TECHNICAL IMPROVEMENT POTENTIALS IN EUROPEAN PASSENGER CARS. BOTTOM-UP ASSESSMENT OF THEIR POTENTIALS IN ENERGY DEMAND AND CO_2 EMISSION REDUCTION BY 2030 UNDER DIFFERENT DIFFUSION ASSUMPTIONS

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ABSTRACT

Personal motor transport has given the public significant mobility that is adjustable to different usages, driving locations and preferences. Currently in Europe, passenger cars use over 65% of total transport energy and produce around 12% of total EU-27 carbon emissions. Since the last few years, growing concerns over global warming, increasing oil prices and looming botheration for energy security have initiated various actions that are aimed at mitigating the problems and to ensure a sustainable mobility. In consideration of this, application of innovative improvement technologies into passenger cars can play an important role in enhancing the vehicle fuel efficiency and offering the potentials for energy demand and emission reduction into future. This study collates two sets of efficiency improvement technologies (referred as *Technology Options 1 & 2*) and utilizes a Bottom-up simulation to assess the effects of these technologies on total energy demand and CO_2 emission from passenger cars until 2030 in the EU-27. The integration of efficiency improvement technologies into the vehicle will serve the purpose of increasing fuel efficiency, enhancing performance and providing further technical and environmental benefits. However, this will also result in incremental costs over the vehicle baseline price. This study also assesses changes in the specific driving costs, cost of CO_2 avoidance and the payback period of incremental costs. The *Technology Options* considered in this study show that a 5% to 22% increase in the car fuel economy is achievable. And, based on

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assumed technology diffusions across total gasoline and diesel cars, this study infers a potential of an overall energy and CO_2 emission saving of between 19% and 34% in the EU-27 up to 2030.

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LIST OF PUBLICATIONS

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2. Suzuki. M., Kehdy. B., Jain. S. (December, 2010). Identifying Barriers for the Implementation and the Operation of Biogas Power Generation Projects in Southeast Asia: An Analysis of Clean Development Mechanism Projects in Thailand. *The GSIM Paper Series, International University of Japan.*

3. Toro. F., Jain. S., Reitze. F., Rosende. D. (August, 2010). Analysis of the technological innovation potentials in alternative automotive systems and their effects on technology learning trends, *11th IAEE European Conference,* Vilnius, Lithuania.

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AFFIDAVIT

I hereby declare that the results presented in this thesis have been developed by me and there has been no use of any dishonest methods in the creation of this Master's Thesis. I confirm that all the data, literature and sources used in this study are indicated fairly and honestly.

This study is also a component of the PhD research of my supervisor, Mr. Felipe Andrés Toro from IREES GmbH, Karlsruhe and the initial results of the methodology stated in this analysis have been partially presented at the 11th IAEE European Conference at Vilnius, Lithuania in August 2010. Furthermore, I being one of the authors of the project report 'Deliverable-8: State of the art for alternative fuels and alternative automotive technologies' of the project *ALTER-MOTIVE* may show some similarities in the explanations and discussions.

An unintended error in the Economic assessment (related to Question –3) was realized after the submission of original Master's Thesis. The error was later-on rectified through a corrigendum and revised assessment. In this document, the amended assessments as per the corrigendum are stated on page 40 & 44, and the results and analysis are presented accordingly.



Sulabh Jain

Freiberg, 8th April 2011

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OUTLINE OF THE THESIS

The introduction (chapter 1) of this thesis starts with the motivation and focus of the research. There are four main research questions that this thesis aims to answer and section 1.1 indentifies these. Section 1.2 includes a brief overview of an ongoing European project 'Project *ALTERMOTIVE*'. Section 1.3 gives an introduction to the concept of AAMTs and 'Technical Improvement Potentials' in European passenger cars.

The focus of chapter 2 is confined to passenger cars within EU-27. Section 2.1 summarizes historical development of the vehicle registration and the fuel economy advancement within Europe. Section 2.2 gives an overview of the significance of passenger cars in total European energy demand and CO_2 emission. Section, 2.3 lists forecasts and expected future passenger car development in the EU-27 until 2030. Section 2.4 includes the concept of the fuel economy, how it is significant in relation to passenger cars and what are the main factors that influence the fuel economy of a car.

Chapter 3 includes details of various AAMTs and Technical Improvement Potentials in Europe. Section 3.1 states the main drivers for innovative technical developments in Europe and the significance of integrated approach targeted by the European Commission. Section 3.2 details several AAMTs along with their current state of the art, technical improvement potentials, the economic and environmental assessment. Section 3.3 includes summary of various technical innovation and improvement potentials in European passenger cars, the expected efficiency increase from them and their readiness and applicability into cars.

Chapter 4, Methodology starts with an overview of the steps involved in the study. Section 4.1 states the details and market readiness of *'Technology Options'* selected for the assessment. Section 4.2 includes the concept and equations involved in the 'energy demand and emission saving assessment'. Section 4.3 includes equations and methods behind the 'economic assessment'. Section 4.4 details the 'bottom-up simulation' and parameters involved in it. Section 4.5 details the steps followed by the author to simulate the new passenger car stock in EU-27 until 2030. Section 4.6 describes the concepts involved in the simulation of technology diffusion

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into European gasoline and diesel cars until 2030. Section 4.7 summarizes the key literature sources and studies utilized in establishing the baseline and further analysis of this thesis.

Chapter 5 summarizes the results and analysis of this study. Section 5.1 and 5.2 describe the assessment and results as the impacts of integration of *'Technology Options'* on the vehicle's energy demand, emission and economic performance. Section 5.3 describes the total energy demand and CO_2 reduction potentials that are a direct impact of technology diffusion at different rates amongst total EU-27 passenger cars. Section 5.4 describes the results of the sensitivity analysis

Chapter 6 contains the conclusion to the analysis and answers to all four research questions. This study concludes that technical interventions and improvements have significant potentials in enhancing the vehicle efficiency and fuel economy, and the diffusion of technologies across car fleet can lead to a reduced total energy demand and consecutive CO_2 emission until 2030 in Europe.

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LIST OF ABBREVIATIONS

AAMTs	Alternative Automotive Mobility Technologies
ACEA	European Automobile Manufacturers Association
AEA	Business name of AEA Technology plc (A privatised consultancy, offshoot of the United Kingdom Atomic Energy Authority)
AFs	Alternative Fuels
B5, B15	Biodiesel blend (5%, 15%)
BEV	Battery Electric Vehicle
CAFE	Corporate Average Fuel Economy Standards
CNG	Compressed Natural Gas
CO_2 Emission	CO_2 emitted due to fuel consumption
CONCAWE	CONservation of Clean Air and Water in Europe
CVT	Continually Variable Transmission
E5, E85	Ethanol blend (5%, 85%)
EC	European Commission
ECMT	European Conference of Ministers of Transport
EPA	Environment Protection Agency (USA)
ETSAP	Energy Technology Systems Analysis Programme
EU T&E	European Federation for Transport and the Environment
EU/EU-27	European Union
EUCAR	European Council of Automotive R&D
EV	Electric Vehicle
FCV/FCEV	Fuel Cell Electric Vehicle
FFV	Flex-fuel Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GSI	Gear Shift Indicators
HEV	Hybrid Electric Vehicle
IAEE	International Association for Energy Economics
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
KMPL	Kilometer per Liter (km/l)
LPG	Liquefied Petroleum Gas
LPGV	Liquefied Petroleum Gas Vehicle
McKinsey	McKinsey (A USA based global management consulting firm)
MJ/PJ	Mega Joule / Peta Joule
MPG	Miles per Galloon
NGV	Natural Gas Vehicle

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NOx	Nitrogen-Oxygen compounds
O&M	Operation and Maintenance
PC	Passenger Car
PHEV	Plug-in Hybrid Electric Vehicle
R&D	Research and Development
RD&D	Research Development and Demonstration
RTD	Research and Technology Development
SoA	State of the art
SUV	Sports Utility Vehicle
TNO	TNO Science and Industry - A research organization, Delft, The Netherlands
TPMS	Tire Pressure Monitoring System
TTW	Tank to Wheel
USA	United States of America
WTT	Well to Tank
WTW	Well to Wheel

This list consists of key abbreviations that are used frequently within the thesis. Other abbreviations related to the text, tables and figures are mentioned at their respective places in the document.

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1. INTRODUCTION

1.1 Motivation and Focus of Research

Across Europe, passenger cars have played an important role in development of the society and the economy, and in providing mobility to people (OICA, 2010). Over the last decade, increasing environmental concerns, rising oil prices and continuous urge for technological developments have stimulated industries and nations around the world to move towards more efficient and better sustainable practices within the transport sector (Kobayashi, Plotkin, & Ribeiro, 2008). Vehicle manufacturers nowadays are aiming at modifying conventional vehicles and introducing alternative vehicle technologies to provide better and more efficient cars and reduce GHG emissions for a sustainable mobility (ACEA, 2007). This fact is clearly reflected in the considerable investments made by the automotive industry (see Figure 13) in research, development and demonstration (RD&D) of numerous innovative technologies (EU T&E, 2009). In addition to the varied upcoming vehicle technologies like battery electric vehicles and hydrogen fuel cell vehicles, nowadays, a large number of vehicle and powertrain improvement technologies are aimed at increasing the fuel economy and efficiency of existing conventional vehicles through technical improvements and the core analysis of this thesis is based on such **'technical improvement potentials'**.

The term **Technical Improvement Potential** refers to the introduction of new technologies or the modification of existing technologies within a car to achieve higher vehicle benefits (EPA, 2008). Technical improvement potentials can serve multiple propose of enhancing vehicle performance, safety and comfort and most importantly, for achieving increased fuel efficiency of the vehicle.

The method implemented for this thesis starts with an intensive study of various technical improvement potentials in European passenger cars along with their potential in enhancing the vehicle efficiency. Subsequently, this study selects two sets of such innovative improvement technologies, ***'Technology Option 1 & 2'*** that can be integrated into conventional gasoline and diesel cars. In the next step, the impacts of integration of *'Technology Options'* on the vehicle's energy demand, emission generation, and economic performance were assessed.

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To assess the total energy demand and CO_2 emission from all EU-27 passenger cars by 2030, this study utilizes a **bottom-up simulation** and evaluates the possible changes in total energy demand and CO_2 emission based on the assumed diffusion of *'Technology Options'* across gasoline and diesel cars (Toro F. 2010).[1]

There are four main research questions that this thesis aims to answer:

1. Assessment of the technical improvements and innovative technologies in European passenger cars along with their potential to enhance the vehicle efficiency. (Section 3.3)

2. Assessment of the improvements in the "fuel economy" as an impact of integration of ***'Technology Option'*** into the car. Assessment of subsequent reductions in "CO_2 emission" as a result of decreased fuel consumption – ENERGY DEMAND AND EMISSION SAVING ASSESSMENT. (Section 5.1)

3. Assessment of the specific driving costs, cost of CO_2 avoidance, the average payback period and other vehicle's economic performance changes, that occur as a result of enhanced efficiency and additional investments in ***'Technology Options'*** - ECONOMIC ASSESSMENT. (Section 5.2)

4. Assessment of the potentials of ***'Technology Options'*** in "overall reduction of energy demand and CO_2 emission" by EU-27 passenger cars up to 2030, based on the assumed diffusion of *'Technology Options'* within conventional gasoline and diesel cars – BOTTOM-UP SIMULATION. (Section 5.3)

[1] The methodology for the bottom-up simulation is adapted from Toro.F., Jain. S., Reitze. F., Rosende. D. (2010). Analysis of the technological innovation potentials in alternative automotive systems and their effects on technology learning trends. *11th IAEE European Conference*, Vilnius, Lithuania.

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To address the research questions and to present the analysis, this document is structured as follows:

Chapter 1 outlines the motivation for this study and introduces the project *ALTER-MOTIVE*, the concept of Alternative Automotive Mobility Technologies (AAMTs) and technical improvement potentials in European passenger cars.

Chapter 2 provides an overview of the European passenger car fleet, historical development of the vehicle registration, the fuel economy advancements and the expected passenger car fleet development in EU-27 until 2030.

Chapter 3 introduces different AAMTs by briefly outlining their current 'state of the art' and the economic and environmental assessment within Europe. In section 3.3, this chapter focuses on innovative technologies and technical improvement potentials for passenger cars along with their potentials in the vehicle efficiency increase. This chapter also answers the research question 1.

Chapter 4 explains the methodology implemented in this study with details of various equations involved in the assessments, the bottom-up simulation tool, various relevant data and sources, and all other factors related to this study.

Chapter 5 draws together the analysis and results of the thesis. Sections 5.1 and 5.2 present the results that are derived from the consideration of integrating *'Technology Options 1&2'* at the vehicular level. Section 5.3 describes the total energy demand and CO_2 reduction potentials, which are a direct impact of technology diffusion at different rates amongst total EU-27 passenger cars. Section 5.4 states the sensitivity analysis of the results.

Chapter 6 presents the main conclusions, discussion, limitations of the study, and possible ideas for future research.

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1.2 Project *ALTER-MOTIVE*

To tackle the problems associated with constantly increasing fuel (energy) demand and greenhouse gas (GHG) mitigation, it has become very important to consider alternative fuels and alternative propulsion systems for meeting economic and environmental benefits. The project *ALTER-MOTIVE* contracted by Intelligent Energy Europe (contract number IEE/07/807/SI2.499569) has the objective of increasing the share of alternative fuels (AFs) and alternative automotive mobility technologies (AAMTs) in Europe, such that the benefits of a ecologically friendly fuel mix and powertrain structure in the individual transport within Europe can be achieved. The core objective of the project *ALTER-MOTIVE* is to derive an action plan for implementing least-cost policy strategies for Europe to achieve a significant increase of AFs and AAMTs to head towards sustainable personal vehicle transport.

For a better understanding and deeper insight into the objective of the project, it is necessary to understand the current "State of the Art" developments and possible improvements potentials in various AFs & AAMTs. This state of the art assessment was carried in workpackage-3 (WP3) of the project through an extensive economic, environmental and technological assessment along the whole well-to-tank (WTT) and tank-to-wheel (TTW) chain for selected AFs and AAMTs. The outcomes of WP3 will serve as input for deriving least cost strategies and action plan in the upcoming work packages of the project. The database on the state of the art assessments of various AFs and AAMTs is organised in excel files that contain all technical and economic values, delivering specific costs, carbon emissions etc. The state of the art assessment of AFs and AAMTs is qualitatively and quantitatively described in Deliverable-8 by including detailed technical descriptions, their current economic and environmental performance as well as the current status of technologies within Europe. [2]

[2] WP3 – Deliverable 8: State of the art for alternative fuels and alternative automotive technologies.

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1.3 Introduction to AAMTs and Technical Improvement Potentials

1.3.1 Alternative Automotive Mobility Technologies

Alternative Automotive Mobility Technologies (AAMTs) include any dedicated, flex-fuel, or dual-fuel vehicle, designed to operate on at least one non-conventional fuel or alternative fuel (like biofuel, gas or electricity). An alternative fuel vehicle can be combined with an internal combustion engine (ICE) designed to run on more than one fuel, usually gasoline blended with ethanol or methanol, or diesel blended with biodiesel.

The flex-fuel vehicles are capable of burning fuel blends (B5, E85 etc.) in the combustion chamber as the fuel injection and spark timing can adjust automatically according to the actual blend detected by electronic sensors (Rutz & Janssen, 2007). Flex-fuel vehicles, where the two fuels are blended in the same storage tank are distinguished from bi-fuel vehicles, where two fuels are stored in separate tanks and the engine runs on one fuel at a time. For example, vehicles with gasoline or diesel tank and compressed natural gas (CNG), liquefied petroleum gas (LPG), or hydrogen tank. The dual fuel vehicle is another AAMT that can use two different fuels at the same time for vehicle propulsion (gas and diesel models).

A hybrid car is a vehicle that uses two or more distinct power sources (generally liquid fuel and electricity) to move the vehicle. The term most commonly refers to hybrid electric vehicles (HEVs) that combine an ICE and one or more electric drive motors.

The battery electric vehicle (BEV) is a vehicle that can run solely on electricity stored in charged batteries. The fuel cell vehicle (FCV) is another kind of electric vehicle, but the electricity is produced on-board through the fuel cell conversion, using hydrogen stored at high pressure in storage tank(s) (Bunzeck & Uyterlinde, 2010). Interestingly, electric vehicles (both BEV and FCV) are considered highly promising for carbon neutral transport as they do not produce any emission during driving (Buenger, 2009). Table 1 states the summary of various AAMTs.

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Table 1: Types of AAMTs

Vehicle Type	Description
Flex fuel Vehicle (FFV)	ICEVs, capable to burning fuel blends stored in one tank (E85, B5)
Bi-fuel vehicles	ICEVs that run on 2 different fuels stored in separate tanks (CNG/LNG with gasoline or diesel)
Dual-fuel vehicles	ICEVs that burn two fuels at the same time (diesel and natural gas vehicles)
Dedicated alternative fuel vehicles	ICEVs that use only alternative fuels to run (CNG/LNG vehicles, electric vehicles, fuel cell vehicle, pure biofuel vehicles)
Gas Vehicles (GVs)	A type of dedicated alternative fuel vehicle that can run on LPG/CNG
Biogas vehicle	A type of dedicated alternative fuel vehicle that can run on purified and upgraded biogas
Hybrid electric vehicles (HEVs)	Vehicles that combine an ICE and one or more electric drive motors, use liquid fuel and electricity for power, engine size is generally slightly smaller than conventional ICEV, battery charging is done on-board, and electricity range from battery is very short
Plug-in hybrid electric vehicle (PHEV)	Vehicles that combine an ICE and one or more electric drive motors, use liquid fuel and electricity for power, engine size is smaller than conventional ICEV, battery charging is done on-board **as well as through grid**, and electricity range from battery is short to medium
Battery electric vehicles (BEVs)	Vehicles that can run solely on electricity stored in charged batteries, do not have an ICE, battery charging **only through grid**, and electricity range from battery is medium to long
Fuel cell vehicle (FCV)	A type of electric vehicle, but the electricity is produced on-board through fuel cells using hydrogen as fuel

Source: Compiled by the author

Abbreviation: ICE = Internal Combustion Engine, ICEVs = Internal Combustion Engine Vehicle

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1.3.2 Technical Improvement Potentials

The term Technical Improvement Potential refers to the introduction of new technologies, or modification of existing technologies within cars to achieve higher vehicle benefits (EPA, 2008). Innovative and advanced vehicle technologies available nowadays are targeted to serve the multiple propose of enhancing performance, safety, comfort and most importantly, for achieving an increased efficiency of the vehicle (Brachmann, 2009).

Currently, a huge diversity of improvement technologies are available in Europe at different levels of R&D, demonstration and commercialization (see section 3.3). Cost reduction, achieving less emissions and better efficiency of existing powertrains are a few drivers for such technological developments and diversification. Since 2005, the European car manufacturers have invested over € 26 billion (which is nearly 5% of the total turnover) in R&D and have introduced more than 50 advanced technologies (like reducing engine friction losses, aerodynamic drag improvements etc.) into the vehicles, that have resulted in reducing the CO_2 emissions by 10-13% (ACEA, 2009).

Technical improvement potentials stated in this thesis are classified in five types, based on the level of their application or integration into the car. The five categories are; **Body technologies** (like light weight construction, aerodynamic improvement), **Engine technologies** (like reduced engine friction, cylinder deactivation), **Transmission technologies** (like gear optimization), **Hybrid technologies** (like regenerative braking) and **Others** (like use of advanced low resistance tires and other advanced accessories). The summary of technical improvement technologies collated within this study is stated in Table 6 on page 31. And the detailed features of the technologies are stated in APPENDIX I.

The current chapter has explained the motivation and the focus of the research. The four main research questions that this thesis aims to answer are stated in section 1.1. This chapter has also given a brief overview of the ongoing European project 'Project *ALTERMOTIVE*', concept of AAMTs and 'Technical Improvement Potentials' in European passenger cars. The upcoming chapter 2 is confined to the passenger cars within Europe. The motive of this chapter is to provide an overview

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of the historical development in the new vehicle registration and the fuel economy advancements in the last few years. This chapter will also show the significance of passenger cars in the total EU energy demand and CO_2 emission, and to be expected future fleet development in the EU-27 by 2030.



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2. AN OVERVIEW OF THE EU PASSENGER CAR FLEET

2.1 History and Production

The first petrol motor was patented by Enrico Bernard from the University of Padua, Italy in 1882. It was a single-cylinder 0.024 horsepower (17.9 W), 122 cc (cubic centimetre) petrol motor, integrated into his son's tricycle, making it the first automobile ever. In 1885 Karl Benz from Mannheim, Germany developed another automobile with a petrol engine, for which he was granted a patent in January 1886. After that, in 1889 Gottlieb Daimler and Wilhelm Maybach from Stuttgart designed a vehicle being able to run on an engine, rather than a horse-drawn carriage. Daimler and Maybach are also considered as first inventors in the motorcycle engine technology in around 1886 (Georgano, 1985).

The automobile industry is one of the biggest backbones of the European economy and net trade contribution. With over 32% of the world's total passenger cars production, Europe holds the lead position in the world in passenger car trade and manufacturing (see Figure 1). The European car industry and manufacturers not only play a key role in providing the personal transport to the European citizens, but also contribute to the European economy on a huge scale via providing employment, production and export revenues (ACEA, 2008).

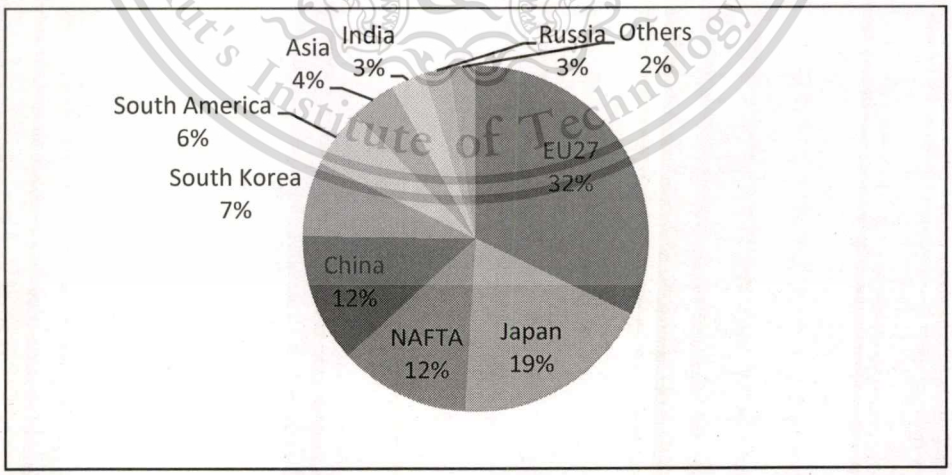


Figure 1: World passenger car production (% share-2007)
Source: ACEA, 2008

Germany, France, Denmark, Italy, Spain, the Netherlands and the UK are considered as the most significant countries in Europe, in relation to the automotive

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production and growth. Interestingly, over 85% of newly registered vehicles in the Europe are passenger cars, and this number has continuously grown during the last 10 years (ACEA, 2008). Table 2 provides the country review of historical developments in the new car registration and the fuel economy in Europe between 2005 and 2009.

