The mandatory use of filters in the truck category is expected from 2014 on with the introduction of the Euro 6 emission standards. Closed particle filters have also very high efficiencies in reducing not only the mass but also the number of particles, as this is measured by the PMP protocol (UN/ECE Regulation 83 – Annex 4).

Non-regulated pollutants

Non-regulated emissions from diesel vehicles are of less important compared to the significant emissions of regulated pollutants. With biodiesel use, aldehyde emissions and an increase of polyaromatic components can be an issue.

Another non-regulated pollutant which is of importance for diesel combustion is volatile and semi-volatile particles produced when diesel exhaust is diluted in ambient temperature. These particles are not controlled by regulations but can impose significant health effects, as some recent research has identified [19]. More studies on the formation and health effects of these particles is necessary before decisions are reached on their possible regulation.

Infrastructure

Similar to spark-ignition vehicles, diesel ones require no additional infrastructure, since they are an established technology. Positive impacts of ICT measures can be also identified here, similarly to spark-ignition vehicles.

Costs

Technology

Diesel engines are the most cost-efficient technology for road freight transport, which is proven by their almost 100% penetration in the relevant market. In the passenger car sector, diesel vehicles are more expensive than spark-ignition ones due to the more robust construction of their engine. In case of long annual distances driven, this additional cost may be paid back by the lower cost of the fuel. Van Vliet et al. [13] estimated that the diesel vehicle production costs were roughly 10% higher than for an equivalent spark-ignition vehicle. This leads to overall some 7% higher annual cost of ownership of a diesel vehicle compared to a spark-ignition one, despite the lower fuel consumption of the former. Despite this small increase, a diesel engine continues to be the second cheapest option as a car propulsion technology, when all cost parameters are included.

Externalities

External costs for diesel vehicles are high due to the significant air pollutant and greenhouse gas emissions they produce. The much higher NOx and

PM emissions of diesel engines mean that their external costs due to the impact to the environment are within a range of 30% to 100% more than that of gasoline vehicles [20]. The widespread use of diesel particle filters is expected to significantly reduce external costs, as it almost eliminates the most significant component of diesel air pollution, namely particulate matter. In any case, the diesel vehicle technology is expected to remain as the one with the highest external costs in comparison with all other technologies available.

Customer perception

The compression-ignition (diesel) engine is the only technology currently accepted by the heavy duty transport industry. This seems not possible to easily change in the future as the combination of cost, efficiency, and performance of large diesel engines is difficult to match by any other technology. In all relevant projection scenarios, road freight is dominated by diesel. It seems that the combination of compression ignition engine and advanced biodiesel fuel is the only technology option which may guarantee long-term sustainability of road freight business.

Compression ignition engines have been also gaining significant ground in the smaller engine size segment used in cars, as a result of their improved fuel efficiency, longer range and lower operation costs over spark-ignition ones. In particular, the company-car sectoras well as private cars driven for long average distances are dominated by diesel engines. This shows that compression ignition engines are highly rated, in particular in Europe, a perception which will be difficult to change in the future.

3.1.3. Low Temperature Combustion (LTC)

Technology description

Low-Temperature Combustion (LTC) is currently an active area of research and it is seen as a combustion approach that can simultaneously reduce pollutants and increase efficiency of internal combustion engines. LTC is defined as the combustion of lean mixtures with maximum local temperatures that do not exceed 2000 K [21]. Various modes of LTC have been demonstrated experimentally or by modelling. Without going into details, LTC combustion has been realized as Homogenous Charge Compression Ignition (HCCI), Controlled Auto Ignition (CAI), Premixed Charge Compression Ignition (PCCI), Reactivity Controlled Compression Ignition (RCCI), and others.

LTC can be realized by elaborate matching of the phasing of the combustion event in relation to the engine cycle [22]. In LTC, a lean and premixed mixture is self-ignited at well controlled temperature and pressure conditions. This leads to a fast and uniform combustion in the cylinder without a particular flame structure being developed. Low temperature is achieved with high exhaust gas recirculation (EGR) rates that may exceed 50%. LTC combines the benefits of diesel and spark-ignition combustion, without having their disadvantages. Hence, combustion is lean and unthrottled and it is initiated without a spark-plug, similar to a diesel engine. On the other hand, combustion is premixed – similar to spark-ignition which means low pollutants formation. LTC can be technically achieved by elaborate control of the fuel/mixture proportion, intake mixture temperature adjustment, proper valve timing, and active control of the exhaust gas fraction recirculated.

A range of thermodynamic benefits can be achieved by LTC combustion. Efficiency gains are mainly achieved by maintaining high compression ratios, operating on a lean mixture (high work production during expansion), and low heat reduction by retaining higher wall temperatures and reducing the temperature of the exhaust gases [23]. In the pollutants front, low PM is achieved due to the premixed combustion and the absence of a diffusion flame while low NOx is achieved by the low combustion temperature. Therefore, LTC can be a very good solution in achieving a number of benefits at the same time.

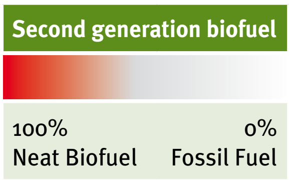
Despite these advantages, there are still several issues that have to be overcome before this technology becomes widely popular for commercial applications. One major issue is that the controlled premixed autoignition is in fact an unstable equilibrium condition between knock and misfire. Hence, if one of the combustion parameters (for example wall temperature) is not at the desired condition, then knock (no useful work) or misfire (no combustion) may occur. As a result, LTC has not been achieved yet in transient conditions because it is not possible to precisely control all boundary conditions over transient operation. A second problem is high hydrocarbon and CO emissions production, due to the low temperature combustion. Aftertreatment may therefore be required to address this issue. Also, overall pressure development may be even higher than diesel at high load conditions which increases mechanical friction and requires a heavy engine construction.

Application range

0.1	0.4	0.5	0.2	1.0
PTWs	Cars	LCVs	Busses	HDTs

LTC can be effectively achieved only under steady-state operation, hence it is better suited for vehicle categories largely operating on steady-state and, for better performance, partial load operation. Large trucks are therefore a very good candidate, while transient busses do not seem a good candidate due to their frequent transient operation between idle and full load.

Biofuelling possibility



LTC requires a specific fuel formulation to operate efficiently. The fuel used should be relatively easy to evaporate and should autoignite at moderate temperatures for combustion to occur. Neither octane nor cetane numbers are exact descriptors of the quality of such a fuel. However, one such fuel could be a gasoline with low octane number so that its resistance to autoignition is limited [24]. In that respect, bioethanol is not a good replacement due to its high octane number. Also, biodiesel is not a good replacement because of its low volatility.

Biofuels, in particular second generation ones manufactured through Fischer-Tropsch procedure, may offer a good possibility for LTC by means of appropriate tuning of their properties. Therefore, producing biofuels of specially designed properties may be combined with LTC for combined environmental benefits. In such a case, it would be preferred that a neat biodiesel instead of blends are used so that properties are well-controlled.

Energy

Efficiency

LTC can offer thermodynamic efficiencies that match or exceed diesel ones. Reported thermodynamic efficiencies of up to 50% in partial load have been reached in experimental engines [23]. GM claims that a commercial vehicle offers 15% better fuel efficiency in HCCI mode that the equivalent spark-ignition mode. In extensive real-world operation, and due to the difficulty to reach LTC in transient operation, one should expect to obtain average thermodynamic efficiencies similar to the diesel one. Perhaps, efficiency gains over the diesel may be achieved due to the absence of diesel particle filter and selective catalytic reduction, which both decrease the overall efficiency of the system.

Security

LTC may be an enabler for optimized biofuels in the future. Through this, it may assist in improving energy security, otherwise its contribution in increasing energy security is limited, as it currently operates on the basis of fossil fuels.

Lifecycle impacts

GHGs

One may assume that GHG emissions at the tailpipe of the vehicle operating on LTC may be similar in level to diesel combustion, due to the similar efficiencies. It is not possible to estimate the impact of the technology on the fuel production (upstream) GHG emissions. As said, this technology requires fuels of specific properties to operate efficiently. Such fuels are neither the current gasoline nor the diesel one. For example, there have been applications of HCCI technology using naphtha [25]. Naphtha is a less advanced fuel than gasoline and requires less energy to produce. Hence, GHG benefits may also originate from the fuel production front (upstream GHGs). In any case given that fuel production does not correspond to more than 10% of total GHG over the lifecycle of the fuel, the actual benefit in reducing total GHG emissions with LTC should mainly come from the use of the fuel on the vehicle, rather than its production.

Materials

LTC can be implemented in engines which are more or less of the same specifications as the ones used for diesel and gasoline combustion. Some more advanced controllers and equipment are necessary to control combustion but no particular impacts on current engine material flow are foreseen for LTC.

Air pollution

Regulated pollutants

Low NO_x and PM are to be expected from LTC engines. NO_x should be even lower than current spark-ignition engines, due to the even lower combustion temperatures involved. However, CO and hydrocarbon emissions may be a problem that will require an oxidation catalyst to resolve. Due to the lean overall combustion, the operation of the catalyst is not expected to be a problem. However, in case of significant thermal recuperation in such engines, efficient heating up of the catalyst may be a challenge.

There is currently very little information about particle mass and number emissions from such vehicle technologies. Combustion as such should not lead to particle formation due to its premixed and lean character. However, some PM emissions have been reported under particular LTC modes [26], perhaps due to limitations in fuel volatility. Moreover, the high wall temperatures and the higher shear forces due to the advanced pressure may lead to some lube-oil related particle emission. These will have to be explored once such engines become more popular.

Non-regulated pollutants

There have been no measurements of non-regulated components from LTC. Moreover, it is expected that the extent of a potential problem of non-regulated pollutant emissions from LTC engines will largely depend on the fuel chemistry properties. For example, an oxygenated biofuel of specific chemical type may lead to aldehydes formation at the low combustion temperatures involved, which are non-existent for a fossil fuel. Also, non-volatile PM linked to high HC emissions may be an issue that will have to be addressed.

Infrastructure

LTC may require changes in the fuel production infrastructure to produce fuels that are of optimum specifications for LTC engines. However, LTC has been also realized with today's fuels by using advanced engine systems. Therefore, there is an investment trade-off between the engine and fuel production industries. This will have to be gradually resolved while LTC gradually matures.

Regarding ICT, LTC does not differentiate over diesel and spark-ignition combustion. In a rather far-fetched scenario, the engine could optimize LTC combustion according to the upcoming driving conditions, if this information were available through ICT. This could lead to even higher efficiency gains.

Costs

Technology

LTC will require advanced sensors and controllers to operate efficiently. Active EGR valves/pumps, variable valve timing and lift, advanced software for combustion control, and others, are systems that will have to become popular for efficient LTC implementation. On the other hand, LTC is expected to be much simpler in its aftertreatment needs, with an oxidation catalyst replacing complex DPF and SCR systems. Hence, LTC technology costs are expected to lie in-between spark-ignition and diesel engines. When/if used to replace heavy duty diesel engines they could actually constitute a cheaper option to diesel combustion with advanced aftertreatment.