Table 2: Historical developments in the EU-27 new car registrations and the fuel economy

Country	New Passenger Car Registrations in Europe					Fuel Economy (l/100km)		
	2005	2006	2007	2008	2009	2005	2006	2007
Austria	307,915	308,594	298,182	293,697	319,403	7.60	7.50	7.50
Belgium	480,088	526,141	524,795	535,947	476,563	-	-	-
Bulgaria	-	32,481	41,042	43,758	25,104	-	-	-
Czech Republic	151,699	156,686	174,456	182,554	167,708	-	-	-
Denmark	146,885	154,385	159,347	150,145	112,007	7.42	7.42	7.41
Estonia	19,640	25,363	30,912	24,579	9,946	-	-	-
Finland	147,949	145,689	125,285	139,611	88,344	-	-	-
France	2,067,789	2,000,549	2,064,543	2,050,282	2,268,671	7.40	7.33	7.32
Germany	3,319,259	3,467,961	3,148,163	3,090,040	3,807,175	8.08	8.10	8.03
Greece	269,728	267,669	279,745	267,295	219,730	7.60	7.40	7.33
Hungary	198,982	187,676	171,661	153,278	60,189	8.25	8.13	8.10
Iceland	18,060	17,129	15,942	9,033	2,113	-	-	-
Ireland	171,742	178,484	186,325	151,607	57,444	7.03	6.86	6.89
Italy	2,237,444	2,326,049	2,493,106	2,161,682	2,158,010	6.86	6.66	6.52
Latvia	16,602	25,582	32,771	19,831	5,367	8.48	8.41	8.37
Lithuania	10,467	14,234	21,606	22,217	7,515	8.57	8.41	8.37
Luxembourg	48,517	50,837	51,332	52,359	47,265	-	-	-
Netherlands	465,152	483,970	505,538	499,918	387,699	7.99	7.97	7.97
Norway	109,907	109,164	129,195	110,617	98,675	-	-	-
Poland	235,522	238,993	293,305	320,040	320,317	7.86	7.80	7.69
Portugal	206,488	194,702	201,816	213,389	160,991	9.36	9.29	9.23
Romania	-	256,364	315,621	270,995	130,001	8.06	8.40	-
Slovakia	57,125	59,084	59,700	70,040	74,717	6.42	6.13	5.79
Slovenia	59,324	59,578	68,719	71,575	57,967	7.66	7.47	7.28
Spain	1,528,877	1,634,608	1,614,835	1,161,176	952,772	7.81	7.77	7.75
Sweden	274,301	282,766	306,799	253,982	213,408	8.64	8.54	8.18
Switzerland	264,941	269,452	284,688	288,557	264,771	-	-	-
UK	2,439,717	2,344,864	2,404,007	2,131,795	1,994,999	7.71	7.49	7.45
Total EU	**15,254,120**	**15,819,054**	**16,003,436**	**14,739,999**	**14,488,871**	-	-	-
Average						**7.83**	**7.74**	**7.62**

Note: No data available for Malta and Cyprus

Source: European Automobile Manufacturers' Association (ACEA), Deliverable-2: Project ALTER-MOTIVE

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As seen in Table 2, between 2005 and 2007, the number of new passenger cars grew from 15.2 million to 16 million; however this number decreased to around 14.5 million in 2009, mainly due to the economic crisis (ACEA-New Vehicle Registration Statistics, 2009) (EU T&E, 2009). The decrease of vehicle registration in 2009 should not be misinterpreted as if the total number of cars in Europe has declined. The data here shows, that, new car registrations in Europe decreased during 2009, but the total number of cars has still grown during between 2005 and 2009.

In the last two decades, the average fuel economy of passenger cars across different European countries has also improved considerably. Between 1990 and 2000, the biggest market share of cars in Europe was dominated by sales of large, powerful and more comfortable cars. During that time, the vehicle efficiency of European cars improved, but at a slow rate. The advanced comfort and luxury features like air-conditioners etc. in those cars utilized more energy, hence cancelling the effects of vehicles being more efficient. Then the period of between 2000 and 2005 showed further improvements in the car's energy efficiency, hence, leading to a decreased average fuel consumption from 11 litres/100 km in 2000 to 10.3 litres/100 km in 2005 (EU Energy and Transport, 2007). Between 2005 and 2007, the average fuel economy of European cars showed further significant improvement of around 2.6%. But further room for vehicle technical improvements, voluntary commitment by the European car manufacturers and an average fleet emission target of 120gmCO_2/km by 2012 act as the driving force for further improvements in the fuel economy of the European cars (ECMT, 2005) (Murphy, 2010).

2.2 Energy consumptions and environmental influence of passenger cars

The private passenger car sector is the fastest growing consumer of energy and one of the biggest single sources of GHG emissions in the European Union. Currently, in the EU-27, passenger cars consume over 65% of total transport energy and produce around 12% of total EU carbon emissions (EU Energy and Transport, 2007) (Directorate General, ec.europa.eu, 2010). With the consumption of over 40% of total EU oil imports, and using around 4.4 million barrels per day, passenger cars

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are rated as the single biggest consumer of imported oil within Europe (EU T&E, 2009).

For the upcoming 20 years, the energy demand by passenger cars in Europe is expected to increase at the rate of 0.8% per year, i.e. +20% as a whole. Figure 2 shows that within the total transport energy demand, the largest consumption of energy in the EU-27 since 1990 has been noticed by private passenger cars, followed by air transport. Moreover, Figure 3 shows that within the EU-27, the road passenger transport accounts as the biggest CO_2 producer. By emitting around 65% of total 1,267 Million tonnes of transport related CO_2 emissions (Fiorello, et al., 2009). Given the trends and forecasts, it is inevitable, that passenger cars within the EU-27 will continue to be one of the most important considerations for reductions in the energy demand and subsequent emissions (AT Kearney, 2009).

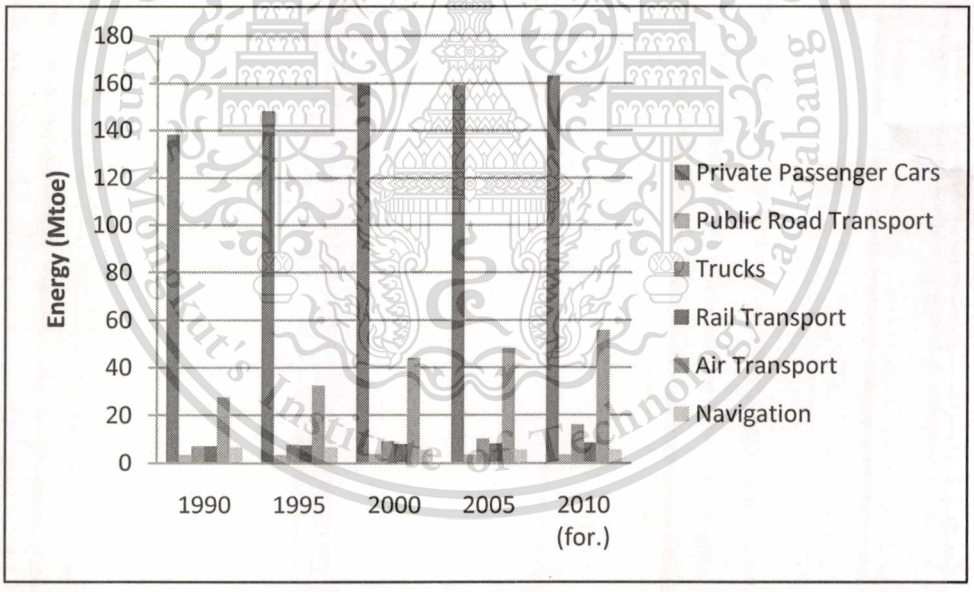


Figure 2: The EU-27 transport energy demand

Source: (EU Energy and Transport, 2007)

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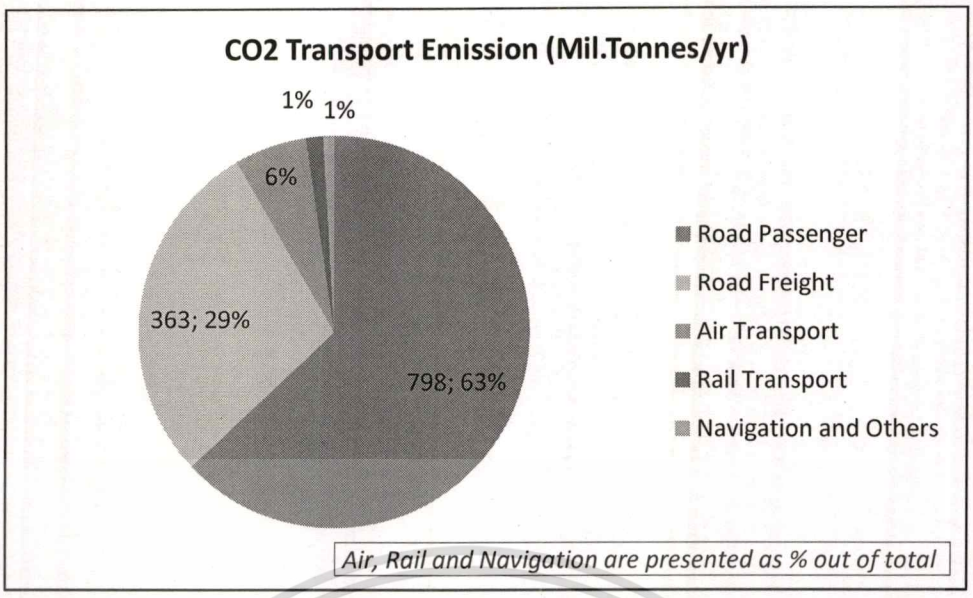


Figure 3: CO_2 emission by different European transport sectors in 2005

Source: (Fiorello, et al., 2009)

2.3 Expected developments in the EU-27 passenger car fleet

Within Europe, rapid transport movement, improved lifestyle and better GDP have triggered the increase in ownership of passenger cars over the last few years. With an expected economy growth rate of around 1.6% per year up to 2030, the personal transport activity in Europe is expected to grow significantly. The passenger car fleet in the EU-27 is expected to grow from 210 million in 2005, to nearly 300 million by 2030 (Fiorello, et al., 2009). Figure 4 shows the historical development of the car fleet in Europe and the expected growth in coming years.

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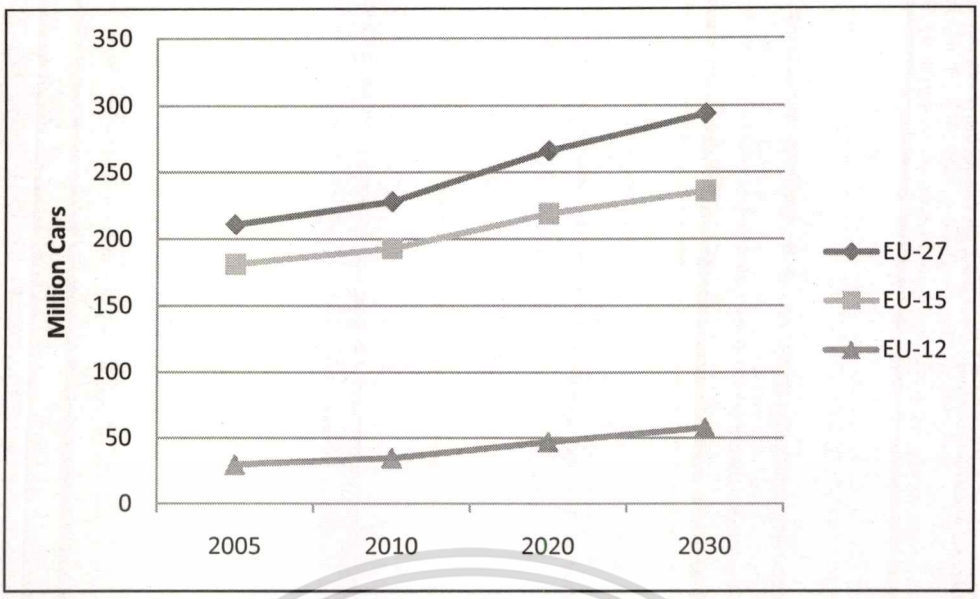


Figure 4: Expected passenger car fleet development in the EU-27 by 2030

Source: (Fiorello, et al., 2009)

There is a very strong relationship between GDP per capita and the number of cars, and both these figures have shown continuous increase over the time for Europe (EUROSTAT 'b', 2009). With a continuous growth in the UK, Germany and France, the highest car ownership level in the EU-27 has been noticed in Italy. However, Denmark seems to be an exception, where GDP per capita growth has been high, but the growth in car ownership has been relatively lower, which probably can be explained through the high level of vehicle taxes in Denmark.

In addition to the increasing number of cars, an increasing share of diesel cars within the total car fleet may also be expected in Europe by 2030. Two of the biggest reasons for this expected prevalence of diesel cars are 'fuel economy' and 'the low and easy maintenance requirements of vehicle'. Moreover, continuous improvements in car technologies for better fuel efficiency will further promote the increasing share of diesel cars within Europe (Pock, 2007). Figure 5 shows the expected trends of gasoline and diesel cars growth until 2030. The figure also states that until 2030 the market will be dominated by small cars followed by medium cars.

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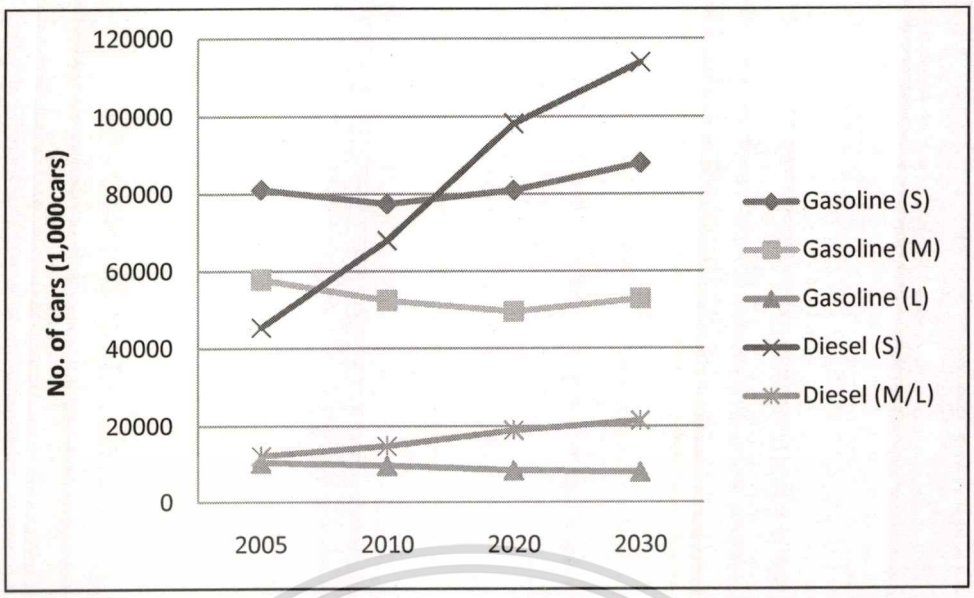


Figure 5: Expected growth of conventional passenger cars in the EU-27 by 2030

Source: (Fiorello, et al., 2009)

Abbreviations: (S) = Small car, (M) = Medium car, (L) = Large car [3]

Figure 6 shows the expected fleet development of AAMTs in the EU-27 over the coming years. The figure shows that, by 2030, the major share in AAMTs is expected to be held by bioethanol and LPG/CNG vehicles. The bioethanol cars may show an exponential increase up to 2030, however, the share of LPG/CNG vehicles may decrease after 2020. The reason for the popularity of bioethanol and flex-fuel cars can be attributed to the developments in bioethanol fuel production and advancements in car technologies, like the example of Brazil, where the market of flex-fuel vehicles and bioethanol is very well established (Wills & Rovere, 2009). The battery electric vehicles may constitute a small share within the total fleet, probably because of the expensive cost of batteries and/or limited driving range affecting the customers' choices (Mollestad, 2009). Developments in the fuel cell vehicles (FCV) will be none or almost nil, as technical and economical barriers exist, and also, for introducing the hydrogen fuel in existing fuel stations and setting up new gas stations, major changes in the infrastructure and investments will be needed (Hydrogen and Fuel Cell Review Days, 2008).

[3] Engine Sizes:
Gasoline <1400 cc = Small, Gasoline 1400-2000 cc = Medium, Gasoline >2000 cc = Large
Diesel <2000 cc = Small, Diesel >2000cc = Medium/Large

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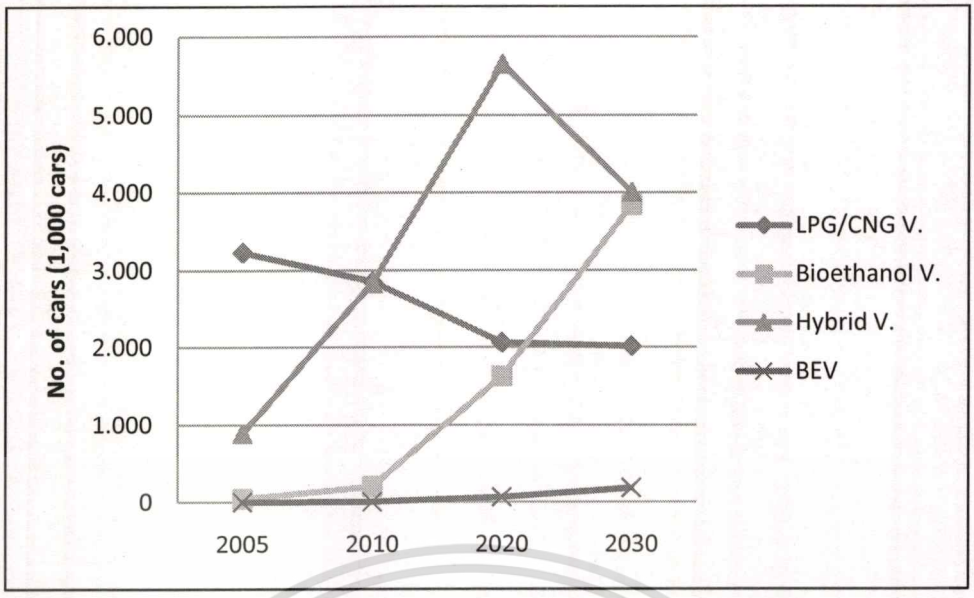


Figure 6: Expected growth of AAMTs until 2030

Source: (Fiorello, et al., 2009)

2.4 Fuel economy and CO_2 emission: Factors affecting them

This section explains the salient factors related to the vehicle's performance, the fuel economy and consequent CO_2 emissions. The term fuel economy in this study is confined to the tank-to-wheel (TTW) perspective at the vehicular level. In other words, it can be defined as 'how much fuel or what amount of energy does a car consume to drive a particular distance'. The fuel economy of a vehicle is a technical characteristic and it depends on various factors like fuel energy content, vehicle size, vehicle weight, urban or highway driving and many other factors. The fuel economy is expressed in terms of kmpl (kilometer per liter), mpg (miles per gallon) or liters per 100 km (l/100km).

The GHG or CO_2 emission is directly related to the fuel consumption or fuel economy of a vehicle (EU T&E, 2009). When a fuel (fossil fuel or renewable fuel) is burnt in the engine, a mixture of CO_2, CH_4, N_2O and few other gases is produced. This mixture of gases (referred as GHG) is measured in terms of gCO_2eq/km or simply g/km.

For this reason, the targets, regulations, statistics etc. across the world for the fuel economy or average CO_2 emission from cars are expressed and compared in

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terms of fuel consumption (l/100km) or emissions (gCO_2eq/km). For example, the European Commission has set a target of limiting average CO_2 emission from car fleet at 120g/km by 2012, and 95g/km by 2020 (see Table 3). However, in the USA, the emission targets for auto manufacturers are rather translated in terms of liters per 100 km i.e. by 2015, attaining 100 km of travelling distance with 5.7 to 6.6 liters of fuel consumption (USA-CAFE Standards).

Table 3: The European car fleet average emission targets

Light vehicle emission targets	Avg. gCO_2 eq/km emission	Avg. fuel consumption (l/100km)
EU – 2008	140	6.0-6.2
EU – 2012	120	5.2-5.4
EU – 2020	95	4.1-4.3

Source: (Regulation (EC) No. 443/2009, 2009)

Gasoline or diesel in a car is stored in a fuel tank and this chemical energy is converted into mechanical energy through the engine (ICE) that finally produces the movement. This overall conversion of energy and movement of a vehicle is done by involving a set of mechanical components and events called as '**drivetrain**'. During the actual driving, 100% of the fuel energy is not converted into 100% of mechanical energy. A huge portion of this energy is lost as 'internal losses' (like engine friction and transmission losses) or 'external losses' (like tire friction and rolling resistance losses). In a driving cycle, on an average, only about 15% of total fuel energy is used to move the vehicle or run its accessories. The rest of the energy is lost in engine losses (as high as 60%), standby/idle (around 17%) and drivetrain losses (around 5-7%) (US-EPA/DOE, 1995). Therefore, the current R&D of the automotive industry is vastly focused on modifications of the existing technologies by the application of advanced innovative technologies that can reduce energy loss and improve fuel efficiency. Figure 7 shows the average energy loss of a mid-size gasoline vehicle during urban driving.

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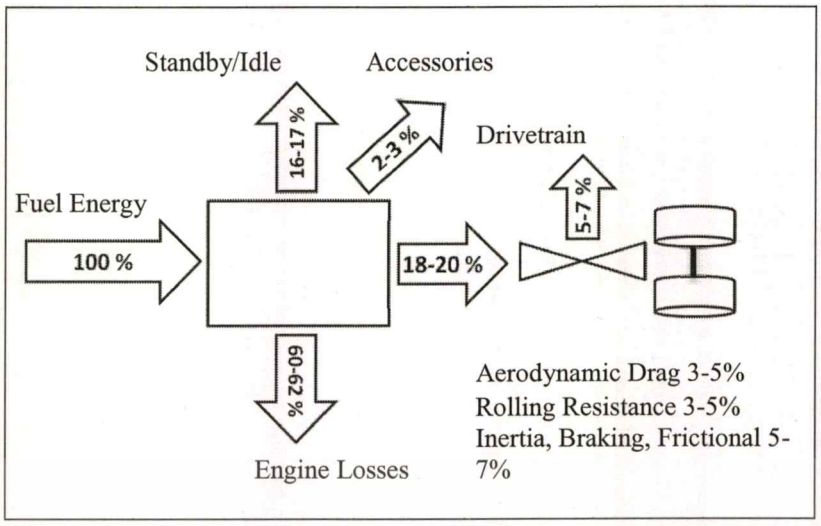


Figure 7: Average energy losses in gasoline light duty vehicle

Source: (US-EPA/DOE, 1995)

The current chapter has provided an overview of the historical development in the new vehicle registration and the fuel economy advancements. Both factors have made significant progress in Europe during the last few years. In section 2.2 the significance of passenger cars in transport energy consumption and carbon related emissions was shown. And, as seen in section 2.3, given the expected GDP growth and technological advancements, the number of cars will continue to grow into future. Section 2.4 has given the overview of the fuel economy and the factors affecting it.

The next chapter 3 mentions the drivers for technological development in Europe, details of the state of the art development of various AAMTS and improvement technologies that are expected to be significant in the future. Section 3.3 answers research question 1 by summarizing various technical improvement potentials that are derived from diverse literature and sources, as well as their potential to enhance vehicle efficiency.

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3. AAMTs AND TECHNICAL IMPROVEMENT POTENTIALS

As stated in section 1.2, within work package-3 of the project *ALTER-MOTIVE*, the 'State of the art' assessment of Europe's emerging AAMTs was done along with analyzing the possibilities of technical improvements and innovations. The method implemented for this assessment corresponds to a detailed study of different AAMTs with respect to tank-to-wheel (TTW) analysis, covering energy balances, GHG emissions and economics at the European level. The analyses of AAMTs in this thesis are presented through a mapping of the current status of various AAMTs in different phases within the market i.e. **technology readiness**. The state of the art assessment of AAMTs is also described in this chapter with their current economic and environmental performance at the EU-27 level.

This chapter answers the research question 1 of this study. The method implemented for collating the technical improvement potentials relates to an intensive review of literature, industrial reports and other published studies. Summary of improvement technologies and expected efficiency increase for them, and the current technology market readiness are stated in section 3.3.

3.1 Drivers for AAMTs and Technical Improvements in Europe

There is no single way to achieve the objective of sustainable mobility in the passenger car transport in Europe. To meet the average per kilometer emission target of 120gCO_2/km from cars by 2012, the Regulation (EC) No. 443/2009 of the European commission has considered an **"integrated approach"**. This integrated approach includes various factors like vehicle technical innovations and improvements, increased use of alternative fuels, eco-driving behavior etc., to meet the emission target. Within the integrated approach, the two most important drivers identified for the sustainable development of personal transport within Europe are, ***reducing the use of fossil fuel*** (by fuel and energy diversification) and ***reducing the energy demand and emissions by technical innovations*** (advanced vehicle technologies and efficiency improvements) (Brachmann, 2009).

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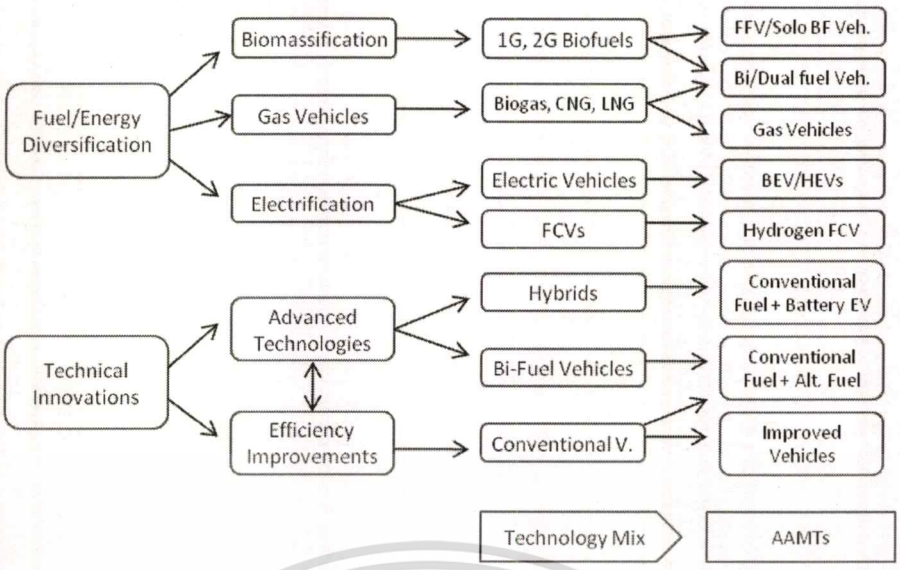


Figure 8: The state of the art innovation in European cars

Source: (Brachmann, 2009), Elaborated by the author

Short forms = 1G: First Generation Biofuels, 2G: Second Generation Biofuels, CNG: Compressed Natural Gas, LNG, Liquefied Natural Gas, FCVs: Fuel cell Vehicles, FFV: Flex-Fuel Vehicle, BEV: Battery Electric Vehicle, HEV, Hybrid Electric Vehicle, Alt.Fuel: Alternative Fuel.

Figure 8 shows the diversified state of the art innovation mix in European passenger cars. The picture gives an overview of the activities and motivations towards sustainable mobility in the personal transport across Europe. Within the context of this thesis, the current status and 'State of the art' of AAMTs (as shown in extreme right side of the figure) are briefed in section 3.2, and the technologies related to efficiency improvements in conventional vehicles are summarized in the section 3.3.

In addition to the European commission, the European automobile industry also believes that only a comprehensive "integrated approach" can provide the solution to reach the average fleet emission target by 2012. The integrated approach will not only address the vehicles themselves, but also the way they are used on roads, and how the whole transport system can be improved (Global Fuel Economy Initiative, 2009). Main elements included in the integrated approach are:

- Technical improvements in conventional vehicles.
- Alternative fuel usage - increased use of biofules, CNG/LNG etc.
- Introduction of innovative vehicle technologies like BEVs, FCVs.

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- Increased system efficiency (highways, transport system, traffic signals etc.).
- Drivers/consumer's behaviour – eco driving, fuel efficiency awareness.
- Travel reduction measures – car pooling, increased use of public transport.
- Public information and education (e.g. emission labelling on cars).

Before the onset of the integrated approach, the European Commission's strategy was based on **"three pillars structure"**, proposed in 1995. This "three pillar" structure involved an comprehensive integration of measures addressing both the passenger car supplier's side (voluntary commitments from manufacturers) and the demand side (from customers' side e.g. CO_2 labeling and taxation). The strategy included following three pillars:

i. *First pillar - the car industry's voluntary commitments:* The voluntary commitments undertaken by the European, Japanese and Korean car manufacturers relating to a target of 140gCO_2/km by 2008 or 2009. To support the progress of the industry, and to ensure that the necessary CO_2 reduction targets are met, the European Commission also repeatedly showed inclinations through several technical and fiscal measures.

ii. *Second pillar - consumer information:* This pillar included delivering unbiased information and awareness to the consumer. 'The labeling directive' which requires the display of a sticker stating fuel consumption and CO_2 emissions from the new cars, the publication of national guides on the fuel efficiency of new cars and the inclusion of fuel efficiency information in printed promotional literature are few such measures.

iii. *Third pillar - the promotion of fuel efficient cars via fiscal measures:* This pillar included tax relaxations, subsidies and other fiscal supports for the RD&D by industry.

The three pillar strategy within Europe succeeded, but only to a certain extent. The average car emission between 1995 and 2004 decreased almost 20% over the period, whereas new cars sold in the EU became significantly bigger and more powerful. But as at 2007, the level of implementation of the three pillar strategy has not been sufficient to achieve emission reduction targets. The progress achieved by 2007 had contributed towards the 140gCO_2/km target by 2008/2009, but additional

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measures still had been necessary to achieve the EU objective of 120gCO_2/km by 2012 horizon. Therefore, in order to achieve the average fleet emission target by 2012 and make significant energy demand and CO_2 reductions, the "integrated approach" was established.

3.2 AAMTs – State of the Art

3.2.1 Technology Readiness and Current Status

Alternative Automotive Mobility Technologies summarized in this section include adaptations of ICEs to be able to run on alternative fuels and/or combinations, and electric vehicles (including BEVs, hybrids and FCVs). Table 4 states various AAMTs mapped under different developmental stages along the technology curve (i.e. Research, Demonstration and/or Commercial state).

Table 4: AAMT - State of the Art in Europe (2010)

	Commercial	Demonstration	R&D
Technologies	**NG (LNG/CNG)** **Flex-Fuel Vehicle** *(conventional fuel + BD/BE)* **Bi-fuels** *(NG + Gasoline/Diesel)* **Gasoline-Electric Hybrid** **Electric Vehicles:** *Micro-Mild Hybrid* *BEV (only light vehicles, no convertor, DC Motor, Range<100 km*	**Solo/High blend BE** **Diesel-Electric Hybrid** **Electric Vehicles:** *Enhanced HEV-PHEV* *BEV (with convertor, AC Motor, Range > 100 km)* *Full Hybrid* **FC hybrids** *(conventional fuel + hydrogen)*	**Solo/High blend BD** **Biogas Vehicles** **Electric vehicles:** *FCV- PHEV (Plug-In functionality for FCV/HEV)* *BEV (extended range, with convertor, AC Motor)* **Dedicated FCV**

Source: (Toro F. A., et al., 2010)

Abbreviations = NG: Natural Gas, LNG: Liquid NG, CNG: Compressed NG, BD: Biodiesel, BE: Bioethanol, EV: Electric Vehicle, HEV: Hybrid EV, BEV: Battery EV, PHEV: Plug-in Hybrid EV, DC: Direct Current, AC: Alternative Current, FC: Fuel Cell, FCV: FC Vehicle

Conventional diesel and gasoline cars and few AAMTs like NGV, flexi fuel cars already exist in the European market on a commercial level. Technologies

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mapped under the Demonstration phase may achieve commercial scale between 2012-2015 or later, depending on the speed of the technological progress and overcoming market and cost barriers. The technologies exhibiting the R&D phase will continue to progress to overcome technical challenges and incompatibilities, and will reach the commercial phase no sooner than 2020-2025.

Conventional vehicles (ICEVs) dominate the market of cars in Europe by over 90% (Wells, Nieuwenhuis, Nash, & Frater, 2010). As seen in Table 4, currently available AAMTs like NGVs, Flex-fuel and Bi-fuel cars (e.g. fossil fuel + gas vehicles) exist in the market on a commercial scale and they also demonstrate continuous technological developments and betterment (EPA-CATP, 2006) (Murphy, 2010). In the near term (by 2015), introduction of solo/high blend biofuel cars (biodiesel or bioethanol) and enhanced hybrid-electric vehicles can be expected, but technologies like FCVs and extended range BEV are foreseen to enter into the market on a commercial scale in long term (after 2020).

Electro-mobility is new in Europe and major RD&D activities currently relate to developments of extended range battery technologies and cost reductions to around 500 €/kWh by 2020 (Toro, et al., 2010). Another type of electric vehicle, the fuel cell vehicles (FCVs) do not have a clear defined time line for commercial scale-up. The foreseen period for commercialization is expected after 2020. Fuel cell research and development nowadays is aimed at achieving high efficiency and durability, low material and manufacturing costs of the fuel cell stack. For fuel cells, scaling-up and reducing Platinum loading can be important factors for the cost of production reduction to around 26-100€/kW (Mock & Schmid, 2008). Interestingly, BEV and FCV do not produce any tail-pipe emissions, hence they are considered promising option for zero emission vehicles, but the emissions generated during the production of electricity or hydrogen (well-to-tank emissions) cannot be overlooked.

The personal car in Europe is very crucial for general public mobility, and the choice of automotive technology depends on the usages, driving locations and consumer preferences etc. In the EU, the numbers of alternative fuel vehicles vary amongst the member states where Germany, France, The Netherlands and Sweden account for the maximum share of alternative fuel vehicles across Europe. 2008 data for Germany shows around 215,000 NGVs, 12,000 hybrids and around 3,000 electric

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vehicles. In France, the maximum share of alternative fuel vehicles was held by NGVs (155,000; around 80% of all AAMTs), nearly 19,000 hybrids and nearly 3,000 flex-fuel and electric vehicles. In the Netherlands, figures from 2007 show a total of around 234,000 AAMTs, of which NGVs account around 220,000, EVs around 10,000 and around 2,000 hybrids. Sweden accounts for nearly 200,000 FFVs and about 3000 NGVs, hybrids and EV's. However, the Czech Republic and Greece show a decreasing number of AAMTs over the time (being 7,200 in 2000 to 5,300 in 2007 in Czech Republic, and 2,200 in 2000 to 500 in 2007 in Greece).[4] CNG vehicles have been most popular in Italy, where the number of NGVs in 2008 was 432,900, which was equivalent to 1.2% of the overall car stock. Vehicles using gaseous fuel have been quite successful in Sweden and Germany, where they account for 0.3% and 0.1% of the total car stock, respectively (Hill, 2008).

3.2.2 AAMTs – Technical improvement potentials

There are continuous technical improvements and technology advancements in AAMTs within Europe, and several authors and published studies have stated future technical improvement potentials of various AAMTs. Following few of those studies, Figure 9 shows a picture of the expected fuel consumption improvements in AAMTs by 2030. The graph is made on literature based values derived from (GM-LBST, 2002), (Heywood, Weiss, Schafer, Bassene, & Natrajan, 2004), (Cheah, Evans, Bandivadekar, & Heywood, 2007), (Bodek & Heywood, 2008), (Kobayashi, Plotkin, & Ribeiro, 2008), (IEA, 2008) and (Concawe, 2008). The graph summarizes how fuel consumption (in terms of l/100 km) from different AAMTs may reduce until 2030, mainly based on technological developments and technical improvements.

[4] Deliverable-3 (D3) of workpackage-2 (WP2) of ALTERMOTIVE project

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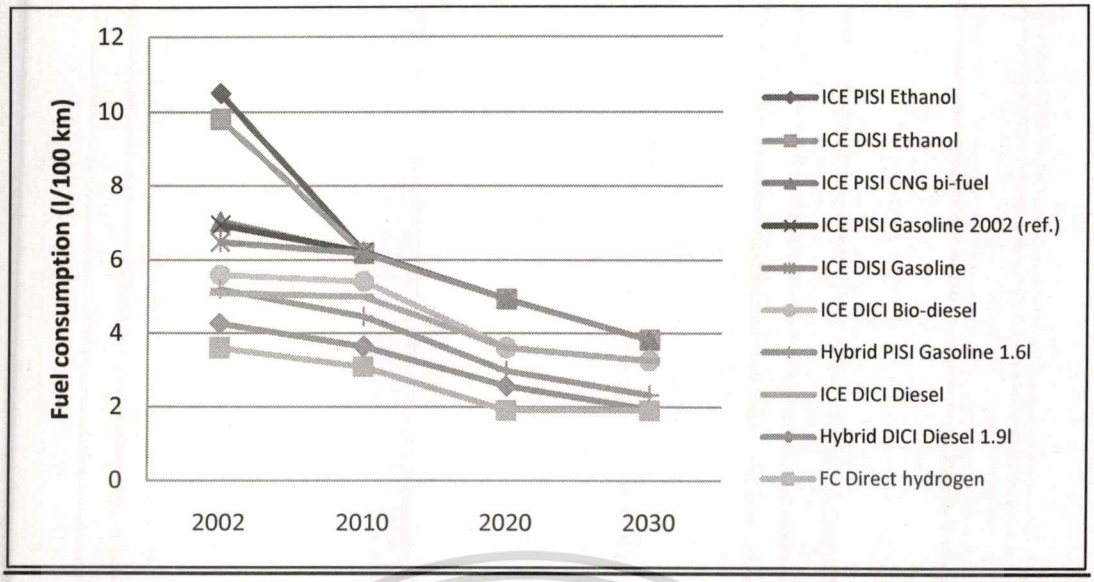


Figure 9: AAMTs fuel consumption improvements until 2030
Source: (Toro F. A., et al., 2010) (Other sources stated in text)

Abbreviations = PISI: Port Injection Spark Ignition, DISI: Direct Injection Spark Ignition, DICI: Direct Injection Compression Ignition, FC: Fuel Cell

Different AAMTs have potentials of 20% to 50% improvement by 2030. Figure 9 states that the maximum potential of technical improvement lies in the Ethanol ICEs (both PISI & DISI), where the fuel consumption from 10-11 l/100km in 2002 may decrease to around 4 l/100km by 2030. The figure also states that Fuel Cell Vehicles (direct hydrogen combustion cars) show the potential to have fuel economy, as high as 2 l/100km by 2030. Taking all the AAMTs into account, the future for achieving an average fuel economy of 2-4l/100km up to 2030 by different AAMTs seems plausible.

3.2.3 AAMTs – Economic assessment

Within the WP3 of *ALTER-MOTIVE*, conventional vehicles and AAMTs including hybrids, plug-in hybrids (PHEV), battery electric vehicles (BEV) and Flex-fuel technologies combined with ICEs were assessed on their economic performance and partially on their environmental performance. Figure 10 shows the specific driving costs in (€/100km) of different powertrain technologies based on the fuel they use (excluding fuel consumption rate or fuel prices). These costs are calculated

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by considering various technical and economic features like engine power, annual driving ranges, investment and O&M costs etc. The specific driving costs by different AAMTs show a varied range of between 28€/100km for conventional gasoline ICEV to around 54€/100km for battery electric vehicle.

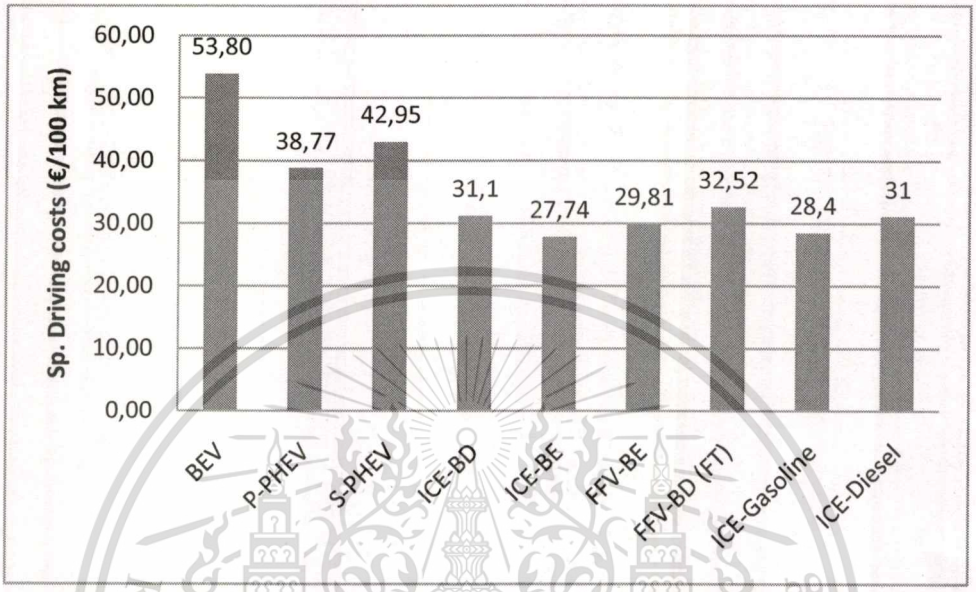


Figure 10: AAMT - Economic Assessment: Specific Driving Costs (€/100km)
Source: (Toro F. A., et al., 2010)

Abbreviations = BEV: Battery Electric Vehicle, P-PHEV: Parallel Plug-in Hybrid Electric Vehicle, S-PHEV: Serial Plug-in Hybrid Electric Vehicle, ICE: Internal Combustion Engine, BD: Biodiesel, BE: Bioethanol, FFV: Flex-Fuel Vehicle, FT: Fischer-Tropsch Diesel

Specific driving costs refer to the costs of driving vehicle per kilometre (excluding fuel expenditure). Specific capital costs or specific driving costs are the highest component of the driving costs for all technologies (as seen in Figure 10), and they increase with increased O&M costs and wear & tear of the vehicle. Currently biofuel-ICEs (both biodiesel and bioethanol) and flex fuel vehicles show specific driving costs close to conventional ICEVs. BEVs or PHEVs show the highest specific driving costs than other technologies. However, the forecasts of batteries to reach the price range of 500 €/kWh (for Li-Ion batteries) by 2020 due to

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technical improvements can make significant contributions towards the reduced capital costs.[5]

Figure 11 shows the comparison between Specific driving costs and Specific CO_2 emissions from different ICEVs running on conventional and alternative fuel. The figure states that biodiesel (1st generation) and Fischer-Tropsch biodiesel (biomass-to-liquid or 2nd generation biodiesel) show better environmental performance than other vehicles. But at the same time, the specific driving costs of these technologies are higher than conventional or flex-fuel vehicles running on ethanol mixtures. Biodiesel and Fischer-Tropsch biodiesel perform more or less same in terms of CO_2 emission, but the 1st generation biodiesel is a cheaper fuel option between the two.

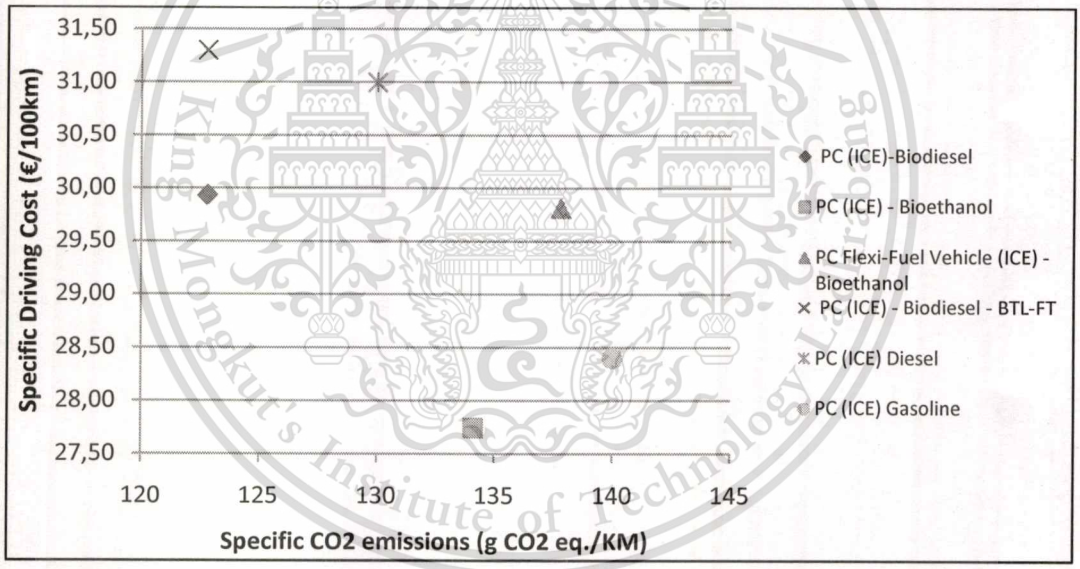


Figure 11: AAMTs - State of the Art Assessment (€/100km vs. g CO_2eq/km)

Source: (Toro F. A., et al., 2010)

Abbreviations = PC: Passenger Cars, ICE: Internal Combustion Engine, BTL- FT: Fischer Tropsch Diesel

[5] Other studies like Pesaran, A.A., T. Markel, H.S. Tataria, D. Howell (2009): Battery Requirements for Plug in Hybrid Electric Vehicles, NREL/CP-540-42240 and F. Nieuwenhout, C. Kolokathis, Oe. Oezdemir, K. Schoots (2009): ITM WP3 Financial and economic analysis of electric vehicles and heat pumps assume the battery cost reductions to the level of around 300€/kWh.

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3.2.4 AAMTs – Environmental assessment

Table 5 states the GHG emissions (CO_2, CH_4 and N_2O) from various AAMTs across Europe. These emission figures are derived from CONCAWE version-3 and the values refer to the TTW emissions for conventional vehicles and AAMTs using biodiesel, bioethanol and blends in the engines (Concawe, 2008).

Table 5: Average TTW GHG emission from ICE vehicles

Fuel/Engine	Specific CO_2 emissions (g CO_2/km)	Specific CH_4 emissions (g CH_4/km)	Specific N_2O emissions (g N_2O/km)	Total (g CO_2 eq/km)
Gasoline (PISI)	139.4	0.5	0.5	140.3
Ethanol	135.6	0.9	0.9	137.4
Gasoline/Ethanol (95/5) (PISI)	139.3	0.5	0.5	140.2
Gasoline (DISI)	137.9	0.5	0.5	138.8
Ethanol (DISI)	134.1	0.9	0.9	135.9
Gasoline/Ethanol (95/5) (DISI)	137.8	0.5	0.5	138.7
Diesel (No DPF)	118.0	0.2	1.5	119.7
Biodiesel (No DPF)	122.8	0.2	1.5	124.5
Biodiesel (BTL-DME)	108	0.2	1.5	124.5
Diesel (DPF)	121.4	0.2	1.5	123.3
Biodiesel (DPF)	126.3	0.2	1.5	123.8
Diesel/Biodiesel (95/5) (DPF)	122.1	0.2	1.5	123.8

Source: (Concawe, 2008)

Abbreviations = PISI: Port Injection Spark Ignition, DISI: Direct Injection Spark Ignition, DPF: Diesel Particle Filter, BTL-DME: Biomass to Liquid- Di-Methyl Ether

Figure 12 compares the TTW emissions (gCO_2 eq/km) of various AAMTs. Amongst all AAMTs, vehicles using BTL-FT biodiesel (DME-Di-Methyl Ether) perform the best in terms of TTW emissions. For other AAMTs, the emissions range between 120 to 140 gm/km. It should be noted that battery electric and hydrogen

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vehicles are not included in the graph because they do not produce any emissions during driving (i.e. zero tank-to-wheel emissions).

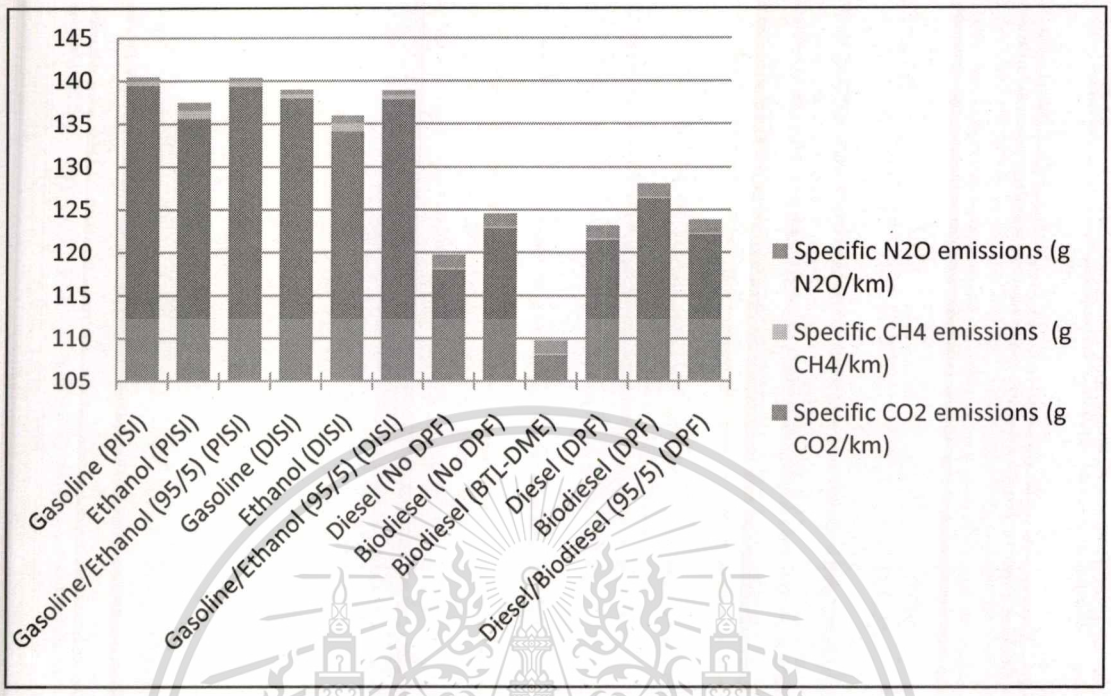


Figure 12: TTW Comparison between different AAMTs

(gCO_2 eq/km for 2010 ICEVs)

Source: (Concawe, 2008)

Abbreviations = PISI: Port Injection Spark Ignition, DISI: Direct Injection Spark Ignition, DPF: Diesel Particle Filter, BTL-DME: Biomass to Liquid- Di-Methyl Ether

Environmental performance or emission per kilometre from any AAMT depends on the vehicle efficiency, fuel blend used, driving behaviour, driving conditions (urban or highway), vehicle maintenance and many more, hence, actual on-road TTW emission from vehicles may differ (ECMT, 2005). The values stated in Table 5 and Figure 12 are derived from Concawe (2008) where the assessment was done with a complex technology model ADVISOR via simulating the original European driving cycle. The values indicate that vehicle technology performs differently on TTW emissions, but when the complete WTW assessment is taken into account, the biofuels in combination to engine technologies may show better results than conventional fuels and ICE vehicles. Therefore, technical efficiency increase across the biofuel production chains (on WTT level) and AAMTs (on TTW level) may offer a combined solution for the fossil fuel demand and emission reduction, and a sustainable transport development (Toro F. A., et al., 2010).