Externalities

LTC pollution is expected to be at the same or even lower level than spark-ignition combustion because of the lower GHG emissions produced. Hence, this is expected to result to lowest overall external costs that can be achieved for ICEVs and similar to the hybrid vehicle levels.

Customer perception

LTC does not require any particular behavioural changes from the driver. However, the vehicle will have to be as much as possible driven in steady speed for fuel economy benefits to maximize. Given that the cost is expected to be higher than a conventional spark-ignition engine but, most probably, lower than a diesel engine, the customer decision will be largely affected by the trade-offs between initial investment and operational costs.

3.2. ICE/Electric Hybrid Vehicles (HEV)

3.2.1. Hybrid

Also referred to as "Parallel Hybrid", "Full Hybrid" or "Strong Hybrid".

Technology description

The fundamental difference of a hybrid vehicle compared to a vehicle only powered by an internal combustion engine (ICE) is that the former combines both an ICE and an electrical motor to power the wheels. In a strong hybrid vehicle, the electric motor and an internal combustion engine are connected in parallel and can both deliver power to the wheels. Also, the electrical motor is of sufficient power (> 50 kW) to move the vehicle at urban conditions, without the need of the engine operating. Hence, a strong hybrid may operate on an all-electric mode at least up to a certain speed and for a given mileage. Such vehicles use a single energy source, i.e. a liquid or a gaseous fuel, with an intermediate storage for electric power. Spark ignition engines are easier to start and stop than compression ignition ones due to their lighter construction; hence they are preferred for hybrid vehicle ICE applications.

The power flow may differ according to the hybrid vehicle configuration. In a full hybrid, the engine and the motor are connected in parallel by a differential gear that delivers the power to the wheels. Energy to the engine is delivered by the on-board fuel. Energy to the motor is delivered by an on-board battery.

Over accelerations then both the engine and the motor provide power to the wheels. Hence, during acceleration the battery operates in a charge depleting mode. Under steady state conditions it is mostly the engine that powers the wheels. Some of the engine output power may also be used to charge the battery, if this is required. This is achieved by a generator which is packaged together with the engine and is also connected to the planetary gear. The battery may be also charged during mild decelerations, when instead of applying the brakes the generator is used to convert the kinetic energy to electrical power. Mechanical brakes are used in emergency braking and to bring the vehicle to a complete stop.

Fuel efficiency gains in a hybrid vehicle are achieved by having the engine operating at quasi steady state and using the highly-efficient motor to assist during transients. The engine of HEV may actually be optimized for higher efficiency than the engine of a conventional vehicle. This is because the ICE on a hybrid vehicle needs to operate over a narrower speed and load range, as it can be assisted by the motor at low and high power conditions. Two more sources of efficiency gains over a conventional vehicle include regenerative braking and by having the engine stopped instead of idling when the vehicle is not moving. Overall efficiency gains achieved are in the order of 20-35% over a normal petrol vehicle of equivalent specifications [27]. Benefits are higher over urban conditions due to the frequency of transients and they significantly decrease for highway operation.

Application range

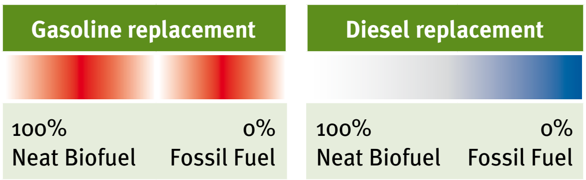
0.3	1	0.5	0.7	0.1
PTWs	Cars	LCVs	Busses	HDTs

A hybrid system is heavier than a conventional ICE due to the weight of the motor/generator, the battery, and power electronics. Hence, it is not suitable for small vehicles, like PTWs. It is very well suited for medium and large sized cars. It may be also used for LCVs. However, these are mostly powered by diesel engines to benefit from the high torque and high overall efficiency and low maintenance costs. Hence hybrid petrol systems have not found their way into this vehicle segment.

Hybrid busses have started to appear and have been shown to achieve fuel consumption improvements of up to 30% [28] compared to conventional diesel ones. This is because urban busses need a large engine mostly to benefit from the high torque during acceleration from stop. If an electric motor is used to assist the engine, then the latter can be significantly reduced in size thus reducing fuel consumption. Hybrid busses may also offer significant air pollutants emission and noise benefits, which are particular health concerns and nuisance factors in the vicinity of bus stops [29]. The disadvantage is that a hybrid system increases the cost of the vehicle to a point that makes it hardly economical compared to a conventional diesel one. Maintenance and associated costs as well as battery durability over the lifetime of the vehicle (often in excess of 1 million kilometres) are also limiting factors.

Finally, hybrid systems are not viable options for long-haul heavy-duty trucks operating on highways. This is because there is not much transient operation in these cases therefore the activity of the motor is limited. HDTs where hybrid systems may be relevant are HDTs operating in cities, such as refuse vehicles.

Biofuelling possibility



Hybrid vehicles need an internal combustion engine which practically has the same limitations regarding biofuel possibilities as in conventional vehicles. Since hybrid cars are mostly equipped with petrol engines, high blends, such as E85 can be used to achieve further CO_2 emission reductions. Such vehicles require careful optimization to match the motor operation to the engine power output variability, depending on the fuel used. With regard to diesel biofuelling possibilities, the same limitations present in conventional diesel vehicles also apply in this case.

Energy

Efficiency

A strong hybrid car offers efficiency gains in the order of 20-35% compared to a conventional car, especially in urban driving. Gains in highway are much limited or even non-existent compared to a diesel car of similar specifications. Diesel busses have been found to offer fuel reductions of up to 30% compared to conventional ones.

Security

Hybrid vehicles mostly operate on fossil fuels and can use biofuels with the same limitations as conventional vehicles. Therefore, their impact on energy security is only marginal, mainly through their contribution in the reduction of total fuel consumed.

Lifecycle impacts

GHGs

Hybrids need more energy to build due to the larger number of components involved in their construction than conventional cars. In particular, batteries are a significant energy consuming component. Approximately 31% of total GHG emissions of a hybrid vehicle are generated by its production, compared to 23% for a conventional petrol vehicle. However, the overall lifecycle CO2 emissions of hybrid vehicles continue to be ~15% lower than conventional ICE vehicles [30].

Materials

A hybrid vehicle requires more materials to build than a conventional vehicle. Batteries require Li or Ni to build which are both rather expensive materials of limited resource. Motors require copper for their wiring and different rare-earth materials for the permanent magnet, such as Neodymium and Dysporsium. The availability of such materials for mass production of hybrid vehicles is still an open issue. Alternative materials are being sought to decrease dependence on rare earths for electric motors. Recycling procedures for these materials have been in place, however limited data on the efficiency and cost of these procedures are currently available.

Air pollution

Regulated pollutants

Hybrids score better than conventional vehicles in emissions of regulated pollutants. This is because most of the pollutants in a conventional engine are produced during transient engine operation. Decreasing transients and operating the engine at quasi steady state has a positive impact on regulated pollutant emissions. In fact, petrol hybrids are among the cleanest commercially vehicles available in all regulated pollutants [31].

Non-regulated pollutants

Not many measurements of non-regulated pollutants have been conducted on hybrid vehicles. However, it is expected that, for the same reason as regulated pollutants, emissions of non-regulated ones are decreased compared to their conventional counterparts.

Infrastructure

There are no additional infrastructure requirements for hybrid vehicles compared to conventional ones. However, maintenance costs are expected to be larger and dealers' workshops need more training than for conventional vehicles. Hybrids may offer greater advantages than conventional vehicles when combined with advanced ICT systems. For example, optimizing the battery state of charge (SOC) level according to the conditions expected to be met during driving can be a way to further reduce CO_2 emissions. Advanced electronics carried onboard by hybrid vehicles may allow easier communication with the infrastructure.

Costs

Technology

Hybrids require much more R&D than conventional vehicles and are associated with higher manufacturing costs. A typical range of premium that the customer needs to pay to purchase a hybrid car is in the order of € 1900-5150 (€/$=1,3) [32]. However, because of their lower fuel consumption, this additional cost can be paid back, especially in cases where the vehicle covers long distances over the year. With the current high fuel prices we experience in Europe and assuming that a vehicle is run for about 15 Mm per year, this cost may be covered as soon as within 4-5 years after purchasing.

Externalities

A hybrid vehicle results to lower air pollutant and greenhouse gas emissions and has a positive impact in reducing the external costs of transport. A study conducted in US [32] demonstrated that a hybrid vehicle leads to a reduction of external costs in the order of 0.20$/gallon (range 0.05-0.50) which amounts to ~7.5 c€/lt consumed. Furthermore, Ogden et al [16] estimated that total societal costs (capital, use, and external) of a spark-ignition hybrid vehicle are roughly € 2300 (€/$=1,3) less than costs of a conventional spark ignition vehicle, despite the 14% higher manufacturing cost of the former. Most of the benefit comes from the reduction of air pollutants and then GHGs.

Customer perception

Hybrid vehicles are generally known to the public as being low emitters and low fuel consumers. However, there is still some reluctance in buying a hybrid vehicle, mostly as an effect of the higher purchase cost but also some concerns on maintenance cost and durability. A study in 2006 showed that hybrid car buyers had a significantly higher household income and education level than buyers of conventional cars [33]. They rated fuel consumption and technology higher at the expense of other criteria, such as brand preferences and design. It was concluded that hybrid vehicles were still mostly bought by consumers from the early adopter segment of the market and that hybrid technology had not yet entered the majority market. This trend may be gradually changing, especially for buyers of large and expensive cars where hybridization offers significant cost benefits. However, it still remains so for the low cost vehicle market and can be a potential barrier in the significant uptake of hybrid cars.

3.2.2. Mild Hybrid

Technology description

A mild hybrid shares several similar components to a full hybrid vehicle. Similar to a full hybrid, it combines an ICE and an electric motor which are connected in parallel to provide power to the wheels. The motor can also act as a generator that can charge the battery from the engine, whenever this is needed, or by utilizing kinetic energy during decelerations. The motor is also sufficiently strong to allow intermittent engine operation, i.e. employ a start-and-stop policy in traffic lights and in congestions.

However, there are also key differences compared to a full hybrid system. First, the electric motor is of a size (< 15 kW) that cannot be used as the only power source to the wheels. Therefore, there is no pure electric mode available for the driver to select. Because of the smaller motor, this is only used in rather strong accelerations to assist the engine. Hence, it acts mostly as a means to increase the power to the wheels rather than a buffer to absorb transients from the engine, as in the full hybrid operation. Because of the differentiated role, power electronics and control devices are simpler, lighter, and more economical than in a full hybrid vehicle. Finally, battery capacity is reduced compared to a full hybrid.

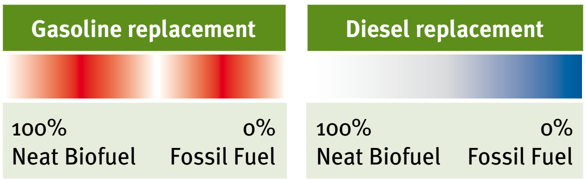
A mild hybrid offers fuel efficiency improvements by using a downsized engine compared to a conventional vehicle of similar specifications. Further efficiency gains are obtained by implementing regenerative braking and engine start-stop. Due to the least frequent use of the motor, efficiency gains are smaller than a full hybrid vehicle. A mild hybrid offers a 10-20% benefit compared to a conventional SI vehicle. On the other hand, its price is in between the conventional and the full hybrid vehicles. Hence, a mild hybrid can be considered as a good compromise between efficiency gains and investment cost.

Application range

0.6	0.8	1.0	0.6	0.2
PTWs	Cars	LCVs	Busses	HDTs

A mild hybrid system is generally more versatile than a full hybrid one, requiring less space and also weighing less. As a result, it can be installed in a wider range of vehicle types than a full hybrid, potentially also including motorcycles. However, weight and balance are always issues with motorcycles and the addition of additional components on the vehicle is not a preferred measure. Small spark-ignition LCVs may be a better category to apply mild hybridisation because their frequent start and stops could be better served by such a system, however without inducing the high investment costs of a full hybrid system.

Biofuelling possibility



Similar to full hybrids, mild hybrid systems need to respect the same limitations of biofuels use as conventional vehicles. Mild hybrids are mostly SI, hence an emphasis is given on E85 blending. For CI mild hybrids, low blending with biodiesel (B5-B7) is more relevant.

Energy

Efficiency

Mild hybrids achieve moderate efficiency gains compared to SI cars of similar specifications, which lies in the order of 10-20%. The efficiency of an SI mild hybrid is therefore comparable to that of a CI vehicle, albeit with somehow better performance. This applies both to the family car sector (i.e. 1.4-1.6 l engine) and to the luxury car sector.

Security
Similar to full hybrids, mild hybrids need a conventional type of fuel to operate (i.e. petrol, diesel, LPG or CNG) – hence their impact in energy security is mostly through the moderate decrease of energy consumption they result to.

Lifecycle impacts

GHGs
The production of a mild hybrid requires more energy and results to more GHG emission than a conventional SI car, due to the energy required to manufacture the additional components of the engine. Similarly a CI vehicle requires more energy to manufacture than the SI car due to the stronger construction of its engine. Due to the fact that running CO_2 emissions of a mild SI hybrid and an equivalent CI vehicle are approximately equal, it is expected that there is not much difference in the lifecycle GHG emission between the two concepts.

Materials
A mild hybrid is more in need of expensive materials than a conventional car, again due to the need to build the battery, the motor and the control and power electronics. Therefore, it requires rare earth components for the manufacturing of the motor, Li or Ni for the batteries, and copper for the wiring of the motor and the electrical system. The quantity of materials is less than a full hybrid due to the smaller size of the individual components.

Air pollution

Regulated pollutants
A mild hybrid is expected to perform similarly or moderately better than a conventional car due to the smaller exposure of the engine to transients. This benefit is proportionally smaller than for a full hybrid. However, in this respect, a petrol mild hybrid can be considered a much lower emitter than a diesel car of similar performance and consumption.

Non-regulated pollutants
Again, emissions of non-regulated pollutants should be comparable or slightly better than conventional cars.

Infrastructure

No particular infrastructure development is required to promote the application of mild hybrids. Potential benefits that can be obtained by means of communication with advanced ICT systems are moderate as there is limited flexibility to operate the vehicle by the motor alone.

Costs

Technology
Costs to manufacture mild hybrids are higher than conventional vehicles due to higher R&D investments and manufacturing costs of the additional components. Similar to the full hybrid, additional costs are heavily dependent on material costs, such as copper, rare earths and Li.

Externalities
The external cost benefit of a mild hybrid lies between the one of a conventional car and a full hybrid. Compared to a petrol car, the reduction in external costs mostly comes by the moderate reduction in CO_2 emissions. Compared to a diesel car of similar in use CO_2 emissions, the reduction in external costs mainly comes from the reduction in regulated pollutants, primarily NO_x. Therefore, a mild hybrid appears to lead to a net reduction in external costs compared to both the conventional SI and CI concepts.

Customer perception

Mild hybridization is offered to vehicle models which are also sold as conventional ones. Their price is also comparable to their conventional counterparts, hence they are promoted as better performers and lower consumers than conventional models. Customer perception for such vehicles is expected to lie somewhere between full hybrid and conventional vehicles. For luxury cars offered as mild hybrids in Europe, the option to go for the diesel equivalent seems also desirable. However, this is not the case in US, where diesel cars are only a small fraction of the stock.

3.2.3. Plug-in Hybrid (PHEV)

Also referred to as Parallel Plug-In Hybrid

Technology description

In a Plug-In Hybrid vehicle (PHEV), the primary energy sources are both a liquid fuel and electricity from the grid. Electricity is provided to the vehicle through an adapter that connects the vehicle to the mains. The main configuration of a plug-in hybrid is similar to a full hybrid vehicle. Hence, power to the wheels is provided both by the internal combustion engine and by an electrical motor. All other functions of the full hybrid vehicle (regenerative braking, start-stop, engine configuration) are present in a PHEV vehicle as well.

The main difference between a strong HEV and a PHEV with regard to their architecture is the larger battery and the larger size of the electric motor in the latter. This is because the vehicle can be directly powered with electricity from the grid. This new energy source can be used not only as a buffer to fill in power to the engine during transients but also as a prime mover of the vehicle. In a commercial PHEV launched in 2012, an all-electric mode can be obtained for speeds up to 100 km/h and for a distance of about 20 km, compared to a full hybrid where maximum electric mode speed in 40 km/h for a distance of a couple of kilometres. Once the battery is discharged to a certain low level then the vehicle shifts to a typical hybrid mode where the motor is only used to assist the engine in transients. It is therefore clear that the true efficiency of a plug-in hybrid will depend a lot on the actual driving patterns involved. The all-electric vehicle operation will be more frequent the shorter the trips are, i.e. for typical urban driving. On the contrary, the benefits of this configuration diminish for long trips.

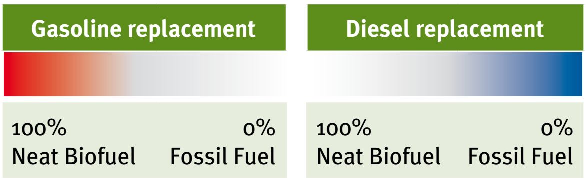
In current PHEVs, the full charging of the batteries from the mains lasts for a few hours. The vehicle is not drivable during this period. The need for recharging also raises some infrastructural requirements and in particular the existence of mains outlets where the PHEVs park. Private parking spaces are available in the suburban US, however this is not common in a European urban context. Hence, a network of publicly available outlets needs to be developed before plug-in hybrids become widely available. Charging schemes will have to be developed and security and safety measures will have to guarantee that no electric power hi-jacking takes place during vehicle charging.

Application range

0.3	1	0.5	0.3	0.0
PTWs	Cars	LCVs	Busses	HDTs

Plug-in hybrid systems have only appeared for passenger cars so far. With an electric mode range of ~20 km, possibilities to introduce this technology to different vehicle technologies are limited. For example, busses run for a few hundred kilometres per day and the electric-only mode would represent only a very small fraction of this, to justify the additional cost and weight. This is even more so for heavy duty trucks. Plug-in EV could still be useful for delivery vans which execute small trips with many intermittent stops. In this case, the electric mode would be highly beneficial. One may consider that plug-in hybrids may be extended to other modes if the energy density in batteries increases so a larger range can be accommodated and/or if charging time decreases. For example, plug-in would be a valid option for a bus if charging can take place at the bus depot within a few minutes (e.g. 20 minutes).

Biofuelling possibility



Currently available plug-in hybrid vehicles encompass a spark-ignition engine rather than a diesel one, because this is easier to start and stop due to the lighter construction. Hence, biofuelling should be mostly seen as a replacement of fossil gasoline fuel rather than diesel. In case of diesel biofuelling, the typical limitations of high biodiesel blend should also be considered. Some plug-in hybrid concepts operating on neat ethanol or methanol fuels have also appeared. A plug-in hybrid, equipped with a large electric motor can theoretically operate without problems in neat ethanol. The problem with neat ethanol in conventional vehicles is that does not evaporate as easily as gasoline at low temperatures and this makes engine start difficult in cold weather, before the engine warms up. Theoretically, this can be avoided in a plug-in hybrid, assuming that the motor may assist the engine to start while in parallel providing power to the wheels. Hence, neat ethanol and methanol may be used as fuels. Methanol in particular could lead to a higher engine efficiency by cooling the intake charge, therefore leading to a higher overall efficiency.

Energy

Efficiency

The calculation of the real-world efficiency of a plug-in hybrid vehicle is a complex problem that depends on a number of independent variables. The most important ones is the actual daily driving pattern, which greatly determines the ratio of electric vs. fuel energy which is used by the vehicle. There have been several publications available, trying first to decouple the two processes, and second to quantify the impacts of upstream and downstream production on the overall energy efficiency of a plug-in hybrid vehicle.

With regard to vehicle efficiency, Samaras and Meisterling [34] estimate plug-in hybrids to be 32% more efficient than today's passenger cars. In general, a PHEV should be rather equally efficient to a strong hybrid with their exact ratio depending on the mean annual driving pattern. For example, Varnhagen et al. [35] showed that the efficiency of a plug-in hybrid vehicle with an electric-only range of 20 miles is more efficient in 15-mile and 400-mile trips than PHEVs with a longer range (40, 60 miles) because it is lighter. PHEVs with an electric only range of 40-60 miles appear most efficient in trip distances between 30 and 150 miles. In a similar analysis, Nemry et al. [36] estimated that over a 50-km trip, PHEV vehicles of sufficient electric range have even higher overall efficiencies even than a fully electric vehicle.

The trade-off between increased battery weight and energy conversion efficiency improvement is what determines the efficiency ratio of a plug-in hybrid compared to a conventional passenger car and a strong hybrid.

Security

PHEVs may contribute to energy security by shifting energy demand from imported fossil fuels to domestic electricity production, ideally by introducing renewables in the national energy mix. This is one of the primary goals of introducing electric power as a primary energy source in the road transport sector. Second, similar to full hybrid vehicles, PHEVs reduce energy consumption in comparison to conventional vehicles and thus decrease total energy demand which is an additional reason for their positive contribution to energy security.