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3.3 Technical improvement potentials in European Cars

To answer question 1 stated in section 1.1 of this study, this section compiles a range of energy efficiency and technical improvement measures in the European passenger cars and summarizes their potentials in improving the efficiency.

With over 80 EU directives and 115 UNECE legislation (United Nations Economic Commission for Europe), the European car industry is one of the most regulated sectors in the EU. To reach the target of an average car fleet emission and an enhanced vehicle efficiency, the European automotive industry has identified multiple categories for innovative technologies to improve car systems and other vehicle components. Every year, European automobile manufacturers spend over € 26 billion on automotive R&D, and the biggest share of this investment is spent on advanced and innovative technologies. Figure 13 indicates the amount of money spent on R&D by leading car manufacturers in Europe during 2005.

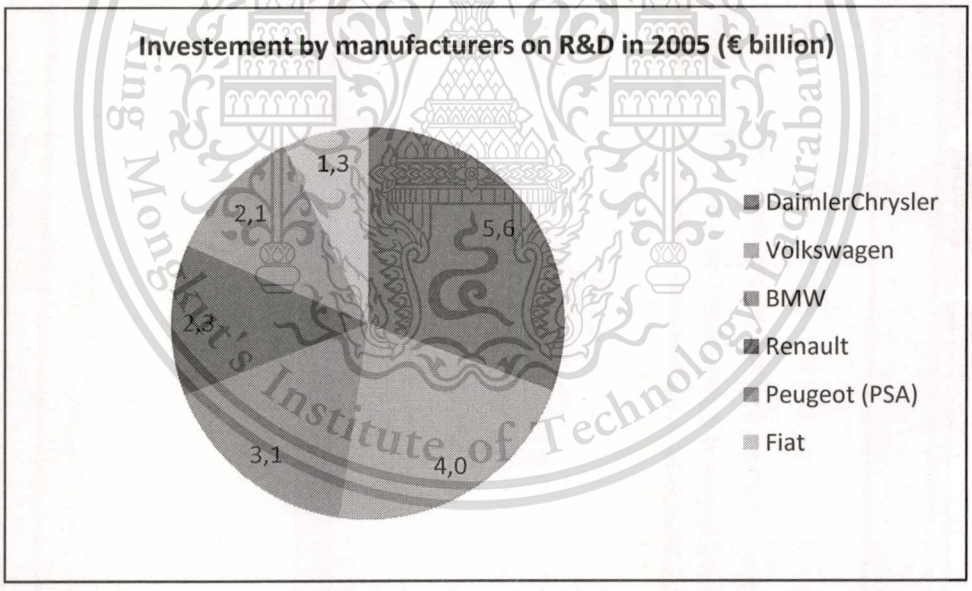


Figure 13: Investment on R&D by European car manufacturers
Source: (ACEA, 2008)

There are numerous technological modifications and advanced technologies that can be integrated or modified to improve the vehicle and fuel efficiency. These technologies have different elements and features to enhance the efficiency by a certain percent. Technical improvement potentials stated in Table 6 are classified in five types based on the level of their application or integration into the car. **Body**

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technologies, Engine technologies, Transmission technologies, Hybrid technologies and **Others.** Table 6 summarizes the technologies and the expected increase in efficiency from them. Please refer APPENDIX I for the details and explanations of technologies.

Table 6: Summary of technical improvement potentials

	Measures	Explanation	Efficiency Increase
Body Technologies	Vehicle weight reduction	Lightweight construction & designing material, reducing low use vehicle features, using smaller capacity fuel tanks	4-6 %
	Aerodynamic drag	Reduction of air drag by better vehicle design and streamlining	2-4 %
Engine Technologies	Variable Valve Timing & Lift	Improves efficiency by optimizing the flow of fuel & air into engine cylinder	1-9 %
	Cylinder Deactivation	Saves fuel by deactivating cylinders when not in use	5-7.5 %
	Downsizing, Turbo & Superchargers	Increases the power by downsizing the engine	2-7.5 %
	Direct Fuel Injection	Injects the fuel directly into the cylinder	3-15 %
	Homogeneous Charge Compression Ignition (HCCI)	Simultaneous ignition of fuel and air throughout the whole cylinder	10-15%
	Optimised/advanced cooling and electric water pump	Cools down the engine and utilizes the spare heat energy	1-3%
	Reducing Engine Friction	Minimizing the friction between moving metal parts in the engine	1-4%
	Heat recovery systems	Utilization of waste heat	1-3%
Transmission Technologies	Continuously Variable Transmissions (CVTs)	Multiple numbers of "gears" to provide seamless acceleration and improved fuel economy	3-8 %
	Automated Manual Transmission (AMT)	Combining the features of manual and automatic transmissions	7-9 %
Hybrid Technologies	Integrated Starter / Generator (ISG) Systems	Turns off the engine when the vehicle stops and restarts, when the accelerator is pressed	3-4 %
	Regenerative braking	Converts the of lost mechanical energy during braking into electricity	5-7%
Other Technologies	Overcoming rolling resistance	Reduction of the mechanical resistance and friction between tires and the road	2.5-5 %
	Use of advanced accessories	Gear shift indicators (GIS), Power steering, Latent heat storage in batteries, GPS Navigations, Tire pressure monitoring systems (TPMS)	3-5 %

Source: TNO (2006); EPA (2008); AEA (2009); Kobayashi (2009); McKinsey (2009)

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3.3.1 Technology Readiness

Considerable opinions and technology status are involved in determining the *maturity or readiness* of technologies. It is not only a matter of availability, but also of how well a technology performs and how much it costs (ORNL, 2000). The innovative and improvement technologies stated in Table 6 exhibit various states of development towards commercialization. For example, low rolling resistance tires, improved aerodynamic efficiency and engine friction reducing technologies have been developed and implemented extensively in various cars in the last few years. And these technologies are at the state of wide scale application within the current car production. However, technologies like cylinder deactivation and strong downsizing are still being researched and have been introduced only in few early prototype vehicles (Wells, Nieuwenhuis, Nash, & Frater, 2010). Table 7 states some technologies and their current status of industrial application and adaptation in the Europe.

Table 7: Technical improvement technologies in Europe (2010)

Technology	Status in Europe
Vehicle weight reduction	Available now, High consideration for application by industry
Aerodynamic drag	Available now, High consideration for application by industry
Reducing engine friction losses	Available now, High consideration for application by industry
Low rolling resistance tires	Available, applicable in new cars
Electric power steering	Available
Petrol-electric hybrid	Available
Start stop system	Available now in hybrid electric vehicles, beyond 2012 for broad application
Tire pressure monitoring system (TPMS)	Available, Broad application by 2012-2013
Cylinder deactivation	Prototypes available, R&D
Variable valve activation	Prototypes available, R&D
Downsizing (Mild)	Prototypes available, R&D
Downsizing (Strong)	R&D
Gear shift indicator	2012 and beyond

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Technology	Status in Europe
Diesel-electric hybrid	2012-2013
Plug-in hybrid (strong hybrid)	2012-2013
Homogeneous charge compression ignition (HCCI)	Beyond 2015

Source: Compiled by the author, (Wells, Nieuwenhuis, Nash, & Frater, 2010)

While assessing the technology readiness, one fact not to be forgotten is, that, the actual state of development of a specific technology may vary from one manufacturer to another. The reason is, that, manufacturers may need to do substantial investments for the introduction of a new technology in enough volume to meet the product lines (EPA, 2008). Some technologies may involve diversification from current production chains and potentially requiring large scale retooling and changes in the current manufacturing units. Moreover, some of the technologies may be so new that manufacturers are not familiar with their reliability, and therefore safety and warranty concerns may come across with the technological development (US-ITA, 2009).

3.4 Conclusions of Chapter 3

The European commission and the automotive industry, both consider the importance of "integrated approach" for meeting the future sustainable mobility in Europe. Over the coming years in the EU-27, varied technical innovations and increasing diversity of AAMTs and fuel diversification will rationalize to several mainstream solutions for environmental mitigation and sustainable transport.

Currently, conventional passenger cars show energy efficiency of only around 15-30%, therefore, for an increased fuel economy and subsequent emission reductions, the chances and benefits of introducing improvement technologies are significant. The European car manufacturers in recent years have introduced several advanced technologies in the cars that have resulted in reduced emissions and better performance of the vehicle.

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Research question 1 as stated in the introduction (section 1.1) can be answered in Section 3.3. In the Table 6, the technical improvement technologies along with their characteristics and potentials in efficiency increase are mentioned.

To answer the question, an intensive review of literature, scientific studies, reports and other publication from automakers and academic groups was done. Almost all of the studies consider a leading role of technologies in reducing energy demand and emissions. They also consider that the technical improvements and new technologies will add an incremental cost to the vehicle. Amongst all referred studies, a large area of variation in the efficiency potential (%) and costs of technologies exists.

There is a significant diversity of technologies and improvement potentials available in the market, but, only a few of them are available for a broad scale production (like reduced engine friction losses, improved aerodynamics, low rolling resistant tires). A few other technologies like gearbox optimization, tire pressure monitoring systems are under advanced R&D, and a few will be considered promising for broad scale application only if they can overcome technical and/or cost barriers and safety concerns (like strong downsizing, homogeneous charge compression ignition).

By taking into account the increasing diversity in innovation and improvements, it is not easy to say which technology will be the most successful. Most likely, the future will see a number of technological combinations entering the market, tailored for different usages, driving circumstances and consumer preferences.

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4. METHODOLOGY

The methods and elements involved in this study for the analysis and to answer all four of the research questions are stated in Figure 14.

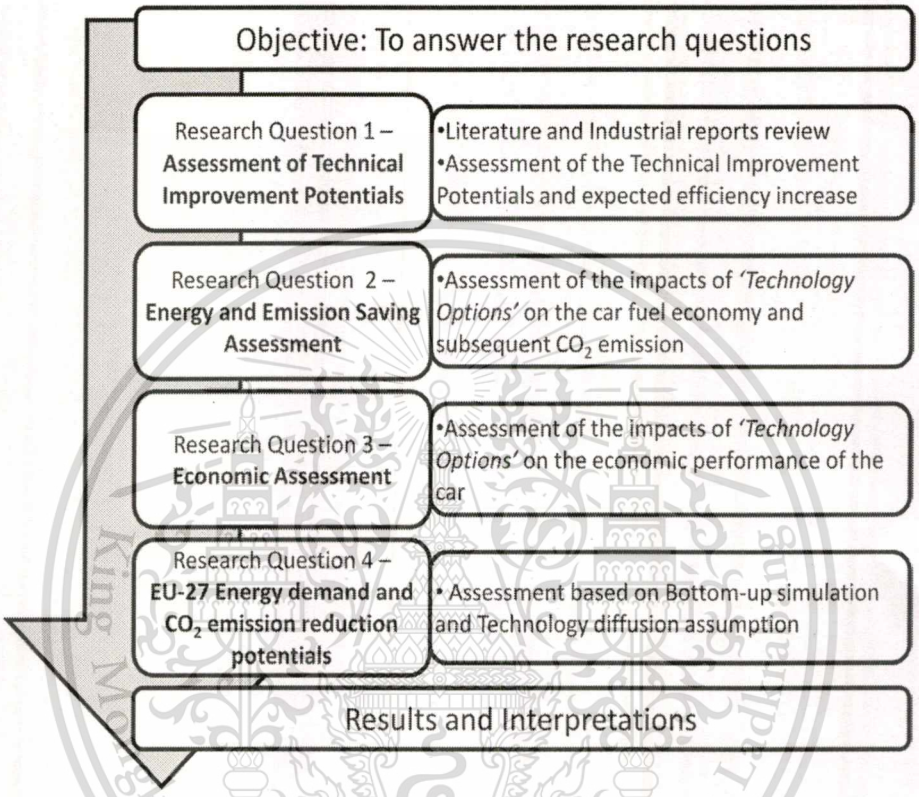


Figure 14: Methodology and elements of research for the thesis

Source: Created by the author

To answer research question 1, the first element of this study relates to an intensive literature and industrial reports review to assess the existing and upcoming improvement technologies, as well as the potentials of these technologies in the vehicle efficiency improvement. The summary of improvement technologies is stated in section 3.3 (Table 6).

To answer research questions 2 and 3, this study selects two sets of innovative improvement technologies i.e. ***'Technology Option 1 & 2'*** from (EPA, 2008) and (McKinsey, 2009) respectively. In the next step, the assessment of the

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impacts of integration of *'Technology Option'* on the vehicle's fuel demand, emission generation and economic performance was done.

To answer the last research question, this study utilizes a **bottom-up simulation** and evaluates the potentials of saving energy and emissions from European passenger cars until 2030, based on the assumed diffusion of *'Technology Options 1 & 2'* into gasoline and diesel cars.

4.1 Technology Options considered for this study

In Europe, in the foreseeable future, conventional internal combustion engines vehicles are expected to make the biggest share of fleet, and remain more cost competitive than other alternative automobile technologies (Skinner, Essen, Smokers, & Hill, 2010). Therefore, improvements in the efficiency of conventional vehicles can be very important to reduce the personal transport's energy demand and GHG emissions. Virtually all the technologies stated in Table 6 are capable of enhancing vehicle efficiency and reducing fuel demand, they all are not equally ready for commercial production. The technologies grouped as *'Technology Option 1 and 2'* in Table 8 are currently on an advanced level in Europe and are applicable into conventional cars within 2012-2015 timeframe.

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Table 8: 'Technology Options' considered for the study

	'Technology Option 1'	*'Technology Option 2'*
Technology Combination (Technologies clustered in the option)	1. Reduced engine friction losses 2. Improved aerodynamics 3. Low rolling resistance tires	1. Improved aerodynamics 2. Vehicle weight reduction (medium) 3. Optimized transmission 4. Mild downsizing with Turbo Charging 5. Start-stop-system 6. Use of advanced devices (tire pressure monitoring system, gear shift indicator etc.)
Expected efficiency increase	Around 5%	Around 22%
Source - eff. Increase	(EPA, 2008) [6]	(McKinsey, 2009) [7]
Cost of Tech. Option - Gasoline car [8]	350€	2,800€
Cost of Tech. Option – Diesel car [9]	350€	2,450€
Status in Europe	High degree of technology readiness. Integrated into new cars by most manufacturers	Medium to high degree of technology readiness. High consideration for application into new cars in the near future

Source: Elaborated by the author

4.1.1 Technology Readiness – *'Technology Option 1'*

The technologies included in *'Technology Option 1'* are highly developed until now and are implemented into new vehicles by European car manufacturers. Nearly all European automobile manufacturers have considered improved aerodynamics and reduced engine friction losses as an upfront solution for enhancing the vehicle efficiency (Technology Action Plan: Advanced Vehicles, 2009).

[6] (EPA, 2008) = EPA Staff Technical Report: Cost and Effectiveness Estimates of Technologies Used to Reduce Light-duty Vehicle Carbon Dioxide Emissions.
[7] (McKinsey,2009) = Der Trend zu energie - effizienten Pkw, Implikationen für die deutsche Automobilindustrie.
[8] Refer section 4.1.3 for details.
[9] Refer section 4.1.3 for details.

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Moreover, the technologies for aerodynamic improvements and reduced engine friction losses are continuous refinement processes, therefore, they will continue to make further technological progress with the time.

Setting maximum rolling resistance limits for the tires of new cars after 2012 is one of the most important considerations within the "integrated approach" proposed by the European commission. Therefore, in future, it will be compulsory for the European manufacturers to integrate low rolling resistance tires into new vehicles (Global Fuel Economy Initiative, 2009).

After analyzing the trends of technology readiness and application, the *'Technology Option 1'* can be considered highly promising for broad scale application into vehicles in near future.

4.1.2 Technology Readiness – *'Technology Option 2'*

Continuous improvements are made in the conventional gasoline and diesel vehicles through various innovative technologies, and technologies included in *'Technology Option 2'* are also seen highly promising by industry for the purpose of enhanced fuel economy. These technologies have a medium to high degree of market readiness. Few of them are already implemented by the manufacturers in currently produced cars, and few others are emphasized by the European Commission for integration into new cars in the near future.

Vehicle weight and aerodynamic drag reductions are already researched and developed considerably in the last few years, and these are seen as both near and long term solutions by several car manufacturers (Skinner, Essen, Smokers, & Hill, 2010). The weight of a vehicle is directly correlated to the fuel consumption and CO_2 emission, and to resolve this issue there is increased application of plastics and other light weight construction materials. The future advanced lightweight materials could include HSLA (High Strength Low Alloy), aluminum, magnesium, fiber reinforced and other composites (AEA, 2009). Moreover, the European Parliament resolution of 16th November 2005 on "Winning the Battle against Global Climate Change"

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supports the evaluation of the possibility of emission reduction beyond 2012 through the use of lighter manufacturing materials into the vehicle.

In the European car fleet, manual transmission systems dominate with a market share of about 80%. But, for better vehicle efficiency, transmission optimization through automated manual transmissions and dual clutch transmissions are considered very important. This fact is reflected through the increasing trend of cars with automatic transmissions systems within Europe (Global Fuel Economy Initiative, 2009). Therefore, in Europe, in the upcoming years, technologies related to transmission optimization will have a widespread share within new cars.

Technologies that can reduce the conventional energy losses are also considered crucial by manufacturers in addition to the innovative technologies. Engine downsizing and turbocharging is good example of such technologies. Currently, internal combustion engines are downsized with turbocharging to increase the engine output and efficiency, without even compromising with the power. Another good example of technologies that can reduce energy loss is the start-stop system. This system turns off the engine when car stops and re-starts the engine when the accelerator is pressed. Both of these relatively low-cost technologies are likely to be used extensively over the next decade within Europe for meeting high fuel economy and GHG emission standards (Technology Action Plan: Advanced Vehicles, 2009).

As stated in Section 3.1, European Regulation (EC) No. 443/2009, approved by the European Parliament focuses on most important technological considerations for the solution of GHG emission cars through "integrated approach". Few of those technological considerations include, compulsory fitting of tire pressure monitoring systems (TPMS) and gear shift indicators (GSI) into new cars after 2012.

Therefore, after analyzing the state of the art of technologies and expected future developments in Europe, the *'Technology Option 2'* is considered to have a medium to high degree of market readiness. Though the technologies are expensive at the moment, but followed by technology learning and scale effect, the cost of production of technologies may decrease.

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4.1.3 Cost of *'Technology Options'*

This section is a part of the corrigendum.

Due to unavailability of any absolute data on incremental cost of technologies, the concept of Retail Price Equivalent Multiplier (RPE) was used to assess the incremental cost of *'Technology Options'*. The RPE factors are empirically derived multipliers intended to account for all direct and indirect costs, including auto manufacturer R&D, other engineering costs, corporate overhead, pensions, marketing, dealer support and profits etc.

The "RPE factors" or "RPE multipliers" are used to assess the direct and indirect costs involved in deciding the retail price of the technology(ies) and they represent the average additional price consumers would need to pay for a technology. The RPE factors are divided into two major types i.e. RPE factor of 1.5 for outsourced technologies or components and 2.0 for products developed and manufactured internally at an automotive manufacturer. The data on additional manufacturer costs is available from (AEA, 2009) and these costs were converted into incremental retail costs by using the "Retail Price Equivalent Multipliers" derived from (Vyas, Santini, & Cuenca, 2000) & (NRC, 2010).

RPE best represents the long-run, substantially learned, industry-average production costs and also incorporates overhead direct and indirect expenses (NRC, 2010). Therefore, the concept of incremental retail price equivalent (RPE) seems to be the most appropriate indicator for assessing the incremental cost of technologies. The formula used for the assessment of incremental cost of *'Technology Options'* is:

$$IC_{TO} = C_M \times RPE\ factor \qquad \text{Eq. 1}$$

Where IC_{TO} is the incremental cost of *'Technology Option'* over the vehicle baseline price, C_M is the manufacturer cost of technologies included in the *'Technology Option'*, and *RPE factor* is the retail price equivalent multiplier.

Out of all the referred studies for this study, none has given the precise incremental costs of technologies or explicitly formulated the real method to do so. And also, there appears to be a great degree of uncertainty about the costs of fuel

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economy technologies and their impacts on fuel consumption between different studies. In any case, changing vehicle designs takes time, and the dynamics of fuel economy improvement are not explicitly considered in any of the studies (except some learning curves for specific technologies). While most studies recognize this fact, RPE seems to be the formal method for incorporating incremental costs into fuel economy potential assessments.

4.2 Energy Demand and Emission Saving Assessment

The term fuel economy refers to the energy consumed by a car to travel a certain distance. In this study, it is considered, that, addition of any efficient technology yields a higher fuel economy than the previous fuel economy of the vehicle.

Figure 15 elaborates the energy demand and emission assessment carried in this study. The upper part of the figure states, that, for an average annual travelling with a fixed fuel economy, the vehicle has a particular energy demand and produces the consecutive emissions. However, as shown in the lower part of the figure, with technical improvements, the fuel economy of the vehicle enhances, and as a result the energy demand and emissions for the same annual travelling distance reduce.

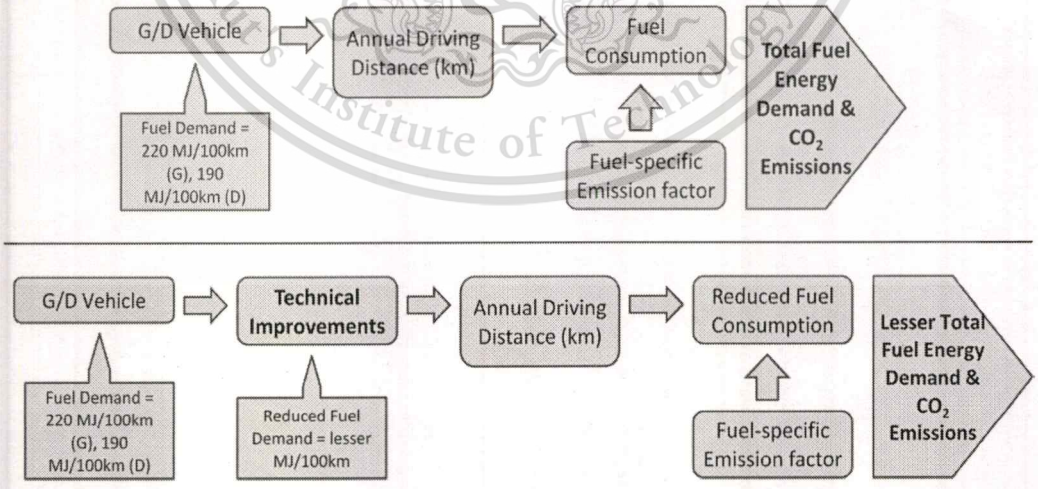


Figure 15: Elements of Techno-environmental Assessment

Source: Created by the author

Abbreviations: G = Gasoline Vehicle, D = Diesel Vehicle

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Equations involved in the energy demand and emission saving assessments are stated as follows.

Changes in the vehicle fuel economy: In this study, it was considered that when *'Technology Option'* is integrated into the car, the baseline fuel economy increases by a certain percentage. The equation used in assessment is:

$$FE_e = FE_b \times (1 - \%E_{TO}) \qquad \text{[MJ/100km]} \qquad \text{Eq. 2}$$

Where, FE_e is the enhanced fuel economy, FE_b is the baseline fuel economy of the vehicle and $\%E_{TO}$ is the percent (%) by which the *'Technology Option'* enhances the efficiency.

Changes in the vehicle CO_2 emission: As a result of improvements by *'Technical Options'*, the fuel demand reduces and therefore the consecutive CO_2 emission also decreases. The equation used in assessment is:

$$CO_{2\,red.} = FD_r \times SE_f \qquad \text{[g/MJ]} \qquad \text{Eq. 3}$$

Where, $CO_{2red.}$ is the reduced emission, FD_r is the reduced amount of fuel as a result FE_e (enhanced fuel economy) and SE_f is the fuel specific emission factor.