Lifecycle impacts

GHGs

Fully understanding the potential of plug-in hybrids in reducing the WTW CO_2 emissions is a field of active research. In an effort to summarize the current understanding, one should acknowledge the fact that PHEVs currently cannot lead to large overall WTW efficiency improvements and CO_2 reductions over conventional hybrid vehicles. In carbon-intensive societies where coal is used for energy production, PHEVs may actually lead to similar or even higher WTW CO_2 emissions to conventional vehicles. Van Vliet et al. [15] calculated a wide range of WTW CO_2 values for plug-in hybrids, depending on the energy mix available. If electrical energy is produced in coal power plants then PHEVs seem to result to 17% higher WTW CO_2 emissions than conventional hybrid vehicles and only 5-7% lower than conventional diesel vehicles.

On the other hand, PHEVs should be seen as one of the options to electrify road transport, hence as a technical measure to introduce electricity as one of the primary energy sources in road transport. Benefits can be attained if this additional energy requirement is met by the introduction of carbon-free sources for electricity production, such as renewables.

Materials

Plug-in hybrids are material intensive vehicles. A plug-in hybrid is estimated to weight approximately 300 kg more than a conventional car of similar performance. The additional weight is largely determined by the battery size. Most PHEVs launched so far rely on Li-Ion batteries to benefit from their relatively high energy density. Hence, Li is one material that is required in large quantities. Other materials required are similar to strong hybrids, such as copper and rare-earth materials. Due to the larger components involved, plug-in hybrids require even larger masses of those materials than conventional hybrids. The materials availability can be considered currently a limiting factor for the wide penetration of PHEVs in the operating vehicle stock.

Air pollution

Regulated pollutants

The all-electric mode of operation of plug-in hybrids practically results to zero emissions in urban conditions. Some trips in an urban network are expected to be longer than the range of PHEVs and the engine will have to start up during these long trips. Therefore, some emissions will be produced during urban driving. Even when emissions occur, these are expected to be at very low level since – similar to conventional hybrids – the electrical motor contributes during transients and the engine operates in quasi steady-state mode. This results in low emissions from the engine. PHEVs are expected to be cleaner on average than conventional hybrids.

Non-regulated pollutants

Non-regulated pollutants are also expected to be emitted at very low levels, similarly to regulated ones. In case that PHEVs with alternative fuels are developed (such as methanol, ethanol) one will have to consider the emission of aldehydes, especially if the catalyst is not fully warmed up. Actually, a not fully warmed up catalyst may often be the case due to the intermittent character of engine operation in these vehicles.

Infrastructure

Wide penetration of PHEVs in the market will require substantial investments in infrastructure to allow charging of the vehicles in parking spots. Therefore, publicly available charging outlets will have to be installed and networks that can support the high currents involved for charging will need to be expanded. Safety and security mechanisms will also have to be devised to protect health and to avoid hijacking of the power lines. Furthermore, paying protocols will have to be streamlined for all users throughout Europe, to avoid currently occurring cases, where e.g. an PHEV from the Netherlands can not be charged in Belgium and vice-versa.

ICT

Further to the infrastructure issues raised with the need to introduce rechargeable vehicles to the market, significant opportunities also occur. The collective storage capacity of the batteries of all vehicles being charged produces a very large energy buffer that can either be used to store energy when production exceeds consumption or, vice versa, to deliver energy when consumption exceeds production. This vehicle-to-grid (V2G) interaction can be very useful to accommodate the power swings associated with renewable energy production. Rechargeable vehicles can thus inadvertently act as a means to stabilize the power grid and thus allow the increase in the penetration of renewable energy sources for energy production.

Several protocols are currently tested to allow this V2G communication. The vehicle has to be recognised by the grid and the remaining storage capacity and the available charge has to be communicated. Such protocols will also implement information on charging policy, i.e. depending on what time, for how long and at what priority the vehicle is charged. It is not the scope of this summary report to outline in detail the communication needs. However, all rechargeable vehicles are in need of significant ICT investments but also provide opportunities for the grid and power production industry themselves.

Costs

Technology

PHEVs implement expensive technology as they combine a strong internal combustion engine and an almost equally strong electric power system and large batteries. Van Vliet et al. [15] estimated the additional costs of a current PHEV over a conventional gasoline car at k€11.5 with 65% of this for the battery alone. It is not possible to estimate how much cost can be reduced and if it can be reduced. Several of the components require materials for which a quasi-monopoly exists (e.g. Dysprosium for the permanent magnet) hence, if demand increases in the future, prices will go up instead of going down. Cost compression for electrical components is currently an open question in the industry. Also, new materials are being sought that may replace conventional ones. The results of these efforts are not yet evident.

Externalities

Regulated and unregulated air pollutants are very low in PHEVs and this is expected to lead to significant reduction of external costs. CO2 related issues can only be addressed with a reform of the upstream energy production sector. These can be large if V2G protocols are developed that will allow the wider penetration of renewables for energy production. Therefore, PHEVs have the capacity to significantly reduce externalities of road transport. Other issues that have to be addressed include recycling of materials; this is not expected to be a problem when large production volumes are reached due to the high cost of the primary material required to build the electrical components. However, before these large volumes are reached, recycling processes may not be financially attractive and potentially toxic or heavy metal materials may be thrown away unprocessed. External costs may be also assumed if appropriate safety means have not been introduced to avoid risks during recharging, etc. Quantification of the total societal cost of the introduction of PHEVs compared to conventional ICE vehicles is at this stage highly uncertain. Also, this is an area of continuous change as it depends on marginal costs of air pollutant and greenhouse gas abatement, the infrastructure cost to develop the necessary charging network, the delineation of the upstream energy production costs attributed to PHEV energy delivery, etc.

Customer perception

PHEVs require substantial changes in the behaviour of their users to deliver their environmental and energy benefits. A PHEV will have to be recharged after practically every time it has been driven for a few kilometres in order for, the all-electric mode to occur. Otherwise the vehicle will only perform as a typical full hybrid. It is evident that it will take time for the average motorist to adjust to this different driving pattern. It is clear that the environment-aware drivers will feel rather comfortable with the change, recognizing the benefits that this change in behaviour may have on the environment. However, less informed people are not expected to compromise their everyday habits, especially if charging spots are not widely available. Fears for the reliability, safety, and dependability of the new technology should also be expected to act as obstacles in the wide penetration of these vehicles. Several hesitations may be lifted if financial benefits may be established, i.e. if electricity charging is linked to low prices to counterbalance the margin it provides for the penetration of renewables.

3.3. Electric Vehicles (EV)

3.3.1. Battery electric vehicle (BEV)

Technology description

An electric vehicle is technically simpler than a hybrid one as it only involves the electrical powertrain and no internal combustion engine. Energy is stored in batteries in the form of electricity. Upon demand, this energy is delivered to the electrical motor which powers the wheels. A generator combined with the electrical motor charges the battery by recuperating the kinetic energy when the vehicle decelerates. Most commercially available electric vehicles use AC permanent magnet motors, which are relatively lightweight and reliable.

With electricity being the only energy source, batteries of electric vehicles have to be of adequate capacity to deliver a sufficient range. Li-Ion batteries are therefore preferred, due to their high energy density, compared to other types. Commercial applications of BEVs carry batteries with a total weight of 200-500 kg, to achieve ranges that, according to manufacturer estimations, may reach 500 km, i.e. comparable to a conventional ICE vehicle.

In general, the battery package and the linked power electronics is the key element that determines BEV performance. The issues that have to be addressed go beyond total weight and energy capacity of the battery and include, cost issues, longevity, discharge capacity and rate, recharging time, reliability, and performance in low and high temperature conditions. These are all technical challenges that have to be addressed. In principle, even the best battery packages available today cannot compete with even a moderate engine / fuel combination, in none of these aspects. The cost of a medium sized engine is at ~k€1.5 while a battery package can exceed k€10. A diesel engine can provide similar performance for several hundred thousand kilometres while batteries have a degraded performance and practically need to be replaced after 100-150 thousand kilometres. Similarly, an engine can perform without trouble from extreme low to extreme high temperature conditions while battery performance can significantly degrade at subzero and +350C. Finally, while vehicle refuelling takes up a couple of minutes to provide a range of several hundred kilometres, batteries take up to 8 hours to fully recharge to provide an equal range.

Today, even the best electric vehicles cannot compete with typical conventional vehicles. However, heavy technology investments have been made in the area and substantial improvements are expected in the years to come. Therefore, BEVs appear as one of the promising technologies that may alter the road transport energy sector. In particular, they shift a large share of the total energy consumption from the fossil fuel network to the upstream electricity production, which is today seen as the long-term solution to the sustainability of road transport.

Application range

1.0	0.7	0.7	0.1	0.0
PTWs	Cars	LCVs	Busses	HDTs

Current battery packages that can offer sufficient ranges for cars lie in the range of 200-500 kg and cost between k€10-30. Weight can be a limiting factor in expanding this technology to smaller vehicles, such as motorcycles. However, electric scooters are already commercially available, hence this technology can be very favourable for two wheelers performing short trips. It may also be well suited for LCVs. In fact, the first applications of BEVs were small delivery vans where frequent start-stops can be ideally treated by electrical motors. The applicability of the BEV concept to larger vehicles, such as busses and HDTs is less favourable due to the long range which is daily required by such vehicles. Achieving these long ranges would require very large battery packages, with significant impacts in vehicle cost and weight.

Biofuelling possibility

Not relevant for vehicle fuelling. Renewable energy, including biofuels, is only relevant as a source of electricity production. In this respect, the role of renewable energy is significant in meeting the requirements of the 20-20-20 energy package and further achieving sustainability in the road transport sector.

Energy

Efficiency

BEVs' powertrain consists of relatively few components of high efficiency. Electrical motors have an efficiency that may exceed 80% and could reach 90% in ideal operation conditions. Batteries also offer efficiency in the same range. In addition, regenerative braking saves up some of the energy consumed to accelerate the vehicle. Therefore, a typical electric vehicle requires only ~0.15 kWh/km to operate, compared to roughly 0.6 kWh/km required by a conventional petrol vehicle. In principle, BEVs are amongst the most energy efficient vehicles available. They could even become more efficient if higher density batteries are invented so that the vehicle weight drops.

Security

Electricity is used as the sole energy source for BEVs. Since electricity is primarily produced nationally, BEVs can significantly contribute to the improvement of the security of the energy system. Significant benefits may be further obtained by utilizing V2G communication. This way, the storage system of BEVs can be used as a buffer to absorb power swings produced by the operation of renewable energy sources (RES). This can be used to increase the penetration of RES in the energy mix, thus further improving the security in energy supply. In this respect, BEVs are better performers than PHEVs due to their larger battery capacity.

Lifecycle impacts

GHGs

The operation of BEVs results to zero GHG generation from the vehicle. However, the energy required has been produced in power stations, generating a quantity of GHGs. Moreover, the vehicle manufacturing and assembly has also resulted in the generation of GHG at the production plant. The reliable estimation of the GHG production that the operation of BEVs results to is a key issue in assessing the benefits of this significant shift in energy use on the transport sector. Taking into account that the carbon intensity in the various countries is anywhere from ~200 gCO_2/kWh to 1000 gCO_2/kWh and assuming a mean energy consumption of a BEV of 0.15 kWh/km, the mean apparent CO_2 emission currently ranges between 30 g/km and 150 g/km for a BEV, depending on the country it operates on. Assuming that a conventional gasoline vehicle of similar specifications emits roughly 120 g CO_2/km shows that the introduction of BEVs today may have either a positive or a negative impact and should be tackled with extreme care.