4.3 Economic Assessment

The introduction of new technologies into vehicles for enhanced efficiency may cause extra investments and additional upfront costs for the manufacturers, and these costs will add extra price over the vehicle baseline prices (McKinsey 'b', 2009). Thus, it is technically feasible to reduce the fuel consumption of new vehicles by implementation of *'Technology Options'*, but additional investment costs will incur. In this study, the effect of these incremental costs on the car's specific driving costs, cost of CO_2 avoidance, the payback period and other economic performance indicators was assessed.

Figure 16 presents an overview of the economic assessment and the effectiveness of technologies on the car. The left hand side of the diagram refers to

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the baseline vehicle values, while the right hand side of the diagram states an improved vehicle into which the *'Technology Option'* is integrated. The diagram shows the changing pattern of specific driving costs, specific CO_2 emission and final energy demand and CO_2 emission by the car.

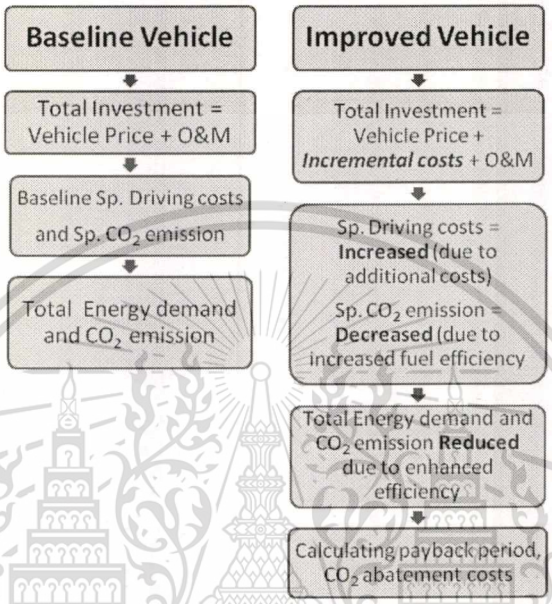


Figure 16: Elements of Economic Assessment

Source: Created by the author

Abbreviations: O&M = Operation and Maintenance, Sp. = Specific

Specific Driving Cost: The Specific driving cost refers to the technology cost of driving the vehicle per kilometre. The specific driving cost for a given vehicle is an integral component of the vehicle's economic performance and this cost in the assessment is interpreted as an aggregate construct of vehicle investment costs linked to O&M costs, average annual traveling distance and vehicle lifetime of 10 years.

$$SC_d = \frac{I_a + O\&M}{D_{annual}} \qquad [€/km] \qquad \text{Eq. 4}$$

Where SC_d is the specific driving cost, I_a is the annual investment cost, $O\&M$ is the operation and maintenance cost (@ 8%/yr) and D_{annual} is the annual distance travelled by the car.

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Average payback period[10]: The average payback period refers to the time period in which the incremental costs on *'Technology Options'* can be compensated through the savings in the money that occur as a result of the enhanced fuel economy or the decreased fuel demand.

$$PB_{avg} = \frac{C_i}{AS_€} \qquad \text{[Years]} \qquad \text{Eq. 5}$$

Where PB_{avg} is the average payback period, C_i is the incremental cost and $AS_€$ is the annual monetary saving (in €).

CO_2 abatement cost or Cost of CO_2 avoidance: It is assumed that for a technically improved vehicle, the driver pays additional costs over the vehicle price. So, the cost (in €) that the driver bears for avoiding or saving each tonne of CO_2 is termed as the cost of CO_2 avoidance. The formula used for calculation is:

$$CO_2\ abatement\ cost = \frac{C_i}{Tonne\ CO_{2\ saved}} \qquad \text{[€/tonne]} \qquad \text{Eq. 6}$$

Where C_i is the incremental cost and $Tonne\ CO_{2saved}$ is the CO_2 saved within vehicle lifetime.

4.4 Bottom-up Simulation

To assess the total energy demand and CO_2 emission from all European passenger cars up to 2030, a bottom-up simulation tool was developed.[11] The bottom-up simulation tool does the estimation by adding the energy demand of new cars entering into the European market to the energy demand of existing cars. For the assessment, various elements on the types of passenger cars (diesel, gasoline etc.),

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[10] This equation is also a part of the corrigendum. The calculation of average payback period in the Thesis was done by dividing incremental costs of technology options by lifetime monetary savings instead of annual monetary savings.

[11] The methodology for the bottom-up simulation is adapted from Toro.F., Jain. S., Reitze. F., Rosende. D. (2010). Analysis of the technological innovation potentials in alternative automotive systems and their effects on technology learning trends. *11th IAEE European Conference*, Vilnius, Lithuania.

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vehicle technical features (fuel economy, engine size) etc. were considered. The general formula for the energy demand assessment is:

$$ED_{t(Fu)} = \sum(F_{i,t} \times D_{i,t} \times FE_{i,t}) \qquad [PJ] \qquad \text{Eq. 7}$$

Where ED_t is the total energy demand (including different fuels *Fu*) in the year *t, i* is the model year. *F* is the number of vehicles of a model year *i* running in year *t* on fuel *Fu*. *D* is the annual distance travelled by a car of model year *i* in year *t* using fuel *Fu*. *FE* is the average fuel economy (MJ/100km) of the car for a model year *i*, using fuel *Fu*.

Data and values used in the bottom-up simulation are detailed in Table 9. Some of the major input parameters used in the assessment are:

1. Base Fleet - The total number and types of vehicles in the European car fleet until 2030. These datasets were derived from iTREN-2030 Reference Scenario report (Fiorello, et al., 2009).

2. New Cars - Number and types of new vehicles in the European car fleet until 2030. These numbers were simulated by the author using base fleet projections derived from (Fiorello, et al., 2009) (See details in section 4.5).

3. Average fuel economy - energy consumed by each type of car for a fixed driving distance. These values were derived from (Concawe, 2008).

4. Average annual travelling distance - the total kilometers traveled by different types of vehicles. For example, 18,000 km/yr by gasoline car, 20,000 km/yr by diesel car and 15,000 km/yr by other cars.

5. Fuel specific emission factor - the CO_2 emission produced by each unit of the fuel. These values were derived from (Concawe, 2008).

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CO_2 emission baseline: Within the bottom-up simulation, the total amount of CO_2 emitted by all types of cars was calculated by considering 'how much CO_2 each MJ of fuel produces'. Thus, by aggregating various fuel demands (gasoline, diesel, LPG/CNG demand) by the whole European car fleet and multiplying that with fuel specific emission factor, the CO_2 emission baseline until 2030 was established. It should be noted that Electric Vehicles (BEVs and FCVs) do not produce any TTW emissions; therefore, the fuel specific emission factor for these cars was taken as zero.

$$Total\ CO_2 = \sum\left(F_{i,t} \times FD_{i,t} \times SE_f\right) \text{ [Million Tonnes]} \qquad \text{Eq. 8}$$

Where *Total* CO_2 is the total CO_2 emission generated by the fuel demand (*FD*). *F* is the number of vehicles of a model year *i* running in year *t*. *FD* is the total fuel demand by the fleet of the model year *i* in year *t*. SE_f is the fuel specific emission factor.

Table 9 summarizes the datasets and values used in the bottom-up simulation.

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Table 9: Values and data on fleet and vehicle characteristic used for the bottom-up simulation

	Unit	2005	2010	2020	2030	Fuel sp. emi. factor[12]	Fuel economy[13]
Gasoline cars fleet size	1,000 vehicles	149,304	139,539	139,027	148,788	74.35	223.5
	% of total fleet	70.74%	61.15%	52.33%	50.57%		
Diesel cars fleet size	1,000 vehicles	57,588	82,723	117,190	135,371	73.54	183.1
	% of total fleet	27.28%	36.25%	44.12%	46.01%		
LPG/CNG cars fleet size	1,000 vehicles	3,229	2,856	2,061	2,016	60.96	223.5
	% of total fleet	1.530%	1.252%	0.776%	0.685%		
Bioethanol cars fleet size	1,000 vehicles	46	204	1,630	3,843	71.38	208.8
	% of total fleet	0.022%	0.089%	0.614%	1.306%		
Hybrid cars fleet size	1,000 vehicles	892	2,841	5,650	4,010	72.10	162
	% of total fleet	0.423%	1.245%	2.127%	1.363%		
Battery Electric Vehicles fleet size	1,000 vehicles	3	9	69	184	0	100
	% of total fleet	0.001%	0.004%	0.026%	0.063%		
Fuel Cells V. fleet size	1,000 vehicles	0	0	0	0	0	100
Total energy demand baselline – iTREN-2030	PJ	8,415	9,253	9,630	10,300	-	-
CO_2 emission baseline* (own calculations)	Mil.tonnes/yr	624	684	712	761	-	-

Source: (Fiorello, et al., 2009), (Concawe, 2008), * Calculated by the author

Abbreviations: V = Vehicle, PJ = Peta Joule

[12] Fuel specific emission factor, Unit = gCO_2/MJ, Source: (Concawe, 2008)

[13] Fuel economy = fuel consumption per 100 km, 2002 vehicle values, Unit = MJ/100km, Source: (Concawe, 2008)

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To establish the energy demand baseline until 2030 for this study, the energy demand projections derived from (Fiorello, et al., 2009) were used as reference. The energy demand and emission baseline values in Table 9 present a quantified projection, as, on what it would be like in 2030 if the fuel economy of each type of vehicle, number of vehicles and yearly travelling distance within Europe are maintained. These projections are used in this study as a baseline to compare the results of possibly changing total energy demand or emission trends until 2030.

4.5 Stock of new cars until 2030 in the EU-27

The decision to buy or sell a car is a choice made by each individual or family on the basis of various financial, socio-economic and technological parameters. Car ownership is an important element of the modern society and its level often reflects a country's average income, population and other consumer behaviors. In Europe, although the degree varies across member states, there is an evident correlation between car ownership and per capita income that has been consistent in the past and is expected to remain so in the future (Christidis, Hidalgo, & Soria, 2003).

To assess the impacts of technology diffusion into new cars through the bottom-up simulation, the stock of new vehicles until 2030 in the EU-27 was simulated by the author. The number of new registrations by 2030 was simulated based on GDP development and fleet size projection derived from (Fiorello, et al., 2009). The steps followed for the simulation are:

1. Reviewing the historical vehicle registration data and the GDP growth in Europe and finding the correlation between them.
2. Establishing the correlation of historical data to the expected GDP growth in the EU-27. (GDP growth projection was derived from (Fiorello, et al., 2009)).
3. Discussion with the experts (Alter-Motive National Stakeholder Workshop, Germany, 2011).
4. Simulating the new vehicle registrations until 2030, including numbers and types of cars.

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5. Complementing the simulated new registration data with other published data on the European passenger car fleet projections (TREMOVE (Basecase pivots v2.7b)).

Table 10 shows the summary of the historical data used to simulate the number of new cars in Europe until 2030. The number of new registrations stated in Table 11 corresponds to the increasing number and types of new cars in the EU-27 fleet until 2030. These numbers can be a result of either the change in the overall car ownership level, or the replacement of cars that are scrapped or removed from the fleet (i.e. in the case of used, accident or too old cars). Within the new registration simulation, no additional consideration was given to the annual scrap rate because the original fleet size projections from iTREN-2030 already consider that.

Table 10: Historical data used for the new car stock simulation

Data	Unit	Source	2005	2006	2007	2008	2009
Total Cars	1,000 Cars	(Fiorello, et al., 2009)	211,062	214,379	217,746	221,168	224,642
New Registration	1,000 Cars	(ACEA-New Vehicle Registration Statistics)	15,254	15,819	16,003	14,739	14,488
GDP	Bill. € (2005)	(Fiorello, et al., 2009)	8,743	8,880	9,020	9,161	9,305

Source: Compiled by the author

Table 11: Number of new cars (1,000 vehicles) until 2030 in the EU-27

Year	Total cars*	Total new	Total old	Total Gasoline*	New G Cars	Old G Cars	Total Diesel*	New D Cars	Old D Cars
2005	211,062	14,759	196,303	149,304	10,441	138,863	57,588	4,027	53,561
2010	228,172	92,105	136,067	139,539	60,575	78,964	82,723	29,180	53,543
2015	246,189	176,040	70,149	139,283	109,550	29,733	98,460	61,490	36,969
2020	265,628	191,207	74,421	139,027	108,024	31,003	117,190	76,871	40,319
2025	279,555	207,537	72,018	143,825	110,320	33,504	125,953	89,895	36,058
2030	294,212	224,438	69,774	148,788	115,415	33,373	135,371	101,194	34,177

Abbreviations: G = Gasoline Car, D = Diesel Car,

Source: Created by the author considering (Fiorello, et al., 2009) fleet projections, *Fiorello, et al., (2009)

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4.6 Technology Diffusion Assumptions

The term Technology Diffusion in this study refers to the widespread integration of *'Technology Options'* into new European gasoline and diesel cars until 2030. The diffusion assumptions explained in this study are based on author's view followed by **technology readiness** and **technical developments**. For the simulation, the diffusion was considered only within gasoline and diesel cars, because both the *'Technology Options'* are compatible into these cars without rendering any change to the engine, size or performance of the vehicle. Moreover, gasoline and diesel cars represent the biggest share of the total EU-27 car fleet, and this trend of majority will continue to increase at least until 2030. Therefore, technical changes and modifications occurring into the majority of baseline vehicles can give wide illustrations of the potentials into future.

In the assessment, there is a direct impact of efficiency increase on vehicle's energy demand and CO_2 emission, when the integration of technologies is considered on the vehicular level. However, when the *'Technology Options'* are diffused at different rates within the total fleet, the total energy demand and emission changes are calculated through the cumulative effect of technology efficiency increase and the number of vehicles involved. The formula used for the assessment in the bottom-up simulation is:[14]

$$ED_t = \sum \left(FNm_{i,t} \times D_{i,t} \times FENm_{i,t}\right) + \left(FNu_{i,t} \times D_{i,t} \times FENu_{i,t}\right) + \left(FOm_{i,t} \times D_{i,t} \times FEOm_{i,t}\right) + \left(FOu_{i,t} \times D_{i,t} \times FEOu_{i,t}\right)$$

Where ED_t is the total energy demand. FN_m is the number of new vehicles involved in the technology diffusion with fuel economy *FENm*. *D* is the annual driving distance for the model year *i,* during time *t*. *FNu* is the number of new vehicles that are not involved in technology diffusion with fuel economy *FENu*, *D* is the annual driving distance for the model year *i,* during time *t*. *FOm* is the total

[14] The methodology for the bottom-up simulation is adapted from Toro.F., Jain. S., Reitze. F., Rosende. D. (2010). Analysis of the technological innovation potentials in alternative automotive systems and their effects on technology learning trends. *11th IAEE European Conference*, Vilnius, Lithuania.

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number of old modified vehicles running for annual driving distance *D* with fuel economy *FEOm* for the model year *i,* during time *t*. *FOu* is the total number of old unmodified vehicles running for annual driving distance *D* with fuel economy *FEOu* for the model year *i,* during time *t*.

The scenarios stated in this study estimate the potentials of energy demand and CO_2 emission reduction through the deployment of improvement technologies across the fleet. However, in reality there are several interactions and measures like European policies, market behavior, cost of technologies, consumers' preferences etc. that affect the effectiveness of technologies and their deployment within the industry (Skinner, Essen, Smokers, & Hill, 2010). Due to the interplay of various socio-economic, technical, and industrial milieus, it is conceptually very difficult to model the precise process and pattern of the technology diffusion, especially, when it also depends on the ways how manufacturers interact and adopt new technologies under different political setups. The potentials presented in this study are an attempt to brief the intricacies of diffusion of advanced technologies under assumed percentages. The two diffusion scenarios considered for this study are explained in the following sections.

4.6.1 Scenario 1 – Technical Potential

This scenario based on the assessment of maximum energy demand and CO_2 emission reduction potential offered by technologies under the assumption that *'Technology Option 2'* diffuses extensively across the cars. As seen in Table 11, new cars make a major share of the total cars in any particular base year, but during the same base year there are many old cars as well that were the newly registered cars before the considered base year. Therefore, to avoid the non-counting of other cars before the base year, the integration of technologies was considered within both old and new cars. The Technical Potential Scenario (Scenario 1) provides an outlook of the maximum diffusion of technologies and their impacts over the baseline values (as the Maximum Technical Potential). Table 12 and Figure 17 present the percentage diffusion assumptions considered in the Technical Potential Scenario. Table 13 and

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Table 14 show summarized data of the number of cars involved in the technology diffusion.

Table 12: Technology diffusion assumptions within the Technical Potential Scenario

Year	Scenario 1 - Technical Potential							
	Diffusion into new G. cars		Diffusion into old G. cars		Diffusion into new D. cars		Diffusion into old D. cars	
	TO1	TO2	TO1	TO2	TO1	TO2	TO1	TO2
2005	100%	0%	100%	0%	100%	0%	100%	0%
2010	90%	10%	90%	10%	90%	10%	90%	10%
2015	70%	30%	80%	20%	70%	30%	80%	20%
2020	50%	50%	75%	25%	50%	50%	75%	25%
2025	25%	75%	70%	30%	25%	75%	70%	30%
2030	0%	100%	75%	25%	0%	100%	75%	25%

Source: Created by the author

Abbreviations: G = Gasoline Car, D = Diesel Car, TO1 = *'Technology Option 1'*, TO2 = *'Technology Option 2'*

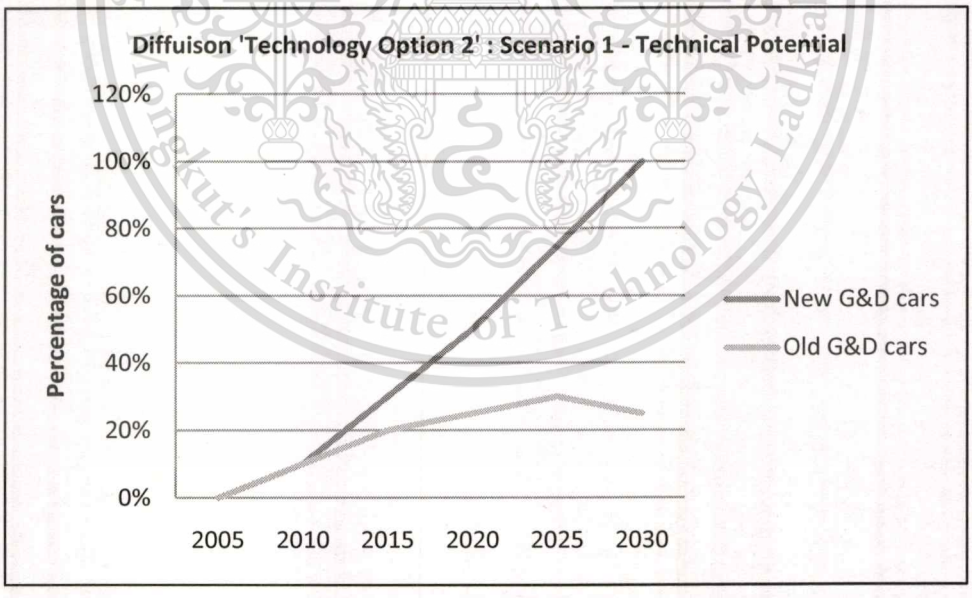


Figure 17: Technology diffusion assumptions within the Technical Potential Scenario

Source: Created by the author

Abbreviations: G = Gasoline Car, D = Diesel Car

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Table 13: Number of gasoline cars within the Technical Potential Scenario

Gasoline Cars	Unit	2010	2015	2020	2025	2030
% of new gasoline cars with Tech.Op.2	%	10%	30%	50%	75%	100%
Number of new gasoline cars with Tech.Op.2	1,000 vehicles	6,057.46	32,864.8	54,011.9	82,740.2	115,414.7
Number of new gasoline cars with Tech.Op.1	1,000 vehicles	54,517.1	76,684.4	54,011.9	27,580.1	-
% of old gasoline cars with Tech.Op.2	%	10%	20%	25%	30%	25%
Number of old gasoline cars with Tech.Op.2	1,000 vehicles	7,896.44	5,946.63	7,750.75	10,051.3	8,343.30
Number of old gasoline cars with Tech.Op.1	1,000 vehicles	71,067.9	23,786.5	23,252.2	23,453.0	25,029.91

Source: Created by the author

Table 14: Number of diesel cars within the Technical Potential Scenario

Diesel Cars	Unit	2010	2015	2020	2025	2030
% of new diesel cars with Tech.Op.2	%	10%	30%	50%	75%	100%
Number of new diesel cars with Tech.Op.2	1,000 vehicles	2,918.01	18,447.1	38,435.6	67,420.9	101,193.8
Number of new diesel cars with Tech.Op.1	1,000 vehicles	26,262.12	43,043.2	38,435.	22,473.6	-
% of old diesel cars with Tech.Op.2	%	10%	20%	25%	30%	25%
Number of old diesel cars with Tech.Op.2	1,000 vehicles	5,354.29	7,393.86	10,079.6	10,817.4	8,544.29
Number of old diesel cars with Tech.Op.1	1,000 vehicles	48,188.5	29,575.4	30,238.9	25,240.7	25,632.8

Source: Created by the author

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4.6.2 Scenario 2 – Autonomous Potential

This scenario is based on the assessment of energy and emission reduction potential form the technologies under the assumption that the *'Technology Option 2'* diffuses to a limited extent within the fleet, however, followed by the autonomous technological progress, the *'Technology Option 1'* diffuses widely across the fleet.

Technologies included in the *'Technology Option 1'* are highly developed until now and are already integrated into new vehicles by several European manufacturers (i.e. the technologies demonstrate high degree of industrial adaptation). Moreover, the European Commission also considers that these technologies are "very crucial" for efficiency enhancement through earliest deployment in the vehicle manufacturing (Regulation (EC) No. 443/2009, 2009). Therefore, it can be considered that, in future, these technologies will be integrated autonomously into most new vehicles and followed by technological progress and learning, the other vehicles will also gain an enhanced efficiency of around 5-8%. Table 21 and Figure 18 present the percentage diffusion assumptions considered in the Autonomous Potential Scenario (Scenario-2). Table 16 and Table 17 show summarized data of the number of cars involved in the technology diffusion.