In a similar calculation, van Vliet et al. [15] estimated that the apparent CO2 emission factor for a BEV would have been 127 g/km if the energy was produced by a coal fired plan, dropping down to 47 g/km for a natural gas power plant and zero for energy production from wind or solar. Thiel et al [37] estimated the WTW CO_2 emissions from BEV at 60 g/km for the average carbon intensity of Europe in 2010. The WTW emissions of a spark-ignition vehicle, at the same study, was estimated to be 160 g/km. In this case, the benefit of BEV introduction is substantial. The variance in this range indicates that the extent of the benefit that has to be expected by the introduction of BEVs ranges and should always be seen in the wider context of power production mix in each country.

CO_2 produced during manufacturing is an additional source of GHG emission related to vehicles and has to be taken into account in the overall budget. A current study by the Low Carbon Vehicle Partnership [30] estimated that the battery manufacturing process is labour and energy intensive and as a result, a BEV would require 8.8 Mt of CO_2 to manufacture compared to 5.6 Mt for a gasoline car. Although the study is naturally bound to high uncertainties, this range of values shows that the GHG benefits of BEVs over conventional vehicles are further reduced. The same study estimates that the lifetime CO_2 emissions of a BEV are 19 Mt of CO_2 equivalent, compared to 24 Mt for a conventional petrol car and 21 Mt for a hybrid vehicle. This study was performed on the assumption of 500 g CO_2/kWh of electricity production. Results would have been different in case of different carbon intensity.

Materials

BEVs require large quantities of expensive materials to manufacture their electrical components. Similar to hybrid vehicles, there are no yet established procedures to fully recycle all materials of batteries and motors for end-of-life vehicles. It can be expected that such procedures will be developed when production volumes increase, as several of the materials can be reused. Material availability and, in particular, rare earths required for the manufacturing of batteries and electric components is one of the challenges for high volume production of such vehicles.

Air pollution

Regulated pollutants

BEVs emit no tailpipe pollutants during while driven. Emissions may only be produced by material wear. Tyre and brake wear PM emissions factors for conventional cars are estimated at ~10 mg/km in an urban network. BEVs with regenerative braking may emit even lower than this because the application of the mechanical brakes is only done at the late stages of braking only. Not much is known about emissions of copper or other metal materials due to the operation of the motor and any volatilization of material from power electronics. Also, BEVs are expected to contribute as much as conventional vehicles in the resuspension of road dust.

Air pollutants are also produced at the power plants where electricity for BEVs is produced. PM is an issue in coal-fired power plants, otherwise emission of regulated pollutants are rather limited and take place outside urban areas. Moreover, in case the additional energy required by BEVs is met by renewable energy, then air pollutant emissions with the use of BEVs are significantly reduced. In summary, BEVs may contribute to significant reduction of air pollution in urban areas, in addition to their energy and GHGs impact.

Non-regulated

BEVs are not considered to contribute substantially to non-regulated pollutant emissions, although this might depend on the method used for power generation.

Infrastructure

The discussion of infrastructure needs for PHEVs are also valid for BEVs. An expanded network of charging spots will have to be developed to allow the wide penetration of BEVs in the cities and grid expansion will have to take place. New ideas have started to appear for the faster and simpler charging of BEVs, such as contactless (induction) charging, that could even be done while the vehicle is stopped but not parked, e.g. in traffic lights. This is a complete new area of developments with several new ideas appearing.

ICT

V2G communications will have to be established to fully take on board the benefits that can be offered by BEVs. In this way, BEVs operation can be streamlined with energy production by RES, as has been analyzed in the relevant sections of PHEV vehicles. Due to the – on average – larger batteries of BEVs, the level of interaction with the grid will however be more important than in the case of PHEVs. Perujo and Ciuffo [38] estimated that with realistic BEV penetration rates and without proper regulation, BEVs will significantly affect the daily pattern of electric power request in a region. These impacts have to be carefully integrated in the regulatory framework prepared for the widespread introduction of BEVs.

Costs

Technology

Technology and material costs for BEVs are still much higher than for conventional vehicles, which is an established and mature technology. A Li Ion battery is currently estimated at 600-1000 €/kWh [15; 37]. With the assumption that a BEV on average consumes 0.15 kWh/km then the cost of the battery reaches €120-150 per kilometre of range that has to be achieved. Therefore, the total cost of the battery alone is estimated in the range of k€ 24-30 to achieve a range of 200 km. As a result, the total cost of a BEV is regularly two or even three times as high as the cost of a conventional vehicle. Prospects have always been that this cost will come down due to economies of scale and the learning curve effect. However, material costs determine much of the total cost in the production of batteries and other components. This is the same with the case of HEV and PHEV but on an even larger scale, due to larger size of components in the case of BEVs. It is expected that material costs will remain as one of the limiting factors in the further promotion of BEVs.

Externalities

External costs of transport should be significantly reduced with the use of BEVs, in particular if RES are used to produce the additional energy required to power these vehicles. The reason is the significant drop in air pollutants achieved by BEVs and the curtailment of GHGs.

Customer perception

There have been several efforts in the past to promote electric vehicles but have failed as the performance of BEVs could not match the performance of ICEs, in terms of ease of use, range, costs and driving pleasure. There is a renewed effort today to promote BEVs and desirable models have become available; even models with sporty performance and styling. A particular roadster BEV, which is commercially available today, achieves better acceleration figures than the conventional gasoline roadster it is based on. However, it is priced more than twice the price of the original car, it requires several hours to recharge and it has a lower range than the conventional vehicle. Hence, unless the driver is extremely environment aware or the cost of electricity is much cheaper than the cost of fuel, a BEV today can still not compete with a conventional or a hybrid vehicle.

For customers to be persuaded to buy BEVs in large numbers, a number of issues will have to be dealt with, i.e. the costs will have to be reduced, the range will have to be increased, and charging spots will have to become more widespread. This is the reason that forecasting simulation models predict a very limited penetration of BEVs at least until 2020 [39]. On the other hand, BEVs may become more popular if fossil fuel prices increase disproportionally compared to electricity. Moreover, the future will tell whether BEVs will continue to follow the conventional shapes and patterns of ICE cars. New concepts allowed by the flexibility given by the smaller power components and the possibility to assemble batteries in many different shapes will start to appear. Hence, other vehicle factors, such as available space for a given size, looks and aesthetics, and trimming and packaging amenities may be positive factors in accelerating the introduction of such vehicles.

3.3.2. Fuel Cell Electric (FCEV)

Technology description

In a fuel cell, electricity is produced when a fuel reacts with an oxidizing agent. In typical fuel cells used in automotive applications, hydrogen is brought onto the surface of a catalyst (anode) which brakes up the hydrogen molecule into a proton and an electron. The proton travels to the cathode through an electrolyte material which is impermeable to electrons. Hence, the electron has to travel towards the cathode via an external circuit thus producing an electrical current. In the cathode, protons, electrons and oxygen form water which is liberated to the atmosphere. As a result of this process, only electricity and water vapour remain as the final products. Hydrogen is a fuel that can be used in all types of fuel cells due to its simple chemical type and the mobility of protons in the electrolyte. However, other fuels can also be used in a fuel cell, notably methanol has been used in direct methanol fuel cells (DMFCs).

In some FCEV applications, hydrogen is produced on board the vehicle by reforming gasoline. In those, gasoline reacts with steam to produce CO and H_2. CO has to be removed before feeding the fuel cell with hydrogen. This system offers the advantage that vehicles can be powered with hydrogen using the existing petrol fuel infrastructure. However, such a system operates as a mini refinery on board the vehicle adding in complexity, weight, cost and requiring space to be installed.

The electricity produced by the fuel cell is used to power an electrical motor, largely in the same fashion as in BEV applications. Therefore, the powertrain of a FCEV and BEV can be identical with the difference located only on the electricity delivery unit.

The main advantage of a fuel cell in comparison to a battery is that it is not so much confined by capacity limitations. Hydrogen is stored on board the vehicle, typically in high pressure bottles. Current energy density for hydrogen power systems is in the order of 1.5 (kWh/kg system) or 0.9 (kWh/l system) [40]. Typical Li-Ion batteries offer 0.2-0.3 (kWh/kg system). Therefore, the same range of a BEV vehicle can be achieved with an FCEV with 1/5 of the total weight for energy storage. For example, the only commercial FCEV available today has a fuel cell and hydrogen storage system that in total weigh approximately 80 kg to achieve a range of approximately 400 kg. A commercial high-end BEV of similar dimensions requires a battery pack of over 500 kg to achieve the same range. The second advantage of an FCHV is that it can refill within a few minutes, i.e. in approximately the same time it takes to refill a conventional car.

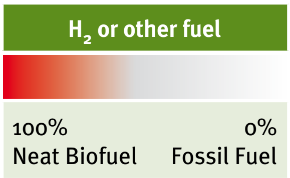
On the other hand, batteries can rapidly deliver higher current outputs, which is not possible by a fuel cell. A fuel cell cannot fully follow the power demand trail of a typical passenger car. Hence, an intermediate storage system such as a battery or a flywheel needs to intervene between the fuel cell and the motor to provide power during peak events. The same intermediate storage device can absorb power during braking to increase the overall efficiency of the vehicle.

Application range

0.5	0.8	0.8	1	0.0
PTWs	Cars	LCVs	Busses	HDTs

Prototype fuel cell cars, light trucks, busses and even motorcycles have been manufactured as demonstrators of the technology. One fuel-cell vehicle is commercially available in California and several small fuel cell bus fleets operate in different parts of the world [41]. Busses offer the best potential for fuel cell applications currently, as they are centrally operated and the new technology requirements can be supported by the trained maintenance staff. Cars and light commercial vehicles also offer a potential. PTWs may have limitations in hydrogen storage safety while trucks would require very large space for fuel cells to provide the power required.

Biofuelling possibility



Fuels (Hydrogen or methanol) for fuel cells can be produced from biomass by means of industrial scale chemical processes. Blending is not an option as the fuel needs to have a rather simple and uniform chemical type for use in the fuel cell.

Energy

Efficiency

Typical fuel cell stacks for automotive applications offer efficiencies in the order of 40-70% [42], with the efficiency dropping as the load increases. The auxiliaries required to feed the fuel cell with fuel and remove the products, as well as power electronics further decrease this efficiency. Schaefer et al. [43] estimated an overall theoretical efficiency of ~60% over a typical driving cycle. A typical diesel internal combustion engine offers real world efficiency in the order of 25-35%, therefore the theoretical efficiency is much better than a diesel engine. NREL [41], based on real-world fuel cell bus application, reports 149% better fuel economy than equivalent CNG busses and 67% better than diesel busses on an energy equivalent basis. A commercial FCEV claims efficiency of 60 mi/kg H2 which corresponds to ~2.2 l gasoline / 100 km. This is ~60% less than a gasoline vehicle of the same characteristics. As a result, the overall efficiency is expected to be much higher than conventional vehicles, much closer to the efficiency of BEVs.