Table 15: Technology diffusion assumptions within the Autonomous Potential Scenario

Year	Scenario 2 – Autonomous Potential							
	Diffusion into new G. cars		Diffusion into old G. cars		Diffusion into new D. cars		Diffusion into old D. cars	
	TO1	TO2	TO1	TO2	TO1	TO2	TO1	TO2
2005	100%	0%	100%	0%	100%	0%	100%	0%
2010	90%	10%	90%	10%	90%	10%	90%	10%
2015	85%	15%	85%	15%	85%	15%	85%	15%
2020	80%	20%	82%	18%	80%	20%	82%	18%
2025	70%	30%	80%	20%	70%	30%	80%	20%
2030	65%	35%	80%	20%	65%	35%	80%	20%

Source: Created by the author

Abbreviations: G = Gasoline Car, D = Diesel Car, TO1 = *'Technology Option 1'*, TO2 = *'Technology Option 2'*

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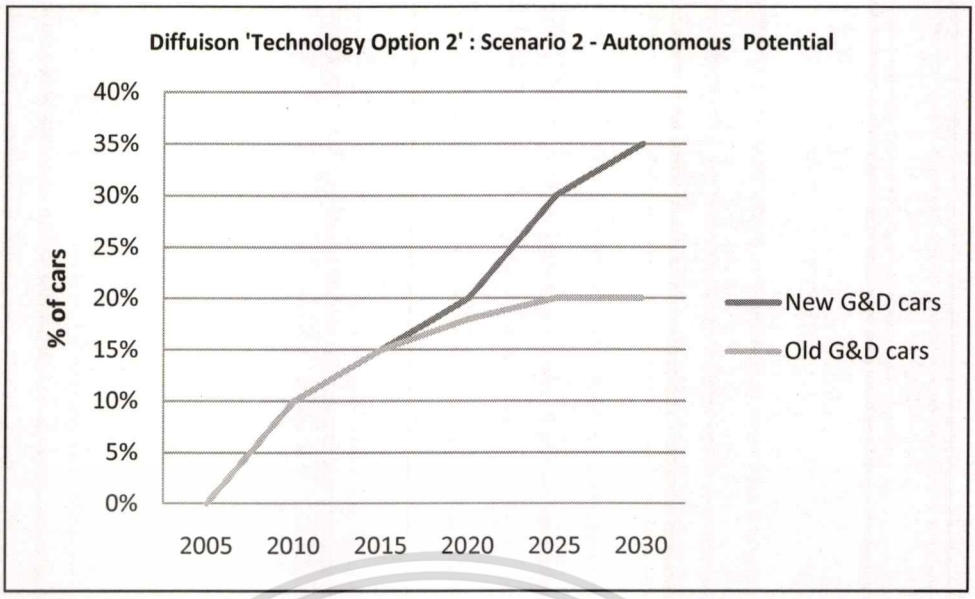


Figure 18: Technology diffusion assumptions within the Autonomous Potential Scenario

Source: Created by the author

Abbreviations: G = Gasoline Car, D = Diesel Car

Table 16: Number of gasoline cars within the Autonomous Potential Scenario

Gasoline Cars	Unit	2010	2015	2020	2025	2030
% of new gasoline cars with Tech.Op.2	%	10%	15%	20%	30%	35%
Number of new gasoline cars with Tech.Op.2	1,000 vehicles	6,057.5	16,432.4	21,604.8	33,096.1	40,395.2
Number of new gasoline cars with Tech.Op.1	1,000 vehicles	54,517.2	93,117.2	86,419.2	77,224.3	75,019.6
% of old gasoline cars with Tech.Op.2	%	10%	15%	18%	20%	20%
Number of old gasoline cars with Tech.Op.2	1,000 vehicles	7,896.4	4,460.0	5,580.5	6,700.9	6,674.6
Number of old gasoline cars with Tech.Op.1	1,000 vehicles	71,067.9	25,273.2	25,422.5	26,803.5	26,698.6

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Table 17: Number of diesel cars within the Autonomous Potential Scenario

Diesel Cars	Unit	2010	2015	2020	2025	2030
% of new diesel cars with Tech.Op.2	%	10%	15%	20%	30%	35%
Number of new diesel cars with Tech.Op.2	1,000 vehicles	2,918.0	9,223.6	15,374.3	26,968.4	35,417.8
Number of new diesel cars with Tech.Op.1	1,000 vehicles	26,262.1	52,266.8	61,497.1	62,926.2	65,776.0
% of old diesel cars with Tech.Op.2	%	10%	15%	18%	20%	20%
Number of old diesel cars with Tech.Op.2	1,000 vehicles	5,354.3	5,545.4	7,257.4	7,211.6	6,835.4
Number of old diesel cars with Tech.Op.1	1,000 vehicles	48,188.6	31,423.9	33,061.3	28,846.6	27,341.7

Source: Created by the author

4.7 Literature and Sources

In this study, to assess the cost and effectiveness of improvement technologies, vehicle and fleet characteristics etc., a number of technical information sources and reports were consulted. This section summarizes the most important studies and data derived from them for the analysis.

iTREN-2030 Reference Scenario (Deliverable-4, 2009), Fiorello, et al., (2009)

Statistics and data for the passenger car fleet development, conventional fuel prices and projected total energy demand in Europe until 2030 were taken from iTREN-2030, Deliverable-4. This report delivers the quantified indicators for energy, transport, environment and economic developments in Europe until 2030. The Reference Scenario Report does this by coupling the TRANS-TOOLS model with three other models, ASTRA, POLES and TREMOVE by using common or comparable set of external assumptions (like growth rates of GDP, population, fuel

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prices, transport energy demand, travel distance etc.), and considering a common set of policies for the EU-27.

Data and values from Reference Scenario Report were chosen because the report delivers reliable set of projections on the EU-27 transport indicators under the given assumptions of stability within socio-economic environment and the policy environment. This study is approved and accepted by the European Commission as an assessment of EU-27 transport developments until 2030. And most importantly, the scenarios and results developed in this report do not consider any political change or vehicle technology development after 2008. Therefore, considering the reliability and approval at the European level, several data from the Reference Scenario were taken for the assessment and analysis in this study. Table 18 states the most important values taken from iTREN-2030 Reference Scenario.

Table 18: Values and data derived from iTREN-2030 Reference Scenario Report

Values	Unit	2005	2010	2020	2030
Total no. of cars in EU-27	1,000 vehicles	211,062	228,12	265,628	294,212
Total Energy Demand	PJ	8,435	9,251	9,630	10,301
GDP	Bill. € (2005)	8,734	9,450	11,188	13,029
Gasoline Price	€/litre	1.07	1.40	1.27	1.34
Diesel Price	€/litre	0.92	1.25	1.16	1.24

Source: (Fiorello, et al., 2009)

Concawe (WTW, Version-2b, 2006 and TTW, Version-3, 2008)

The average values and datasets for European passenger cars were derived from 'Concawe Well-to-Wheels analysis of future automotive fuels and powertrains in the European Context' (well-to-wheels report, Version-2b, May 2006) and (tank-to-wheel report, Version-3, October 2008). Considering the approval of studies and results by the European Commission, and acceptance and wide-scale usage of data by researchers across Europe, the aforementioned Concawe reports were used. Table 19 shows the summary of data and values derived from the Concawe reports.

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Table 19: Data and values derived from Concawe reports

Attribute	Gasoline Car	Diesel Car	Source
Vehicle price	19,000 €	20,000 €	(Concawe, 2006)
Fuel capacity/Engine power	77 kW	74 kW	(Concawe, 2008)
Fuel economy	223.5 MJ/100km	183.1 MJ/100km	(Concawe, 2008)
Fuel specific emission factor	74.35 gCO_2/MJ	73.54 gCO_2/MJ	(Concawe, 2008)

Source: Compiled by the author

(TNO, 2006), (EPA, 2008), (AEA, 2009), (McKinsey, 2009) [15]

The above mentioned studies were referred to review the potentials of innovative technologies in efficiency increase and related costs of technologies *(Technology Options)* for passenger cars. For the economic and environmental assessment of the technologies, these studies have considered technology efficiency potentials and cost analysis by implementing several analytical methods from various disciplines of economics and automotive engineering. To a certain extent, these sources have also mentioned credibility of individual vehicle technologies, as well as technology readiness by exemplifying the technologies that are currently available or will be available in the next five to ten years. The summary of technical improvement technologies and expected efficiency increase from them can be seen in Table 6, and APPENDIX II explains and compares the aforementioned studies. Table 20 contains the references of the studies used.

[15] **(TNO, 2006)**; Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars, **(EPA, 2008)**; EPA Staff Technical Report: Cost and Effectiveness Estimates of Technologies Used to Reduce Light-duty Vehicle Carbon Dioxide Emissions, **(AEA, 2009)**; Assessment with respect to long term CO2 emission targets for passenger cars and vans, Deliverable D2: Final Report, **(McKinsey, 2009)**; Der Trend zu energieeffizienten Pkw, Implikationen für die deutsche Automobilindustrie

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Table 20: Studies considered for *'Technology Options'*

Attribute	Sources for *'Technology Option 1'*	Sources for *'Technology Option 2'*
Technology combination/cluster	(EPA, 2008)	(McKinsey, 2009)
Expected efficiency increase	(EPA, 2008)	(McKinsey, 2009)
Manufacturer's cost of Technologies	(AEA, 2009)	(AEA, 2009)

Source: Compiled by the author

Current chapter has provided an overview of the methodology followed in this study. Details and market readiness of *'Technology Options'*, methods and equations involved in the assessments, details of the bottom-up simulation, concepts involved in the simulation of technology diffusion assumption and all other parameters and factors involved in the analysis are explained throughout the current chapter. The next chapter, Chapter-5 summarizes the results and analysis to answer all the research questions aimed for this study.

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5. ANALYSIS AND RESULTS

Section 3.3 answers research question 1 of this study. To answer further research questions, this chapter presents the results and analysis of assessments. To answer research questions 2 and 3, the results and interpretations presented in sections 5.1 and 5.2 quantify the impact of *'Technology Options'* on the vehicle fuel economy and CO_2 emission, and other vehicle's economic performance indicators. To answer research question 4, the overall potentials of technologies in energy demand and CO_2 emission saving are presented in section 5.3 along with the illustrations of scenarios of technology diffusion across gasoline and diesel cars.

Baseline values: These are the average reference values considered for gasoline or diesel cars in this study. These baseline values are either derived from published studies or assumed by the author for the assessment. Table 21 summarizes the baseline values.

Table 21: Baseline values & characteristics of the car

Baseline Values	Unit	Gasoline Car	Diesel Car	Source
Vehicle Price	€/vehicle	19,000	20,000	Concawe
Engine Power	kW	77	74	Concawe
Vehicle lifetime	Years	10	10	Assumed
Specific Driving Costs	€/100 km	24.18	22.90	Calculated
Fuel economy	l/100km	6.78	5.30	Concawe
Fuel economy	MJ/100km	220	190	Concawe
Fuel economy (kmpl)	km/litre	14.7	18.9	Concawe
Specific CO_2 emission	gCO_2eq/km	165	140	Concawe
Yearly driving distance	km/yr	18,000	20,000	Assumed
Yearly energy demand (for fixed yearly driving cycle)	MJ/year	39,600	38,000	Calculated
Yearly CO_2 emissions (for fixed yearly driving cycle)	Tonnes/year	2.94	2.79	Calculated

Source: Compiled by the author

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5.1 Results of the Energy Demand and Emission Saving Assessment

This section presents the results to answer research question 2, i.e. "*Assessment of the improvements in the "fuel economy" as an impact of integration of 'Technology Option' into the car. Assessment of subsequent reductions in "CO_2 emission" as a result of decreased fuel consumption – ENERGY DEMAND AND EMISSION SAVING ASSESSMENT*".

5.1.1 Improvements in the fuel economy (l/100km)

The fuel economy or fuel efficiency in this study refers to the amount of fuel a car requires for driving a particular distance. Figure 19 shows the improvements in the fuel economy. The black bars in the graph show the baseline fuel economy of cars. The light grey bar shows a 5% improvement in the fuel economy resulted due to *'Technology Option 1'*. As a result, the fuel consumption reduces from 6.78 l/100km to 6.44 l/100km and 5.30 l/100km to 5.04 l/100km in the gasoline and diesel car respectively. The dark grey bar shows a 22% increase in the fuel economy resulted due to *'Technology Option 2'*. As a result, the baseline fuel consumption reduces to 5.29 l/100km and 4.13 l/100km in the gasoline and diesel car respectively.

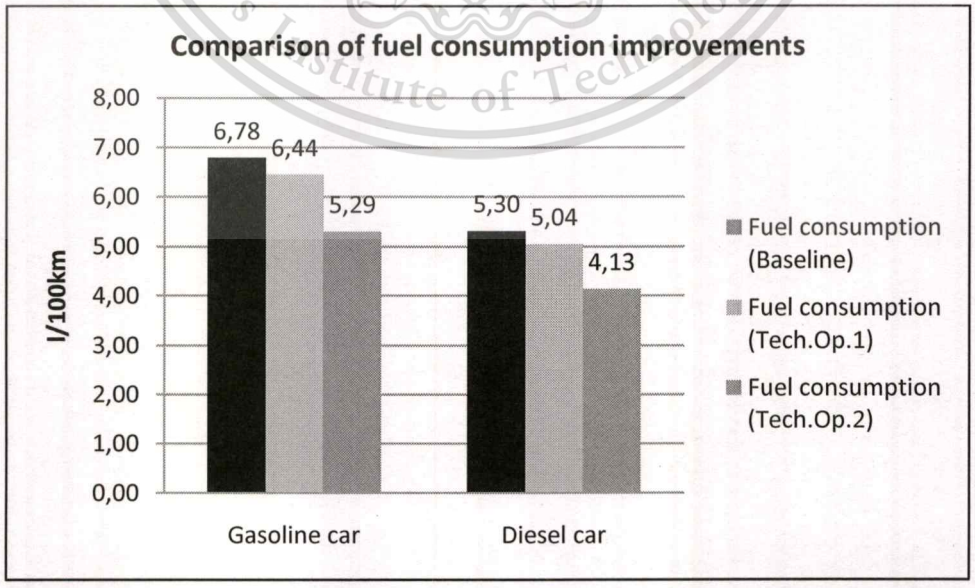


Figure 19: Comparison of changes in the fuel economy (l/100km)
Source: Created by the author

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5.1.2 Improvements in the fuel economy (kmpl)

Figure 20 shows the increasing pattern of mileage that occurs as a result of technical improvements. *'Technology option 1'* has the potential to enhance kmpl from 14.7 kmpl to 15.5 kmpl in the gasoline car, and 18.9 kmpl to 19.9 kmpl in the diesel car. And, integration of *'Technology option 2'* has the potential to increase the fuel economy from 14.7 kmpl to 18.9 kmpl in the gasoline car and 18.9 kmpl to 24.2 kmpl in the diesel car.

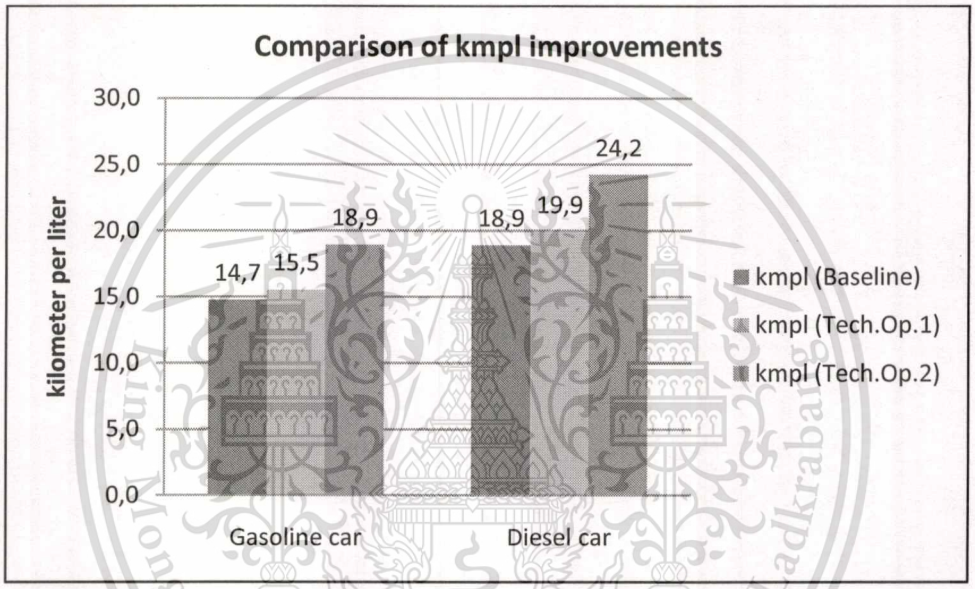


Figure 20: Comparison of changes in the fuel economy (kmpl)

Source: Created by the author

5.1.3 Changes in expenditure on the fuel (€/100km)

After the assessment of improvements in the fuel economy, through a techno-economic assessment, the results of decreased fuel consumption were converted into the fuel expenditure per 100 kilometer (€/100km). For the conversion of fuel economy into monetary units, the conventional fuel prices (€/liter) for the year 2010 derived from Fiorello, et al. (2009) were considered. Figure 21 shows the changes in fuel expenditure for a 100 km driving cycle. The decreasing pattern of expenditure on the fuel is evidently a reflection of the increased fuel economy, as seen in Figure 19.

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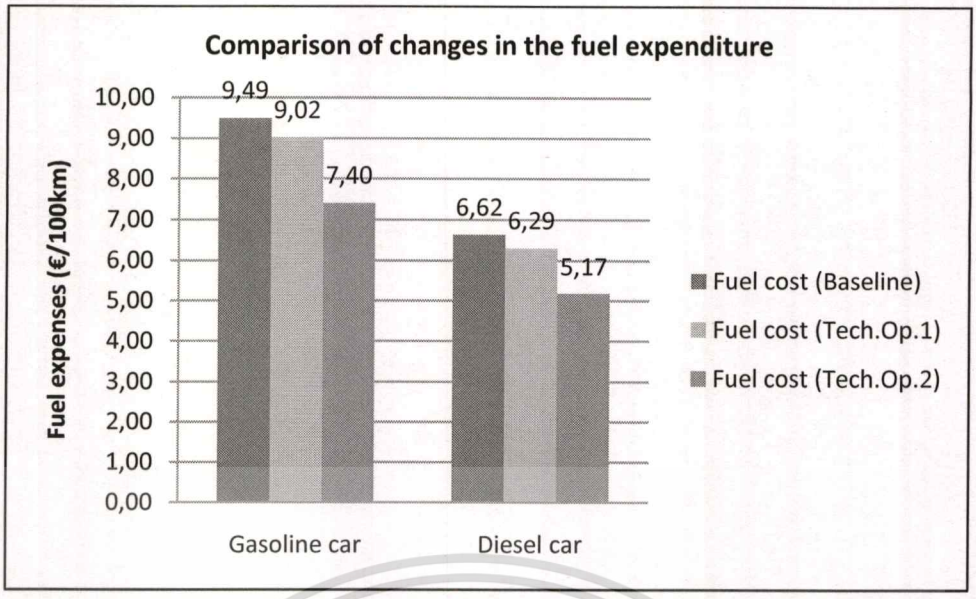


Figure 21: Comparison of changes in the fuel expenditure (€/100km)
Source: Created by the author, considering 2010 gasoline/diesel fuel price

5.1.4 Changes in the annual energy demand (MJ/Yr)

The results presented in Figure 22 refer to the yearly energy demand changes by the vehicle for a fixed driving cycle of 18,000 km for the gasoline car and 20,000 km for the diesel car. Results show that, *'Technology option 1'* has the potential to save around 1,900 MJ energy per year and *'Technology option 2'* has the potential to save around 8,500 MJ energy per year.

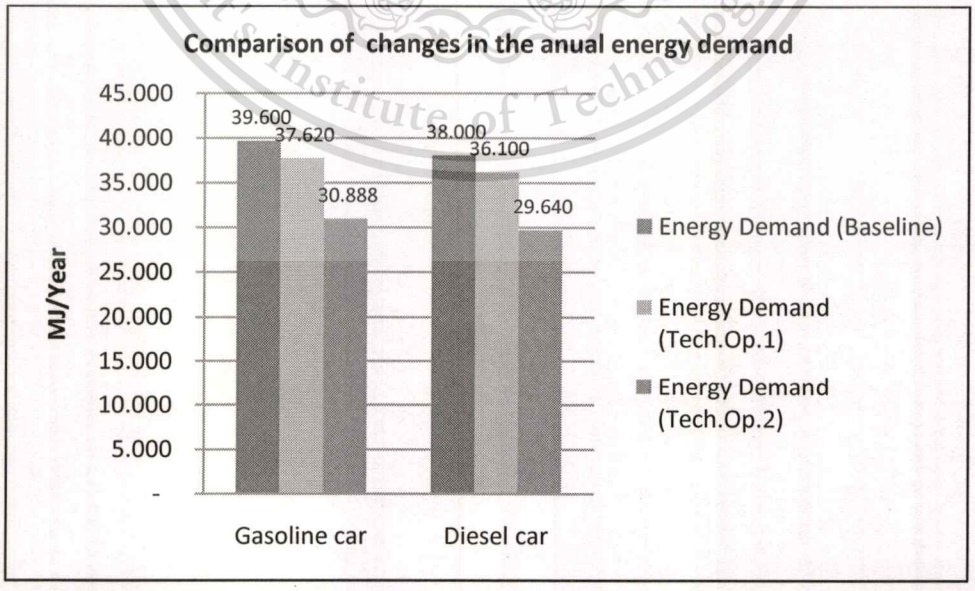


Figure 22: Comparison of changes in the annual energy demand
Source: Created by the author

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REBOUND EFFECT: When the energy efficiency of a car increases, GHG emissions are reduced as a result of decreased fuel consumption. But, if prices of the fuel remain constant, the cost per kilometer of driving decreases. Any decrease in the cost of travel may encourage additional travel by the driver, and this additional travel will produce additional GHG emissions. This increase in the travel as a result of reduced fuel expenditure through technical improvements is called as the **"rebound effect"** (Greene & Schafer, 2003). For an example, if the fuel economy increases by 10% and the fuel price remains same, and if there is a 1 to 2 % increase in the vehicle travel. So, the net benefit of fuel demand and emission reduction would be only 8 to 9 %.

In the case of personal transport, there is not such a strong relationship between the vehicle fuel expenditure and energy efficiency improvements (Greene & Schafer, 2003). The possible reason for a small rebound effect in cars can be, that, the fuel costs generally constitute a small share (10 to 20 percent) of the total cost of vehicle travel. In reality, the cost of the vehicle, value of the traveler's time and other costs such as maintenance and insurance etc. dominate the decision towards traveling. Therefore, an increased efficiency of the car even without an increase in the price of energy can be an effective way to reduce energy demand and GHG emissions.

5.1.5 Changes in the Specific CO_2 emission (g/km)

The term specific CO_2 emission refers to the emissions generated during each kilometre of driving by the car. There is a relation of direct proportionality between the fuel consumption of a car and the generated emissions. These values in the assessment were calculated considering the average vehicle and fuel characteristics and fixed fuel economy of the cars. In real on-road driving conditions, specific CO_2 emission from different propulsion technologies perform differently, which depends on size of the engine, chemical properties of the fuel, fuel-blend used in the engine, urban or highway driving conditions, vehicle maintenance etc. Figure 23 presents the results of the changing specific CO_2 emission from cars.

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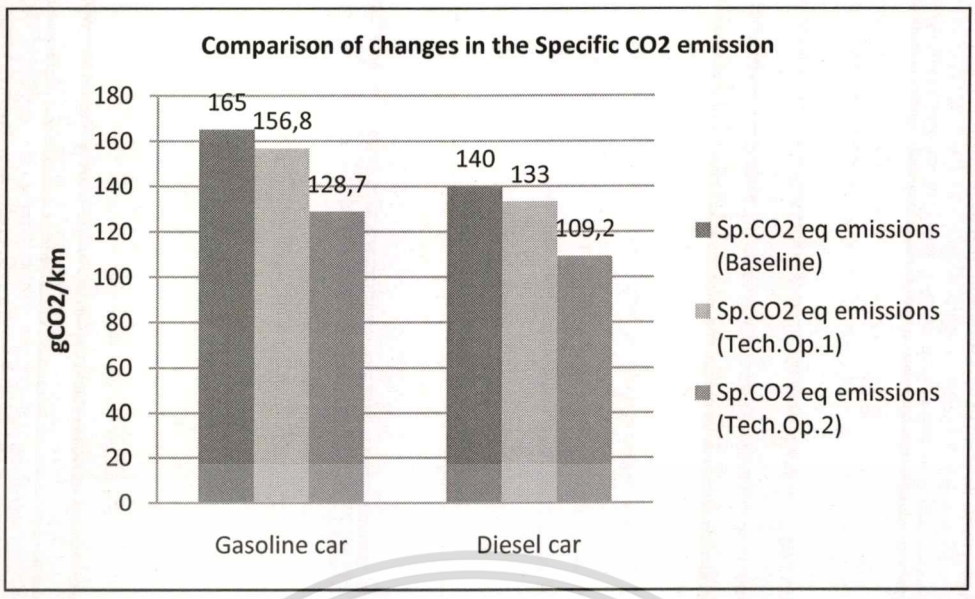


Figure 23: Comparison of changes in the Specific CO_2 emission

Source: Created by the author

An important aspect regarding the aforementioned results is the compliance of values with the European regulations on average gCO_2/km emission. The average per km emission stated in the results are calculated from the average fuel economy and other assumed vehicle characteristics, and therefore, the emission figures are higher than the average fleet emissions targeted by the European Commission. A main consideration should be kept in mind while comparing these results is that, the average CO_2 emission target by the European Commission is established by averaging emissions (g/km) of all car models weighted by the sales volumes of the manufacturers. Therefore, when the baseline emission values are compared to the European targets, then this does not imply that all the cars drive at the same mileage and emit same amount of CO_2. All car models across Europe possess varying mileage range; therefore, different vehicle models, car segments and the fuel used in them contribute differently to the average on-road CO_2 emission.

5.1.6 Changes in the annual CO_2 emission (tonnes/year)

The results on CO_2 emission reduction presented in this part are yearly emissions generated by the car for a fixed annual driving cycle. The results are calculated by assuming a car with the fixed fuel economy, using the pure conventional fuel. Therefore, the results may change significantly, if the annual driving distance, fuel economy or fuel properties (blending percentage) change.

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Figure 24 states the results on annual CO_2 emission changes over the annual baseline values. Results show that *'Technology option 1'* has the potential to save around 0.14-0.15 tonnesCO_2/year in gasoline and diesel cars. And *'Technology option 2'* has the potential to save around 0.61-0.64 tonnesCO_2/year from the cars.