Security

Fuel cell vehicles may increase energy security. Hydrogen may be produced domestically by utilizing renewable energy sources or other energy resources. Also, methanol may be produced by biomass available in each country. In fact, transporting hydrogen to large distances is less economical than producing hydrogen close to the consumption source. However, since neither methanol nor hydrogen are fuels freely available in nature, the production involves significant shifts in the energy mix of each national system.

Lifecycle impacts

GHGs

Calculating the lifecycle greenhouse gas impacts of using hydrogen fuel cells as automotive propulsion systems is largely depended on the energy pathway utilized to produce hydrogen. According to JRC analysis [12], H_2 production may achieved with a range of technologies, some of them being some 40 times as carbon intensive as current gasoline fuel production. Similarly, Jaramillo et al. [44] estimated that coal-derived H_2 may lead to total GHG emissions of up to 500 g/km, compared to some 180 g/km for a conventional gasoline vehicle. This clearly removes any benefits that the use of hydrogen as a fuel could bring. In real terms, Lipman and Delucchi [45] estimate an overall GHG benefit in the range of 25-50% over a conventional car. On the other hand, Garrain et al. [46] provide a summary of a number of relevant studies and demonstrate that overall GHG benefits of FCEVs over ICEVs range substantially, depending in the assumptions carried out. In summary, calculating the GHG benefits of introducing H_2 FC vehicles is even more uncertain than electric vehicles, due to the even wider selection of energy pathways available to produce H2 than electricity.

Regarding vehicle production, Sorensen [47] estimated that GHG emissions of a fuel cell vehicle exceeded GHG emissions during the production of a conventional car by roughly 70%. Schaefer et al [43] estimated approximately equal quantities of GHGs produced in the manufacturing of typical gasoline and fuel cell vehicles. Hence, such estimates are quite uncertain and methods may improve if larger economies of scale develop.

Materials

Manufacturing a fuel cell is material intensive. Proton exchange membrane (PEM) fuel cells are the most widespread systems for automotive use. Mehta and Cooper have reviewed the materials and manufacturing options for PEM FCs [48]. Synthetic materials are required for the membrane manufacturing, precious metals for the catalyst, permeable and semi-permeable layers which are mostly carbon-based, and finally casing and packaging materials. All such materials are unknown to the current vehicle manufacturing industry, and significant changes in the industrial infrastructure will be needed to accommodate the new propulsion powerplants. With regards to cost and availability, precious metals may be a component increasing the cost and decreasing the price flexibility of FCEVs.

Air pollution

Regulated pollutants

Fuel cell vehicles powered by hydrogen result only in the production of water vapour and no other pollutant. Gasoline reforming vehicles may lead to the production of CO in case that the CO scrubber system underperforms. However, these vehicles are not expected to become widespread. Hence, no regulated pollutants are expected to be emitted by fuel cell vehicles. Similarly, methanol fuel cells may result in emissions of some pollutants. However, these are expected to be at trace levels only.

Non-regulated

PM emissions from component attrition should be the only non-regulated pollutant from hydrogen fuelled fuel cell cars. In general, such vehicles are not expected to result to significant quantities of pollutants emitted.

Infrastructure

The infrastructure development is the most significant obstacle in the widespread application of fuel cell vehicles. Hydrogen production facilities, transport of hydrogen and refuelling stations will have to be widely developed. Production lines of vehicles will have to be completely overhauled. Moreover, safety protocols and procedures will have to be developed. Due to some individual hydrogen properties (high diffusivity and low molecular size) the materials and procedures for the transport and storage need to be more advanced than gasoline ones.

ICT

No significant ICT benefits of FC vehicles over conventional ones may be identified. This is different to battery electric vehicles, where the storage of energy as electricity allows significant vehicle to grid interaction.

Costs

Technology

Current manufacturing costs for FC vehicles exceed costs of conventional vehicles by a great margin. A report in the framework of the NextHyLights project [49] estimates the capital cost of a fuel cell bus to M€1.3-1.8 compared to less than M€0.2 for a conventional diesel one. Although economies of scale may lead to a reduction of this cost, material needs mean that this cost cannot be compressed to conventional vehicle levels. Even under the most optimistic scenarios in and a post-2020 horizon, the cost remains more than 50% higher than conventional busses.

Externalities

External costs of fuel cell vehicles are expected to be very low, due to the limited or even zero air pollutant production. Their external cost is mostly determined by the method used to produce hydrogen (or methanol if this is used as a fuel). Ogden et el. [16] report a reduction in external costs by FCEV that may exceed 90% of the costs of advanced gasoline ICE vehicles, i.e. a drop from €1500 per lifetime to less than €150 per lifetime (€/$=1.3), when hydrogen is produced by offshore wind electrolytic production. However, external costs are reduced by only 35% when hydrogen is produced by coal.

Customer perception

Hydrogen storage can provide vehicle ranges which are comparable to those of fossil fuels. Also, refuelling patterns are no different to conventional fossil fuels. Vehicle performance may actually be better than internal combustion engines due to lower noise, negligible vibrations and good torque characteristics. The two limitations of wide FCEV market penetration from a customer perspective are the zero infrastructure development and safety concerns. Availability of hydrogen in many fuel stations will be necessary. Also, the need of carrying fuel at high pressure is by many very negatively perceived due to safety concerns both during normal use but also in case of accident. The industry will need to heavily invest in both achieving a high safety level and also persuading the public opinion about the safety of such vehicles.

3.3.3. Electric vehicle with ICE range extender (ICEREV)

Technology description

One of the main problems of battery electric cars is the limited range due to the low energy density and increased cost of batteries, which limit the maximum battery size that can be carried on board the vehicle. A solution to this problem is to store energy in a different form and then produce on-board electricity when required to either charge the batteries or directly power the electric motor. This on-board energy storage and conversion system is being established as a “range extender”, i.e. a system that can extend the vehicle operation range between refuelling.

A conventional fuel tank and an internal combustion engine coupled to a generator may play the role of such a range extender. When needed, fuel is consumed by the engine to power the generator and produce electricity. This can be either used to recharge the batteries or to produce current to directly power the electric motor of the car. Hence, this type of system decreases the total size of the batteries both because their total energy capacity can be reduced and because the max current from the batteries may be limited. The engine is more or less a conventional engine for automotive use. However, it is usually smaller and optimized for steady state operation as it is used as a generator rather than a propulsion system for the car. Some applications use a gas turbine instead of a reciprocating engine as a range extender [50]. A gas turbine offers higher power density than a reciprocating engine and higher efficiency. However, cost, safety and drivability concerns may be an issue. In any case, this is an area of increasing interest for the future.

Such a vehicle technology is refuelled at a gas station in the same manner as a conventional car does. In addition, its batteries can be recharged with electric grid power. Such a vehicle has been commercialized under a different brand name in both US and Europe. This vehicle has an all-electric range of ~60 km, depending on driving style. The range extender engine increases this to ~500 km. The vehicle’s batteries can be recharged every time the vehicle is parked. Depending on the trips performed (i.e. daily trips of 60 km or less) the vehicle may operate as a neat electric vehicle.

An electric vehicle with ICE range extender may be confused with a hybrid vehicle, since their powertrains are built of more or less the same components. A range-extender type of system is sometimes referred to as a “series” hybrid [51], as opposed to the “parallel” hybrid, to denote that power is always transferred through the electric motor of the system. However, based on the definitions adopted in this work, a range-extender electric vehicle is a better terminology for this technology. The vehicle is pure electric, because power to the wheels is provided only by the electric motor.

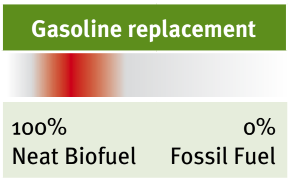
Due to the similarities between a plug-in hybrid and an electric with range extender vehicle type, many of the indicators receive a similar score and assessment between the two technologies. Hence, the evaluation of this technology is mostly done in comparison with a plug-in hybrid to identify the main performance differences of the two technologies.

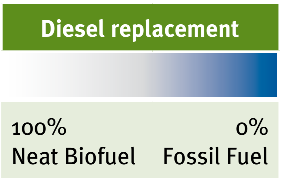
Application range

0.3	1	0.7	0.5	0.0
PTWs	Cars	LCVs	Busses	HDTs

Electric with ICE range extender may offer some better characteristics than the plug-in hybrid configuration because it has relatively larger battery capacity so it can be used for longer all-electric range. Therefore, it may be extended to other vehicle categories such as busses and light commercial vehicles. It still does not appear as a good candidate for trucks, which operate for daily distances much longer than 50-60 km, that is the all-electric range.

Biofuelling possibility





A spark ignition engine may be better suited as a range extender due to its lighter construction, smoother operation and better start-and-stop characteristics, as is the case with plug-in hybrids. Hence, limitations about biofuelling of spark-ignition engines are present here. On the other hand, the motor cannot be used to assist the engine, therefore higher ethanol blends cannot be used, as is the case with plug-in hybrids. Diesel range extenders will most possibly start to appear. These again have limitations for biofuelling. However, their more or less steady state operation means that they could be optimized to operate on higher biofuel blends, if necessary.

Energy

Efficiency

On average, the efficiency of an ICEREV vehicle should be similar to a PHEV, as they consist of the same components. Differences will occur because of the power flow and the component size in the two applications. These differences are not straightforward and will also depend on the efficiencies of the individual components of the two systems. Imai et al. [52] attempted a comparison between the plug-in hybrid and range extender systems and found out that their relative efficiency is greatly affected by the driving pattern and trip distribution. Van Vliet el al. [13] estimated 44% better efficiency for a series diesel hybrid (the equivalent of an electric with diesel range extender) than a conventional diesel car, which is in the same range as a PHEV. However, only real-world evaluation of actual vehicles can provide a realistic answer. Therefore, as a general rule, ICEREV vehicles may be assumed to be at least 30% more efficient than today's conventional gasoline passenger cars, with the possibility that this can greatly increase for short trips and frequent recharging patterns. Tank-to-wheel efficiency improves the shorter the trip becomes as this will mean less and less frequent operation of the range extender.

Security

ICEREV shift energy demand from fossil fuels to electric power which is positive regarding the energy security, in a similar fashion as PHEVs.