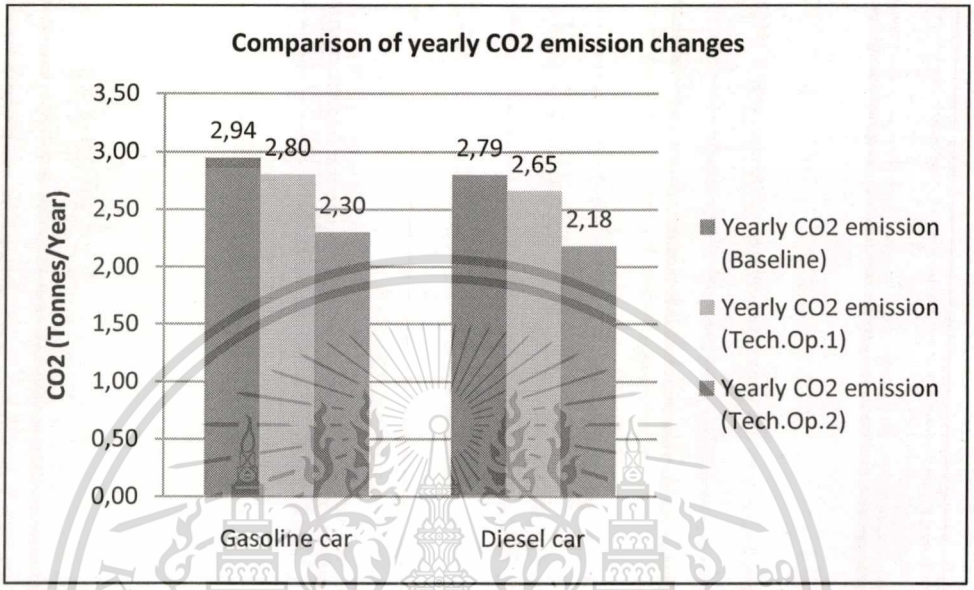


Figure 24: Comparison of changes in annual CO_2 emission

Source: Created by the author

5.2 Results of the Economic Assessment

This section presents the results of the analysis to answer research question 3, i.e. *"Assessment of the specific driving costs, cost of CO_2 avoidance, the average payback period and other vehicle's economic performance changes, that occur as a result of enhanced efficiency and additional investments in* ***'Technology Options'*** *- ECONOMIC ASSESSMENT".*

5.2.1 Average cost of *'Technology Options'*

The extra investment cost over the vehicle baseline price that incurs due to the integration of improvement technologies into the car is referred to as average cost of the *'Technology Option'*. The concept of RPE multiplier as detailed in section 4.1.3 was used for the assessment of average incremental cost of technologies. The data on additional manufacturer costs is available in (AEA, 2009) and these costs

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were converted into incremental retail costs by using the "Retail Price Equivalent" derived from (Vyas, Santini, & Cuenca, 2000) & (NRC, 2010).

Although the assessment was done as a straightforward way to analyze the incremental costs, the values stated in (AEA, 2009) still have a chance of being underrated compared to the actual vehicle pricing, because of the level of complexity of technologies and other costs involved. In reality, there are many factors like cost of production, cost of technology integration, level of complexity of technology, R&D, other direct and indirect costs etc. that decide the actual cost of the technology into the market (Alson, Ellis, & Gnass, 2005). The direct costs of changing an automobile technology may depend on three major factors: inherent production costs, timing of investments and market risks. The effect of 'Techno-innovation' (learning by searching) and 'Scale Effect' (learning by doing) are other two major aspects that decide the real cost of technologies and their decrease over the time (Eichhammer, et al., 2009).

Although the data availability and limitations are considered, the RPE multiplier seems to be the formal method for incorporating incremental costs into fuel economy potential assessments. Figure 25 shows the incremental costs assumptions. The dark grey part of the bar shows the baseline vehicle price (derived from Concawe, 2008), while the light grey part shows the additional cost of *'Technology Option'*, and together they constitute the increased price of the new vehicle.

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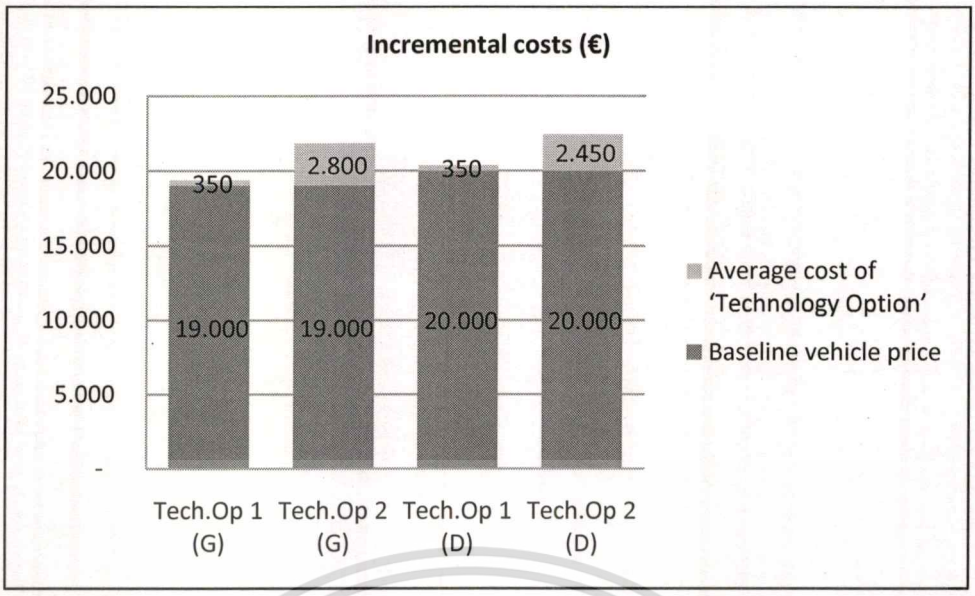


Figure 25: Assumed incremental costs with *'Technology Options'*

Source: (AEA, 2009), Concawe (2008)

Abbreviations: (G) = Gasoline Car, (D) = Diesel Car

Figure 25 shows the assessed incremental costs, which means, the car gets more expensive for the customer. This may give rise to a big question of, how to promote customers to buy an expensive car? Answering this question can be trivial, as the customer's motivation to buy any car is affected by his preferences and decisions like travelling needs, income, family size etc. So, for promoting the sales of efficient and improved cars, governmental and political support to both manufacturers and customers plays a big role. For example, European Parliament's recommendation on inclusion of compulsory measures like tire pressure monitoring system (TPMS) or low rolling resistance tires will need a coordinated action which will involve R&D organizations, car manufacturers, tire manufacturers and other stakeholders. Hence, governmental and political interventions to provide necessary support to vehicle manufacturers (like direct subsidies and tax benefits for the R&D and infrastructure) and providing enough lead-time for integration of technical measures into the production line etc. will play a crucial role.

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5.2.2 Changes in the Specific driving costs (€/100km)

Specific driving costs refer to the cost of driving each kilometre of the car. The estimation is detailed in equation 4, section 4.3. Figure 26 shows the results of changes in the specific driving cost. The results show an increase in specific driving costs over the baseline costs, which evidently is a direct impact of incremental costs in *'Technology Options'*.

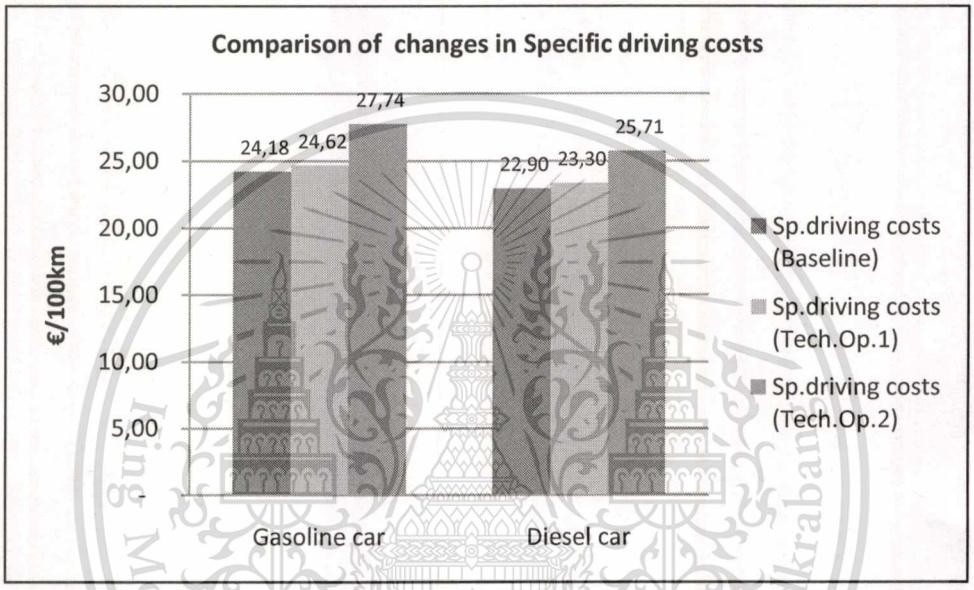


Figure 26: Comparison of changes in Specific driving costs
Source: Created by the author

5.2.3 Comparison between Specific driving costs and Specific CO_2 emission

The technical cost of travel or specific driving costs for a given vehicle is an integral component of a vehicle's economic performance. Specific driving costs in this study are evaluated by considering vehicle baseline prices, annual investment costs and O&M costs etc. for a fixed yearly driving distance. But, for calculating overall 'cost of ownership' (or total driving costs), other costs and expenses like the fuel price, insurance, license & registration, depreciation, financing, other variable costs need to be involved.

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Economic impacts form the customer's point of view can be referred as **'costs' and 'benefits',** where 'costs' and 'benefits' have a mirror-image relationship. A cost can be defined as a reduction in benefits or a benefit can be defined as a reduction in the costs. Within the context of this study, 'cost' is defined as the incremental price a customer has to bear, in order to gain the 'benefits' of fuel saving and CO_2 emission reduction.

Figure 27 presents a comparison between the Specific driving costs and Specific CO_2 emissions calculated in this analysis. An interpretation for the results presented in the graph can be, that, a driver has to pay the 'cost', as an additional investment in order to attain the 'benefit' of energy and emission saving. Both *'Technology Options'* offer energy saving and better CO_2 performance than the conventional baseline vehicles, but also exhibit higher specific driving costs than the baseline values.

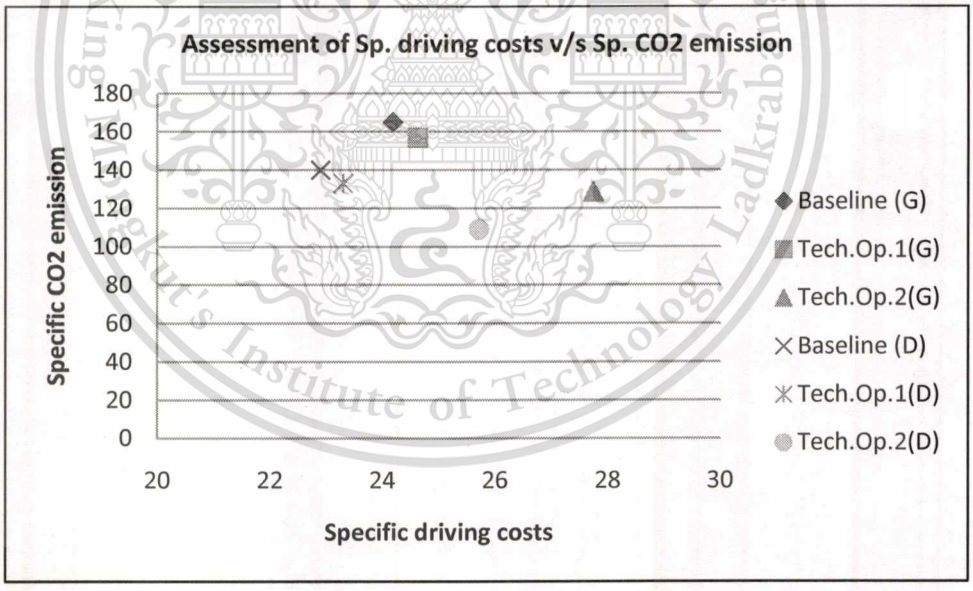


Figure 27: Comparison between sp. driving costs and sp. CO_2 emissions

Source: Created by the author

Abbreviations: (G) = Gasoline Car, (D) = Diesel Car

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5.2.4 Comparison between Specific driving costs and expenditure on the fuel

The relationship presented in Figure 28 is a techno-economic assessment to compare the increased specific driving costs with the reduced fuel expenditure that occur as a result of implementation of *'Technology Options'* into the car. The fuel expenditure values (€/100km) are calculated by using 2010 conventional fuel prices derived from Fiorello, et al. (2009).

An important outcome from the graph is, that, under the baseline conditions, the specific driving costs of both cars are low, but the fuel consumption is high, and, as a result, the money spent on the fuel is high as well. After the integration of technical improvement, there will be incremental costs that will increase the specific driving costs, but at the same time, the increased fuel economy will reduce the money spent on the fuel. This message can be used as an important tool to compare the benefits between a cheaper inefficient car and an expensive but fuel efficient car. An important message for the customer can be *"although the efficient car is more expensive than the inefficient car, the money spent on the fuel for every km of driving the efficient car is lesser"*. By correlating the reduced fuel expenditure with the average payback period, another important message can be drawn, i.e. *"After the payback period is over (i.e. the breakeven point is achieved), every other kilometre travelled by the car will keep on bringing additional benefits of the reduced fuel expenditure from the enhanced fuel economy"*. Further benefits can be also measured in terms of reduced energy demand and reduced CO_2 emission.

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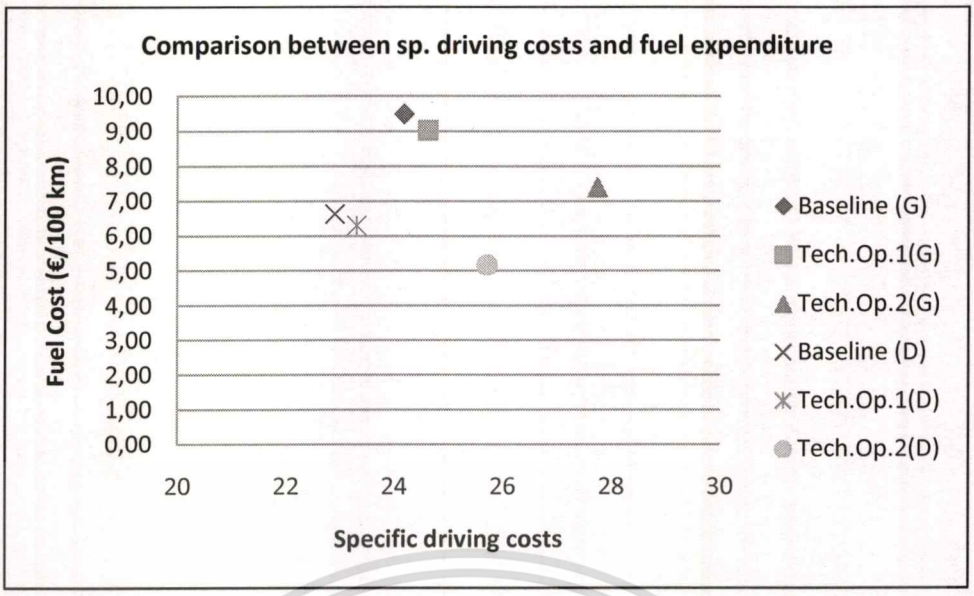


Figure 28: Comparison between the sp. driving costs and fuel expenditure

Source: Created by the author, considering 2010 conventional fuel price

Abbreviations: (G) = Gasoline Car, (D) = Diesel Car, Op.1 = *'Technology Option 1'*, Op.2 = *'Technology Option 2'*

5.2.5 Cost of CO_2 avoidance (€/tonne)

The cost of CO_2 avoidance involves the concept of cost and benefit i.e. the 'cost' (in €) a driver has to pay, to save each tonne of CO_2 as the 'benefit'. Figure 29 shows the results of the cost of CO_2 avoidance. One important point to be noted is that, the cost of CO_2 avoidance is highly sensitive to the vehicle technical life and the yearly driving distance, and this relationship is detailed in the sensitivity analysis in section 5.4.2.

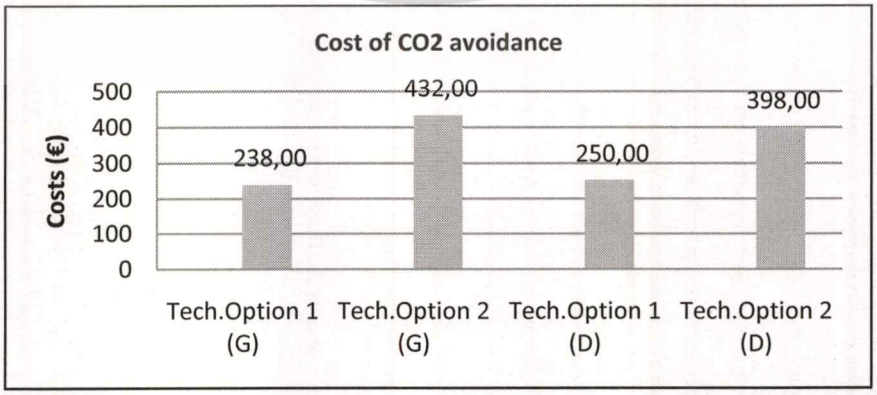


Figure 29: Cost of CO_2 avoidance

Source: Created by the author

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The cost of CO_2 avoidance presented in Figure 29 is calculated by dividing the incremental costs with the lifetime CO_2 saving (as explained in section 4.3). However, if the NPV of lifetime monetary savings due to reduced fuel consumption is also considered, then the results by taking into account the 2010 fuel price will be; -342.88 €/Tonne and -223.40 €/Tonne for *'Technology Option 1'* in Gasoline and Diesel car respectively and -148.36 €/Tonne and -75.40 €/Tonne for *'Technology Option 2'* in Gasoline and Diesel car respectively. The negative values show that, the lifetime monetary savings as a result of enhanced fuel economy by technical modifications are much higher than the incremental costs of technologies.[16]

The CO_2 abatement costs presented here are elucidated projections, and such cost estimations can be useful to compare the cheaper CO_2 emission saving option, when several technology options are involved in the assessment (Skinner, Essen, Smokers, & Hill, 2010). However, the CO_2 abatement costs shall not be considered as the only decisive factor, as they may mislead the decision for cheaper or expensive option. For example, promotion of a least CO_2 abatement cost technology for industrial application might not be appropriate, as a transition and integration of technology into production of cars may require incremental costs and the lead time. Moreover, some options may not be cost effective yet, but their lead time in contributing for the sustainable mobility can be short. For example, taking compulsory lessons on 'eco-driving and behaviour' while applying for a driving license may be costly, but this strategy can be implemented in short time through the coordinated regulations.

5.2.6 Average payback period

The average payback period is the time period in which the driver can reimburse the incremental costs of *'Technology Option'* through the monetary savings that occur as a result of an enhanced fuel economy and the reduced fuel expenditure. The average payback period can vary as per the type of technology, the time horizon chosen and the annual driving distance, because it is influenced by

[16] The results of cost of CO_2 avoidance with NPV are assessed by considering 2010 fuel price derived from (Fiorello, et al., 2009). These results may change significantly if the fuel price, annual driving distance, vehicle's technical lifetime, vehicle fuel economy, fuel properties (fuel specific CO_2 emission) etc. vary over the values used in the assessment.

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factors like incremental cost of technology, fuel price in that particular year and the annual driving distance. In this study, the average payback period was calculated by considering following features:

- Incremental costs = additional investment on *'Technology Options'*
- Fuel price projections until 2030 derived from (Fiorello, et al., 2009)
- Fuel economy (MJ/100km)
- Vehicle lifetime of 10 years

Table 22 and Table 23 present the results of the average payback period for different time horizons.

Table 22: Comparison between the gasoline fuel price and the payback period

Assessed value	Unit	2005	2010	2020	2030
Gasoline price*	€/l	1.07	1.40	1.27	1.34
Payback period - Tech.Op.1**	Years	5.4	4.1	4.5	4.3
Payback period - Tech.Op.2**	years	9.7	7.4	8.2	7.8

Source: *Fiorello, et al. (2009), ** Calculated by the author

Table 23: Comparison between the diesel fuel price and the payback period

Assessed value	Unit	2005	2010	2020	2030
Diesel price*	€/l	0.92	1.25	1.16	1.24
Payback period - Tech.Op.1**	Years	7.2	5.3	5.7	5.3
Payback period - Tech.Op.2**	years	11.4	8.4	9.1	8.5

Source: *Fiorello, et al. (2009), ** Calculated by the author

There is a relationship of inverse proportionality between the payback period and the market price of the conventional fuel. The results of the assessment show that, when the price of conventional fuel is high, the payback period is short and vice versa. A reason within the dimensions of this study is, that, during a fixed annual

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driving cycle, the driver saves fuel due to enhanced fuel efficiency, but the amount of money the driver saves depends on the market price of the conventional fuel. In other words, after the technical improvements of the car, the driver saves some quantity of fuel all the time, but the amount of money being saved depends on the price of the conventional fuel during that time period (i.e. saving in monetary terms is higher when the price of the conventional fuel is high). Therefore, the driver saves fuel all the time, but less money, when the price of conventional fuel is low and consecutively, the time period needed to compensate additional investments on *'Technology Option'* gets longer. The effect can be evidently seen through the values stated in Table 22 and Table 23, and the relationship stated through trends in Figure 30 and Figure 31.

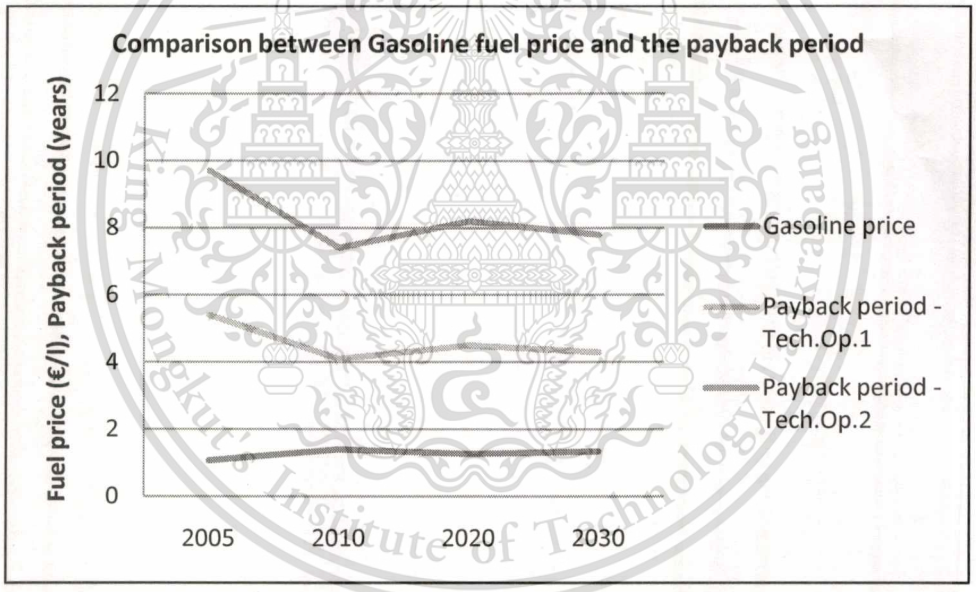


Figure 30: Comparison between gasoline fuel price and payback period

Source: Fiorello, et al. (2009), Calculated by the author

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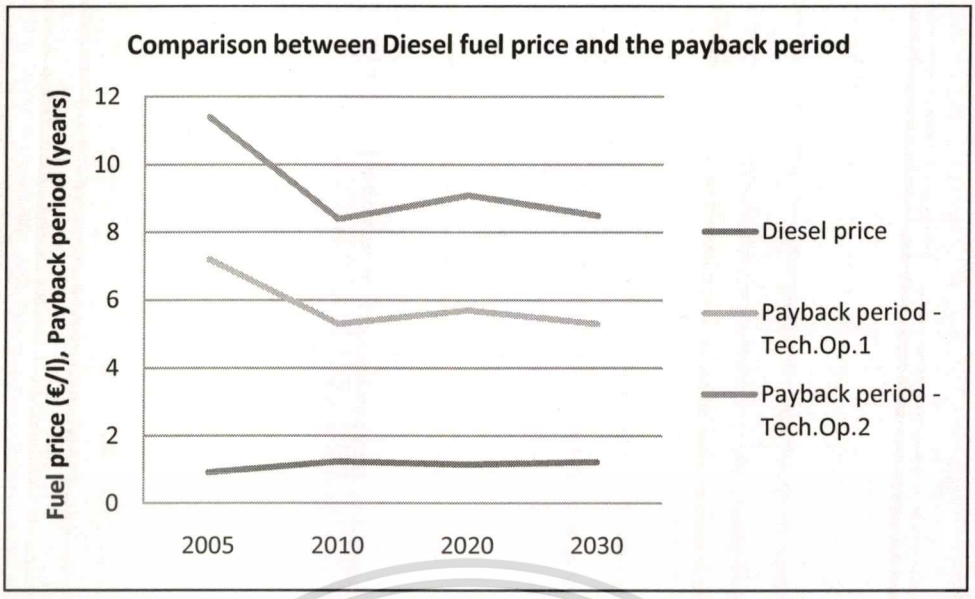


Figure 31: Comparison between diesel fuel price and payback period

Source: Fiorello, et al. (2009), Calculated by the author

The trend patterns stated in Figure 30 and Figure 31 show the relationship between the conventional fuel price and the payback period. For buying a fuel efficient car, the customer needs to do an extra investment, and the payback period can be an important factor for the customer's car buying decision. The payback period can be used as an indicator to show to the customer that, the high fuel economy of an expensive but efficient car will bring benefits through monetary saving, even without reducing travelling distance, size or performance of the vehicle (Alson, Ellis, & Gnass, 2005). Another important point to be considered is that, after completion of the payback period, whatever fuel/emission/money the driver saves, becomes an "additional benefit".