Lifecycle impacts

GHGs

In an ICEREV, CO_2 emissions are only linked with the source of electricity production in all-electric mode, over short trips. In this case, they perform as typical battery electric vehicles so their WTW CO_2 benefit will be similar to a BEV. Hence, in urban driving, their GHG emission benefit will largely depend on the carbon intensity of the electricity production in the area of operation. Depending on the frequency of longer trips, i.e. trips extending beyond the all-electric range, there will be on-board CO_2 production. The efficiency of the energy conversion in this case would be just marginally better than the efficiency of a typical spark ignition vehicle. The engine efficiency as a range extender will however be better than a propulsion engine because it operates under optimized steady state conditions. Still, the power produced will have to be converted in the generator, the power electronics and then the motor, before it reaches the wheels, thus compromising overall efficiency.

There has been no real-world evaluation of commercial range-extender vehicles to appreciate their true GHG emissions. In simulations with a range of approximations and assumptions for power production energy intensity and conventional vehicle consumption, Van Vliet et al. [13] estimated some 34% lower WTW CO_2 emissions by a diesel range extender vehicle, compared to a conventional diesel one. In any case, similar to plug-in hybrids, ICEREV should be seen as a potential pathway to electrify road transport. Hence, their penetration should be combined with renewable electricity production to maximize CO_2 benefits.

Materials

ICEREV are material intensive, similar to plug-in hybrids. Due to their extended range, they are also in need of a larger battery pack than plug-in hybrids. Material availability may be an issue for the wide deployment of such a vehicle fleet.

Air pollution

Regulated pollutants

Minimum or even zero air quality impact is expected in urban conditions, assuming that the batteries are frequently recharged so that the all-electric mode can be sustained. In extra-urban conditions, air quality is less of a problem. However, even in these conditions, the engine is expected to operate under steady state hence emission levels should be low. One possible issue is cold-start, assuming that the engine operates under intermittent operation so it might occur that more than one cold-starts are encountered under typical operation. Advanced thermal management of the engine and aftertreatment system will be required to get around this potential issue.

Non-regulated

Similar to plug-in hybrids, non-regulated pollutants emissions may be a potential problem, especially for ethanol blend fuelled vehicles and intermittent cold-start operation. No measurements or real-world evidence of the extent of this particular issue is available for ICEREVs.

Infrastructure

ICEREV and PHEVs require the same substantial investments in infrastructure to enable their wide deployment. In fact, the longer all-electric range of ICEREVs means that they are even more depended on the availability of recharging stations than plug-in hybrid vehicles to deploy their environmental and energy efficient benefits. Until this infrastructure develops, ICEREVs should be expected to represent only a niche in car technologies.

ICT

Similar to plug-in hybrids, vehicle to grid communication can provide benefits both to the road transport GHG performance but may also offer the needed flexibility to the grid to accommodate power fluctuations by renewable energy production.

Costs

Technology

The technological and material costs are still high for this technology. The only range extender vehicle available in Europe today costs more than twice as its conventional counterparts. R&D, assembly and material costs are all much higher than a conventional car. Although R&D and assembly costs are expected to drop, this may not be the case for the material costs, which depend on material availability and commercial pricing strategies rather than economy of scale. In fact, increase in the needed quantities of some materials will shift their prices up and not down in the future. As a result, price reduction should not be expected for such vehicles, at least not in the near future.

Externalities

ICREVs should be expected to decrease total externalities of road transport over conventional vehicles, because of significant reduction of air pollutants and moderate to high reduction of greenhouse gases. As is the case of plug-in hybrid cars, it is not possible to estimate the exact benefit because this depends on local conditions and driving patterns.

Customer perception

In order to benefit from all electric vehicle mode, a range extender vehicle will have to be charged practically every time it is parked or, at least, every time is parked at home or office for a typical home-to-work commute. Compared to a plug-in hybrid of today, a range extender is expected to have a longer all electric range, which means that it could be better perceived by a potential customer. The charging patterns required, together with higher purchase costs and no track of real-world performance and durability means that only special customers will wish to obtain such vehicles in the near future.

3.3.4. Electric vehicle with fuel cell range extender (FCREV)

Technology description

This technology shares the same concepts with an ICEREV. However, the range extender in this case is not an internal combustion engine but a fuel cell system that delivers electric power directly to the electric motor of the car or to the batteries in order to recharge them. Similar to the ICEREV, this kind of configuration uses two different sources as primary energy providers, direct electric power from the grid to recharge the batteries and a fuel to be converted in electricity by the fuel cell.
Such a configuration offers technology advantages over both the FCEV and the BEV. The FC offers the extended range, which is not possible or very expensive by batteries alone. Also, the FC operates under quasi steady state conditions, while batteries take care of the power surges when this is required. The whole system may be optimized to reach higher cost-effectiveness than either the FCEV or the BEV can offer.

In such an application, the FCEV can operate either directly on hydrogen or with a hydrocarbon fuel, by implementing an on-board reformer. In fact, there is a better possibility to implement a reformer in such kind of application than in an FCEV because the size of the FC in an FCREV can be smaller than in an FCEV, which also decreases the size of the reformer.

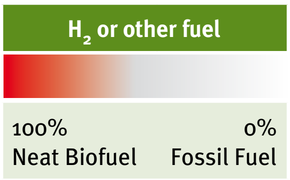
The major disadvantage of this technology is the high complexity and the technology and material costs associated with its realization. Moreover, a FCREV operating on hydrogen requires the development of two different infrastructure networks not available today, namely electric charging stations and the hydrogen network.

Application range

0.3	0.5	0.5	1.0	0.0
PTWs	Cars	LCVs	Busses	HDTs

A FCREV configuration seems most appropriate for transit busses, which are centrally operated and maintained, hence the twin infrastructure (H_2 and charging stations) will be easier to deploy in this case.

Biofuelling possibility



As with the non-hybrid application of fuel cells, neat biofuel seems as the better option in order to have a uniform chemical type of the fuel. In this case, H_2 can be considered as a biofuel when produced by a process involving biomass or other RES.

Energy

Efficiency

The efficiency of an FCREV should be similar to a BEV or an FCEV and would little depend on whether the battery or the fuel cell is used for power delivery to the motor, as they both exhibit more or less the same efficiencies. In long trips that exceed the battery range, theoretical efficiencies of up to 60% could be expected, similar to a typical FCEV, although true efficiency should be rather closer to the 40-50% range due to power losses in auxiliaries and power electronics. In short distances, with battery all-electric operation, the efficiency would even marginally increase, reaching or exceeding 70%, similar to BEVs. Hence, FCREVs could be overall amongst the most efficient vehicles. Karstedt et al. [53] presented a study where an automotive fuel cell system coupled to a methane reformer is used as arrange extender. The system achieves an overall efficiency of 25%. The reformer itself offers an 85% efficiency in the conversion of methane to hydrogen.

Security

Both electricity for the batteries and hydrogen for the fuel cells are produced locally therefore contribute to the security of energy production. If a reformer is used, then the improvement of energy security will depend on the fuel used as an energy source to the reformer.

Lifecycle impacts

GHGs

As it has been presented to both FCEV and BEVs, calculating the impact of these technologies to lifecycle GHGs depends on the pathway that has been selected for the hydrogen and electricity productions, respectively. In FCREVs, the balance becomes even more complicated as the exact ratio that the two energy carriers will be used depends on the trip distribution of the car considered. Hence, it should be expected that overall GHG benefits over conventional cars should be between the benefits achieved by FCEVs and BEVs.

Materials

This technology combines the needs of materials from both the BEV and FCEV technologies. It has to be expected that this is the most material-demanding technology available as it requires materials to build the electrical components, the fuel cell and the Hydrogen storage system, the batteries, and the reformer, if such a device is used. Most information on the materials required are given in the description of the BEV and FCEV.

Air pollution

Regulated pollutants

Zero air pollution effects should be expected when hydrogen is used as a fuel for the fuel cell. In case of hydrocarbon fuel is used in a reformer, then CO emissions may be produced but there has been no real-world evaluation of such an application.

Non-regulated pollutants

No non-regulated pollutants are expected from the propulsion systems used, only PM due to the attrition of components. Hydrocarbon fragments may be produced in case of use of a reformer.

Infrastructure

FCREVs is to the most demanding technology in terms of infrastructure development, as it requires parallel investments in both the hydrogen network development and the charging station development. The significant difficulties and costs that this investment requires is one of the two most important reasons that limit the interest in this technology. Using a reformer on board the vehicle would mean that a hydrocarbon fuel could be used, thus developing the hydrogen infrastructure would not be needed anymore. This could be an option, which however decreases the overall efficiency of the system and increases complexity and cost of the vehicle itself.

ICT

Batteries and charging practices on board the vehicle offer possibilities for vehicle to grid communication. The battery size should be expected to be smaller than a full BEV but larger than a plug-in hybrid, hence the average energy buffer these an offer is also in between these two vehicle types.

Costs

Technology

R&D and assembly costs for this technology should be amongst the highest of all vehicles as it consists of several individual components that need to be linked to each other and coordinated for a streamlined operation. No completed (even as a prototype) such application is yet known, hence costs are difficult to predict. Material costs will also be high. The battery over the fuel cell system costs competition will basically determine whether the material costs for this technology are expected to be higher or lower than BEVs. Therefore, it is expected that this technology should be the most expensive one currently, reaching costs several times higher than conventional cars. The potential for substantial decrease in the foreseeable future seems also quite limited.

Externalities

This is one of the three technologies – including BEVs and FCEVs – with the lowest external costs among all foreseen technologies. External costs will only be high in case that carbon intensive energy sources are used for the production of H_2 and electricity which is required to power FCREVs.

Customer perception

Similar to an ICEREV, FCREVs would be well perceived by customers provided that charging and refuelling infrastructure were developed and that costs could be controlled. The reason is that performance-wise FCREVs could exhibit similar or improved characteristics over conventional vehicles, including similar range, improved low-rev torque, low noise and smooth operation. An issue could be safety concerns and the lack of a track record of technology performance in terms of durability and long-term dependability.

4. Summary evaluation

4.1. Fuel technology combinations

Based on the detailed analysis presented per technology in the previous section, it is possible to identify a number of technology/fuel combinations. These are shown in Table 2 and distinguished into "Best", "Good", or "Possible". The vehicle technologies have been classified in the two Tier levels. Fuels are also distinguished into fossil, biofuel, and hydrogen. It should be made clear that this table should be read either by column or by row and should not be used to make absolute judgments for the different combinations. Just to give an example, the LTC/B2G combination is marked as "best" because B2G can be the best fuel for LTC combustion. On the other hand, the SI/EtOH is marked as "Good" because the SI/Petrol combination is better for this vehicle technology. However, it is not fair to judge that LTC/B2G is better than SI/Petrol because these two markings correspond to both different fuels and different technologies.

Table 2. Vehicle classification according to different Tiers

Tier 1 (Category)	Tier 2 (Type)	Fuel								
		Fossil				Biofuel				H2
		Petrol	Diesel	NG	LPG	Biodiesel	EtOH	MtOH	B2G	H2
ICEV	SI	xx		xx	xx		x	(x)	x	x
	CI		xx			x	(x)		xx	
	LTC	(x)	(x)				(x)		xx	(x)
HEV	Mild	xx	x	xx	xx	x	x	(x)	x	x
	Full	xx	x	xx	xx	x	x	(x)	x	x
	PHEV	xx	x	xx	xx	x	xx	(x)	x	x
EV	BEV									
	FCEV	x*		x*			(x)	x	(x)	xx
	ICEREV	xx	x	xx	xx	x	xx	(x)	x	x
	FCREV	x*		x*				x	(x)	xx

Legend:
xx: Best
x: Good
(x): Possible
** Requires an on-board reformer*

Some general comments for this table include the following:

- The fuels marked as “best” per technology are the ones that offer the best overall performance, including first and foremost compatibility with the specific propulsion system. However, all criteria identified in the previous section (efficiency, cost, LCA performance, customer perception, infrastructure needs) are taken into account in the final judgment.

- Second generation biofuels (B2G) represent the least defined fuel type category. In general, the table assumes that B2G can be tuned by means of changing their production process to achieve properties that cannot even be achieved by today’s fossil fuels. This is why for example B2G appear as the best candidate for low temperature combustion.

- All other biofuels are considered with their today’s properties and in blends that are today available. Bioethanol is highly regarded for PHEVs and ICEREVs because their engines operate as power generators rather than propulsion engines, hence they can be optimized for bioethanol use and benefiting of its high octane number to increase compression and hence, efficiency.

- Some combinations may be technically possible but are not scored due to very low commercial interest. For example, an FCREV with a reformed could operate on LPG but there is no point in doing so, hence this combination is not included in the matrix.

4.2. SWOT analysis for Tier 1 categories

It should be clear from the analysis in the previous section that there is no single technology or technology/fuel combination that seems to be the silver bullet in improving the sustainability of the road transport sector. Technologies with high efficiency potential lack the necessary infrastructure and are currently offered at much higher cost than conventional vehicles. A holistic evaluation of the different technology possibilities can be made by means of a SWOT analysis. This is shown in Figure 1 for the three different Tier 1 vehicle categories.

In principle, Figure 1 summarizes the discussion presented in details in the previous sections. In a nutshell, ICE vehicles are mature and well perceived by customers but suffer by high CO2 emissions and increasing cost of fossil fuel prices. HEVs offer efficiency, GHG and AP improvements but are also heavily dependent on fossil fuel price and availability. Finally, EVs have the potential to offer GHG reductions required by the long-term aspirational targets, however are expected to remain very expensive, are in need of substantial infrastructure investments and material availability for high volume production output remains a question.

ICE

Strengths	Weaknesses
Mature Reliable Developed Infrastructure Positive customer perception Moderate R&D cost	Low efficiency High GHG High AP Energy security
Opportunities	**Threats**
Second generation biofuels Low temperature combustion No other competitive technology or road freight transport	High fuel cost / fuel availability Stringent CO_2 targets

HEV

Strengths	Weaknesses
Mature Developed Infrastructure (non PHEV) Reduced GHG (urban) Reduced AP	Cost Infrastructure needs (PHEV) Development phase (PHEV) Long-term performance Material intensive
Opportunities	**Threats**
Further technology improvement Mid-term CO_2 targets Second generation biofuels	Increasing cost of materials Customer perception

EV

Strengths	Weaknesses
Potential for extremely low GHGs ~Zero AP High efficiency Contribute to energy security	Still in development Very high cost of materials Small range (BEV) Require user 'training' (low customer perception) Material intensive Heavy infrastructure investment requirements Weight (not FCEV)
Opportunities	**Threats**
CO_2 emission targets Concentrated R&D efforts Increasing fossil fuel prices New vehicle concepts	Increasing cost of materials Availability of materials Customer perception Infrastructural challenges

Figure 1. SWOT analysis for the three Tier 1 vehicle categories

4.3. Best technology per vehicle type

Different vehicle types have different requirements, and application needs, hence propulsion technologies can be better suited for particular vehicle types. Table 3 offers a summary of the applicability of each technology for each particular vehicle type. The table is relevant when read by row only, i.e. in which vehicle type each propulsion technology is best suited. Reading the table in the vertical direction (by column) makes no sense because there is no single propulsion technology which can be considered the best option for a particular vehicle type, due to the main factors involved in such an assessment.

The following general remarks can be made, following the values in Table 3.

- HDVs is the one vehicle category for which most of the upcoming technologies seem not appropriate. In the high load, constant speed operation of these vehicles on freeway, the diesel engine offers a unique combination of efficiency, cost, power density and range that can be hardly matched by any of the foreseeable technologies. Low temperature combustion and biofuelling seem as the most probable possibilities for achieving sustainability in road freight transport.

- Hybrid technologies and electric with range extender seem most appropriate for passenger cars and light commercial vehicles. Hybridisation in motorcycles and busses is very expensive compared to conventional technology to justify its efficiency benefits.

- Fuel cell related technologies seem to be best suited for urban busses, at least for the short-to-medium term future. Urban busses use specific depots for fuelling and maintenance and it would be much easier to develop the necessary H2 or alternative fuel infrastructure in these locations only.

- Finally, full electric propulsion seems to be most appropriate for small vehicles, such as PTWs, since they are of low total energy requirement and perform small trips which can be served by on-board battery energy. Neat electric propulsion becomes increasingly different the larger the vehicle and the longer the trips are.

Table 3. Applicability of different technologies to different vehicle types (1.0 = Best, 0 = no applicability). Table should be only ready by row (horizontally)

Tier 1 (Category)	Tier 2 (Type)	PTWs	PCs	LCVs	Busses	HDVs
ICEV	SI	1.0	0.7	0.5	0.3	0
	CI	0.1	0.6	0.8	0.9	1.0
	LTC	0.1	0.4	0.5	0.2	1.0
HEV	Mild	0.6	0.8	1.0	0.6	0.2
	Full	0.3	1.0	0.5	0.7	0.1
	PHEV	0.3	1.0	0.5	0.3	0.0
EV	BEV	1.0	0.7	0.7	0.1	0.0
	FCEV	0.5	0.8	0.8	1.0	0.0
	ICEREV	0.3	1.0	0.7	0.5	0.0
	FCREV	0.3	0.5	0.5	1.0	0.0

4.4. Summary classification per assessment criterion

A summary evaluation of the technology potential per criterion is attempted in Table 4. In this table, CI propulsion is considered as the reference and is given a zero level in all criteria. Then, each other technology is evaluated in relation to CI and receives a score ranging from -3 (poorest performer) to +3 (best performer). An assessment for the scores given may be derived from the analysis of each technology in the previous section.

Table 4. Applicability of different technologies to different vehicle types (1.0 = Best, 0 = no applicability). Table should be only ready by row (horizontally)

Tier 1 (Category)	Tier 2 (Type)	Energy		Lifecycle		Air Pollutants		Infrastructure		Customer Perception	Costs	
		Efficiency	Security	GHG	Materials	Regulated	Non Regulated	General			Technology	Externalities
ICEV	SI	-1	0	-1	1	2	1	0	0	0	1	0
	CI	0	0	0	0	0	0	0	0	0	0	0
	LTC	1	0	1	1	1	1	0	0	1	-1	1
HEV	Mild	0	0	0	0	2	1	0	0	0	-1	1
	Full	1	0	0	-1	2	2	0	2	-1	-1	2
	PHEV	2	1	1	-2	2	2	-2	3	-2	-2	2
EV	BEV	3	3	3	-3	3	3	-3	3	-3	-3	3
	FCEV	2	3	3	-2	3	3	-2	2	-2	-3	3
	ICEREV	2	2	1	-2	2	2	-2	3	-2	-2	2
	FCREV	2	3	3	-3	3	3	-3	3	-2	-3	3

The table shows what is generally expected, i.e. that electric vehicles offer the largest advantages in environmental performance and sustainability but also do raise significant challenges in terms of cost and infrastructure needs. This trade-off will determine the rate at which EVs will become popular on European roads or not.

5. Conclusions

The main conclusions from this work can be summarized in the following points:

1. There is no technology available today that can score higher than already used (conventional) technologies in all sustainability criteria established. In other words, there is no unique technology to replace existing ones, at least in the near future.

2. The potential of conventional ICE vehicles is still substantial as they will continue to offer high cost-effectiveness and driving performance, that can be hardly matched by alternative technologies. Technology breakthroughs lead to continuous fuel economy improvements. However, the relatively low thermodynamic efficiency limits and strong dependence on fossil fuels means that conventional technologies will have to be gradually phased out and replaced by more efficient alternative technologies, at least for small to medium sized vehicles.

3. Road freight transportation, which is currently heavily depended on compression ignition (diesel) engines, is one sector for which only few alternatives can be found to improve sustainability. Increase of the biofuel share and combination of second-generation biofuels with new combustion concepts (low temperature combustion) may offer significant benefits for a simultaneous improvement in efficiency and reduction of AP and GHG.

4. Electric vehicles have the potential to offer substantial GHG and AP reductions over conventional technologies. However cost, infrastructure needs, and battery capacity are still significant obstacles in their widespread penetration. While technology rapidly improves, there are still no definitive answers as to whether and how much the cost-efficiency of batteries can improve. In addition, the availability and cost of materials for large volume battery and motor production is still in question.

5. Fuel cell technologies based on hydrogen or other fuels also offer significant benefits in terms of AP and GHG. Combined with medium sized batteries, fuel cell electric vehicles may already offer similar or better performance than today's conventional vehicles in terms of performance and range with the potential for zero GHG and AP emissions. This cannot be yet matched by neat electric vehicles. However, this technology is limited by the need to efficiently produce and distribute hydrogen, which basically means developing new infrastructure from scratch. Cost of fuel cell production is also a limiting factor.

6. Hybrid vehicles offer some benefits compared to conventional cars in terms of GHG and AP emissions. However, these cannot be seen as a long-term solution because of their significant dependence on fossil fuels. Also material and R&D cost will continue to suppress their cost-effectiveness compared to the best of the conventional vehicles of today.

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Abstract

A number of propulsion technologies are assessed in this report regarding their potential to improve the road transport sustainability. These technologies are distinguished into internal combustion, hybrid, and electric vehicle propulsion systems. Each category is further distinguished into more technologies, which are expected to appear in variable degrees as road transport propulsion systems.

All technologies have been evaluated following a structured group of criteria. These criteria are assumed to offer a holistic view of the sustainability of each technology.

Key technological characteristics for each propulsion system are described. Also, their applicability to different vehicle types (power-two-wheelers, passenger cars, light commercial vehicles, busses, and heavy duty trucks) is assessed based on the cost, space requirements and performance of each technology. Biofuelling possibilities, using first and second generation biofuels, are considered an asset and the potential of each technology is examined. An effort has been made to provide quantified information o efficiency, GHG emissions and costs (including externalities) for each technology. Both the current trends and the expected situation are outlined, in an effort to accurately reflect the current status and the potential of each technology.

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