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The results and analysis presented in sections 5.1 and 5.2 answer the research questions 2 and 3 respectively. The results presented in both sections have shown the potential impacts and benefits of efficiency improvements in gasoline and diesel cars by application of *'Technology Options'*. Table 24 summarizes the results that were assessed and mentioned in detail within these last two sections.

Table 24: Summary of assessments at the vehicular level

Assessed value	Unit	Baseline value (G)	Gasoline Car		Baseline value (D)	Diesel Car	
			Tech. Op.1	Tech. Op.2		Tech. Op.1	Tech. Op.2
Average cost of *'Technology Option'*	€	-	350	2,800	-	350	2,450
Specific Driving Costs	€/100 km	24.18	24.62	27.74	22.90	23.30	25.71
Fuel economy	MJ/100km	220	209	171.6	190	180.5	148.2
Specific CO_2 emission	gCO_2/km	165	156.8	128.7	140	133	109.2
Fuel expenses	€/100km	9.49	9.02	7.40	6.63	6.29	5.17
Fuel economy	km/litre	14.7	15.5	18.9	18.9	19.9	24.2
Fuel economy	l/100km	6.78	6.44	5.29	5.30	5.04	4.13
Yearly energy demand	MJ/yr	39,600	37,620	30,888	38,000	36,100	29,640
Yearly CO_2 emission	TonnesCO_2/yr	2.94	2.80	2.30	2.79	2.65	2.18
Cost of CO_2 avoidance	€/Tonne	-	238	432	-	250	398
Average payback period	Years	-	4.1 – 5.4	7.4 – 9.7	-	5.3 – 7.2	8.4 - 11.4

Source: Calculated by the author

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5.3 Results of energy and emission saving potentials (Bottom-up simulation)

This section answers the final research question 4 considered for this study, i.e. *"Assessment of the potentials of 'Technology Options' in "overall reduction of energy demand and CO_2 emission" by EU-27 passenger cars up to 2030, based on the assumed diffusion of 'Technology Options' within conventional gasoline and diesel cars – BOTTOM-UP SIMULATION".*

It is important to note that the technology diffusion assumptions explained in this section are based on the author's view, supported by **technology readiness** and **technical developments** in Europe. In reality, there may be several interactions and measures (like EU policies, market behavior, cost of technologies, consumers' preference etc.) that will influence the relative effectiveness of technologies and their deployment within cars by the industry (Skinner, Essen, Smokers, & Hill, 2010).

The term Technology Diffusion Assumption in this study relates to the widespread application of *'Technology Options'* into new European gasoline and diesel passenger cars between the timeframe of 2005 and 2030. *'Technology Options 1 & 2'*, at a constant vehicle size and engine power, offer a 5 and 22% increase in the vehicle efficiency respectively. In the assessment, when the *'Technology Options'* integrate into the car, a direct impact on vehicle's energy consumption is considered. However, when *'Technology Options'* are diffused at different rates within the total fleet, total energy demand and emission changes through the bottom-up simulation are calculated by considering the cumulative effect of technology efficiency increase and the number of vehicles involved. Table 25 shows the two scenarios considered for the assessment.

Table 25: Technology diffusion assumptions considered for this study

Scenario name	Technology Diffusion Assumption
Technical Potential (Scenario 1)	Assessment of the maximum energy demand and emission saving potential offered by *'Technology Option 1&2'*
Autonomous Potential (Scenario 2)	Assessment of the energy demand and emission saving potential offered by the widespread diffusion of *'Technology Option 1'*

Source: Created by the author

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Scenario 1 – Technical Potential: This scenario is based on the assessment of maximum energy demand and CO_2 emission reduction potential offered by technologies under the assumption that *'Technology Option 2'* diffuses extensively across the fleet. The details related to the Technical Potential Scenario are stated in section 4.6.1, and Table 26 presents the percentage diffusion assumptions considered in this scenario.

Table 26: Technology diffusion assumptions within the Technical Potential Scenario

Year	Scenario 1 - Technical Potential							
	Diffusion into new G. cars		Diffusion into old G. cars		Diffusion into new D. cars		Diffusion into old D. cars	
	TO1	TO2	TO1	TO2	TO1	TO2	TO1	TO2
2005	100%	0%	100%	0%	100%	0%	100%	0%
2010	90%	10%	90%	10%	90%	10%	90%	10%
2015	70%	30%	80%	20%	70%	30%	80%	20%
2020	50%	50%	75%	25%	50%	50%	75%	25%
2025	25%	75%	70%	30%	25%	75%	70%	30%
2030	0%	100%	75%	25%	0%	100%	75%	25%

Source: Created by the author

Abbreviations: G = Gasoline Car, D = Diesel Car, TO1 = *'Technology Option 1'*, TO2 = *'Technology Option 2'*

Scenario 2 – Autonomous Potential: This scenario is based on the assessment of energy demand and CO_2 emission reduction potential form technologies under the assumption that the *'Technology Option 2'* diffuses to a limited extent within the fleet, but followed by autonomous technological progress the *'Technology Option 1'* diffuses widely across the fleet. The details related to the Autonomous Potential Scenario are stated in section 4.6.1, and Table 27 presents the percentage diffusion assumptions considered in this scenario.

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Table 27: Technology diffusion assumptions within the Autonomous Potential Scenario

Year	Scenario 2 – Autonomous Potential							
	Diffusion into new G. cars		Diffusion into old G. cars		Diffusion into new D. cars		Diffusion into old D. cars	
	TO1	TO2	TO1	TO2	TO1	TO2	TO1	TO2
2005	100%	0%	100%	0%	100%	0%	100%	0%
2010	90%	10%	90%	10%	90%	10%	90%	10%
2015	85%	15%	85%	15%	85%	15%	85%	15%
2020	80%	20%	82%	18%	80%	20%	82%	18%
2025	70%	30%	80%	20%	70%	30%	80%	20%
2030	65%	35%	80%	20%	65%	35%	80%	20%

Source: Created by the author

Abbreviations: G = Gasoline Car, D = Diesel Car, TO1 = *'Technology Option 1'*, TO2 = *'Technology Option 2'*

Baseline: The baseline has been considered for the study under the assumption that no specific changes or increase in the efficiencies of vehicles take place until 2030. Also, the fleet and fuel characteristics like average yearly travelling distance, fuel specific emission factor etc. do not change. The baseline for energy demand was derived from Fiorello, et al. (2009) and the baseline for CO_2 emission was created by the author, as explained in the Methodology chapter.

Other than the *'Technology Options'* and the technology diffusion scenarios discussed here, there are several other technical measures to realize the vehicle efficiency increase, but the uncertainty may lie within the time necessary to achieve complete deployment of such technologies within the production of cars. Because of the interaction of various socio-economic, technical, and industrial milieus, it is conceptually very difficult to model the precise process and pattern of the technology diffusion, especially, when it also depends on the ways how manufacturers interact and adopt new technologies under different political setups. Therefore, the results presented in this analysis are an attempt to brief the intricacies of diffusion of advanced technologies under assumed rates and achievable potential reduction in the energy demand and CO_2 emission.

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The key results from the defined scenarios are presented Table 28. Figure 32 and Figure 33 illustrate the changing trends of energy demand and CO_2 emission potential in the EU-27 until 2030.

Table 28: Results – Energy demand and CO_2 emission reduction potentials

Results - Energy Demand Changes	**2010**	**2015**	**2020**	**2025**	**2030**
Baseline (PJ)	9,253	9,439	9,630	9,959	10,300
Technical Potential (S1)	9,121	8,197	7,935	7,550	6,797
Autonomous Potential (S2)	9,186	8,600	8,514	8,344	8,328
Scenario 1/Baseline	-1.43%	-13.16%	-17.59%	-24.19%	-34.01%
Scenario 2/Baseline	-0.72%	-8.89%	-11.59%	-16.21%	-19.14%
Results – CO_2 Emission Changes	**2010**	**2015**	**2020**	**2025**	**2030**
Baseline (Mil.tonnes)	684	698	712	736	761
Technical Potential (S1)	674	606	587	558	502
Autonomous Potential (S2)	679	636	629	617	615
Scenario 1/Baseline	-1.41%	-13.11%	-17.59%	-24.15%	-34.03%
Scenario 2/Baseline	-0.70%	-8.84%	-11.57%	-16.16%	-19.14%

Source: Created by the author

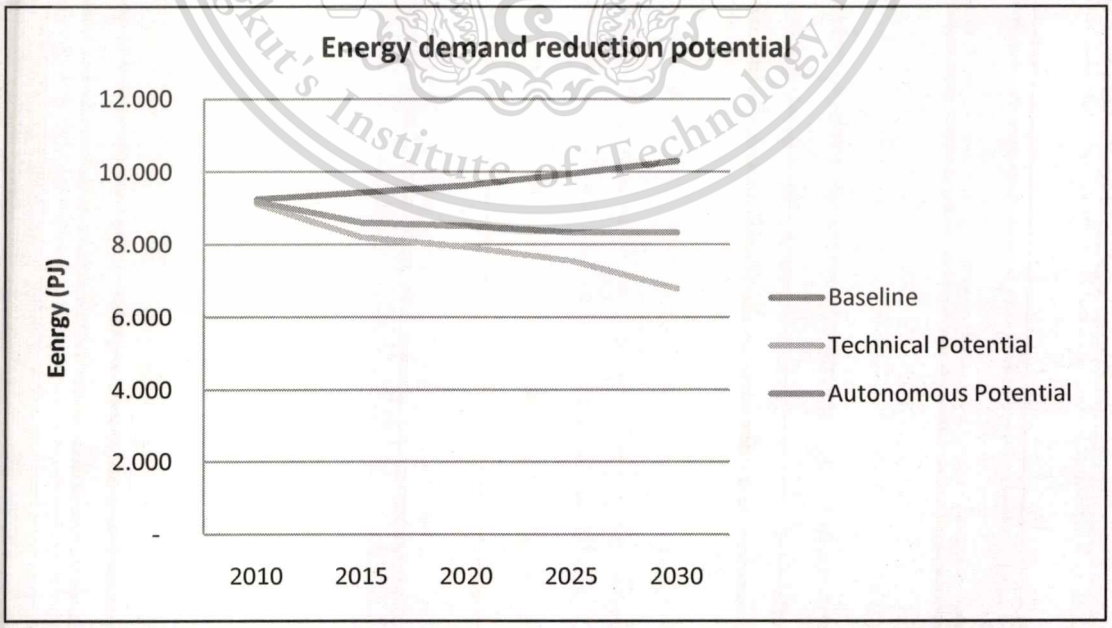


Figure 32: Energy demand reduction potentials under considered scenarios

Source: Created by the author

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Figure 32 shows the potentials of energy demand reduction as per the assumed diffusion scenarios. The energy demand projection baseline shows a continuous increase, which may reach to around 10,300 PJ in 2030. However, as considered under the Technical Potential Scenario (Scenario-1), the energy demand can be significantly reduced to around 34% lower than the baseline. This scenario provides an outlook of the maximum potential of technologies and their impacts on the baseline values. And, as assumed under the Autonomous Potential Scenario (Scenario-2), there is a potential of around 19% saving in energy demand up to 2030.

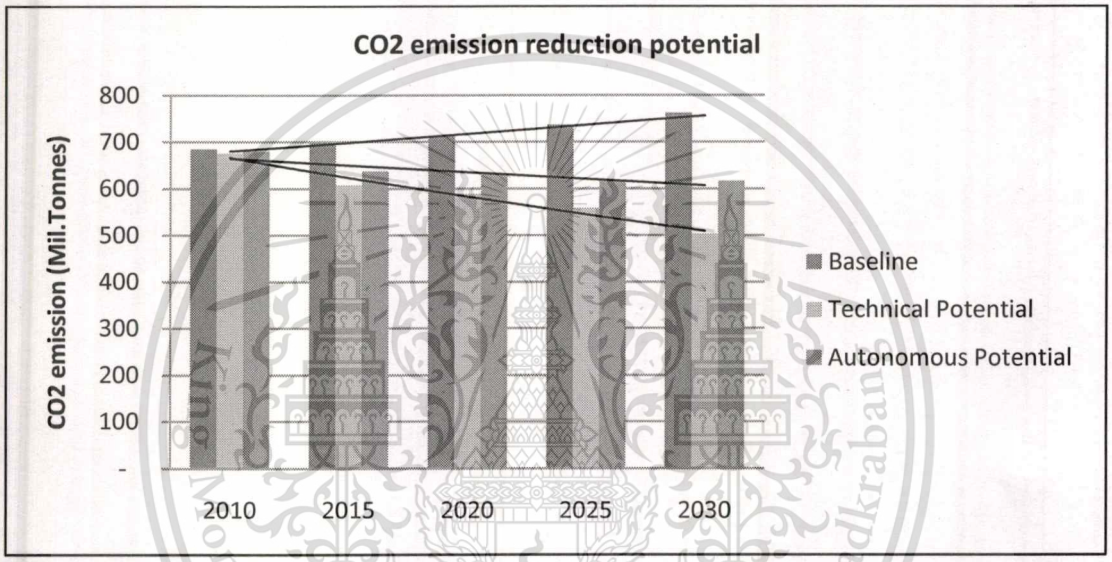


Figure 33: CO_2 emission reduction potentials under considered scenarios
Source: Created by the author

Figure 33 shows the potential changes in CO_2 emission from cars across Europe until 2030. The baseline for CO_2 emission was calculated by considering the fuel demand and related CO_2 emission generated from the fuels. The decreasing emission potentials stated in the graph are an impact of the 'reduction in energy demand through technical improvements'. Under the baseline conditions, the total CO_2 emission from all passenger cars in Europe by 2030 may reach around 761 million tonnes/year. However, under the Technical Potential Scenario (Scenario-1) this emission level may reduce to a lower level of around 502 million tonnes/year, which shows a 34% reduction potential. Under the Autonomous Potential Scenario (Scenario-2), the CO_2 emission can be reduced to around 615 million tonnes/year by 2030, which will be around 19% lower than the baseline.

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The scenarios defined within this analysis show that a 19% to 34% reduction in total energy demand and subsequent CO_2 emission can be achieved in Europe up to 2030 by widespread diffusion of *'Technology Options'*. To summarize the results, Figure 34 shows the overall potentials in energy demand and CO_2 emission savings assessed within this study. The figure is converted in percent changes rather than energy demand (PJ) or emission (million tonnes) units for the ease of understanding and combining the changes until 2030. The Technical Potential Scenario (Scenario-1) shows around 34% reduction potential and the Autonomous Potential Scenario (Scenario-2) shows a 19% reduction potential in energy demand and CO_2 emission over the next 20 years.

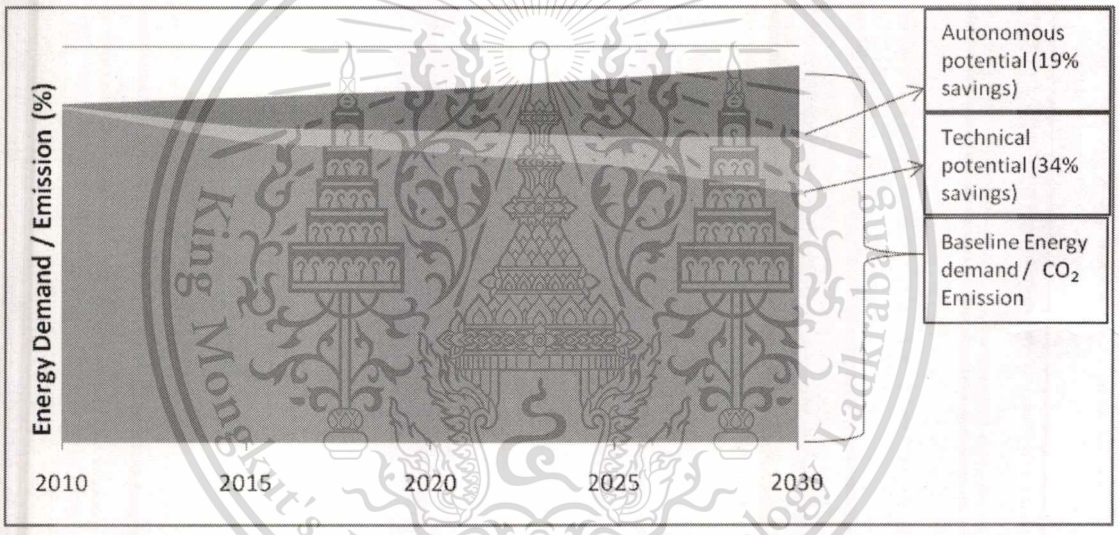


Figure 34: Total energy and CO_2 emission saving potentials
Source: Author's elaboration

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5.4 Sensitivity Analysis

A sensitivity analysis can be a useful tool to find the correlation or uncertainties between the input and output values that are associated with the changing input parameters in a model (Breierova & Choudhari, 2001). The sensitivity analysis in this study was done to determine "how sensitive" the assessments are to the changing input parameters, and how the output results change under those varying input value circumstances.

The term "changing input parameter" refers to the changing input values like efficiency of *'Technology Options'*, diffusion rates, vehicle lifetime, annual driving distance etc., that were used in the assessment. Two sets of sensitivity analysis were performed in this study. First, at the level of car fleet (Bottom-up simulation), where the efficiencies of *'Technology Options'* and diffusion within total fleet were considered changing over the baseline conditions. Second, at the vehicular level, where the vehicle lifetime and the annual traveling distance were considered varying over the baseline values.

5.4.1 Sensitivity Analysis – At the level of car fleet (Bottom-up Simulation)

The sensitivity analysis within the bottom-up simulation was performed to assess the maximum potential of different technologies in total energy demand and CO_2 emission reduction. In addition to the *'Technology Options'* and technology diffusion scenarios discussed in section 5.3, there are several other technical and behavioral measures to realize the overall transport energy demand reduction. The European Commission and European automobile industry believe that only an "integrated approach" can provide the solution to reach the average fleet emission target by 2012. Therefore, in future, vehicle technologies, driver's behavior and other transport related measures will act together for the overall vehicle efficiency enhancement.

Two sensitivity analyses named as Case A and Case B were done at the fleet level. In both cases, the technology diffusion assumption, autonomous efficiency

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increase and the percent efficiency increase by *'Technology Option 2'* were considered as changing parameters. The correlation between the changing parameters is already explained in section 4.6 (Technology Diffusion Assumptions) and Table 29 summarizes the conditions for the sensitivity analyses in Case A and Case B.

Table 29: Cases A and B for the sensitivity analysis at the level of fleet

Assumption			
Case name	**Efficiency by *'Technology Options'***	**Technology Diffusion**	**Autonomous efficiency increase**
Case A	Around 45%	Widespread diffusion	Around 20%
Case B	Around 40%	Same as the Technical Potential Scenario (Scenario 1)	Around 25%

Source: Created by the author

5.4.1.1 Case A

In this case, it was considered that the technology options diffuse widely into new cars. And, as an impact of other innovative technologies and the integrated approach, the efficiency by *'Technology Options'* increases to around 45%. Moreover, followed by autonomous efficiency growth, the efficiency of other cars (that are not involved in the technology diffusion) increases to around 20%. Table 30 summarizes the technology diffusion assumptions.

Table 30: Technology diffusion assumptions within Case A

Year	Sensitivity analysis - Case A							
	Diffusion into new G. cars		Diffusion into old G. cars		Diffusion into new D. cars		Diffusion into old D. cars	
	AEI	TO	AEI	TO	AEI	TO	AEI	TO
2010	0%	100%	100%	0%	0%	100%	100%	0%
2015	0%	100%	90%	10%	0%	100%	90%	10%
2020	0%	100%	80%	20%	0%	100%	80%	20%
2025	0%	100%	70%	30%	0%	100%	70%	30%
2030	0%	100%	60%	40%	0%	100%	60%	40%

Abbreviations: G = Gasoline Car, D = Diesel Car, AEI = Autonomous efficiency increase, TO = *'Technology Options'*

Source: Created by the author

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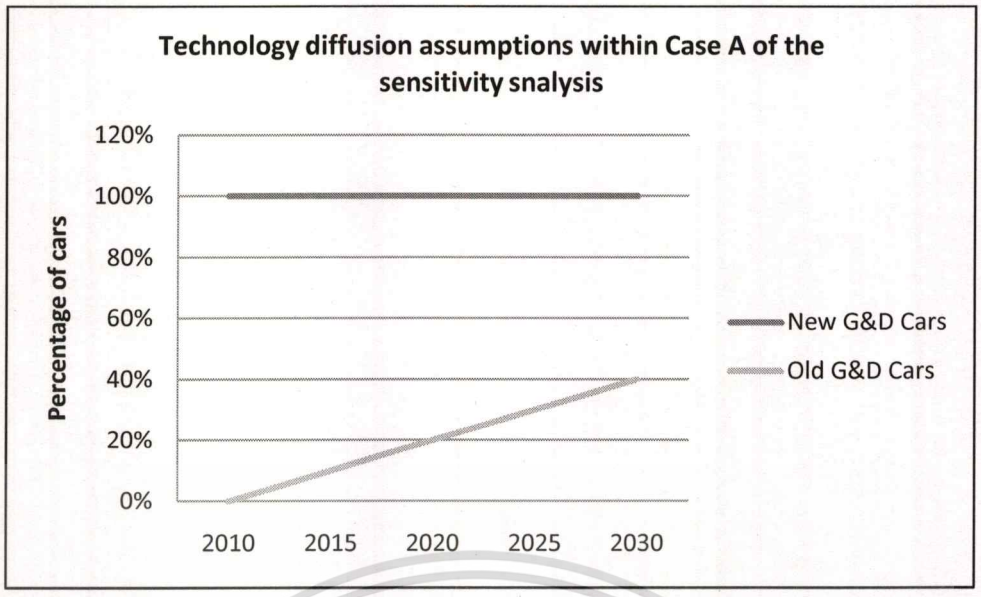


Figure 35: Technology diffusion assumptions within Case A

Source: Created by the author

Abbreviations: G = Gasoline Car, D = Diesel Car

5.4.1.2 Case B

In this case, technologies diffuse in similar percentage, as assumed in the Technical Potential Scenario (Scenario 1) (see section 4.6.1). The vehicle efficiency by technologies increases to around 45%. And, followed by autonomous efficiency growth, the efficiency of other cars (that are not involved in the technology diffusion) increases to around 25%. Table 31 summarizes the technology diffusion assumptions.

Table 31: Technology diffusion assumptions within Case B

Year	Sensitivity analysis - Case A							
	Diffusion into new G. cars		Diffusion into old G. cars		Diffusion into new D. cars		Diffusion into old D. cars	
	AEI	TO	AEI	TO	AEI	TO	AEI	TO
2010	90%	10%	90%	10%	90%	10%	90%	10%
2015	70%	30%	80%	20%	70%	30%	80%	20%
2020	50%	50%	75%	25%	50%	50%	75%	25%
2025	25%	75%	70%	30%	25%	75%	70%	30%
2030	0%	100%	75%	25%	0%	100%	75%	25%

Abbreviations: G = Gasoline Car, D = Diesel Car, AEI = Autonomous efficiency increase, TO = '*Technology Options*'

Source: Created by the author

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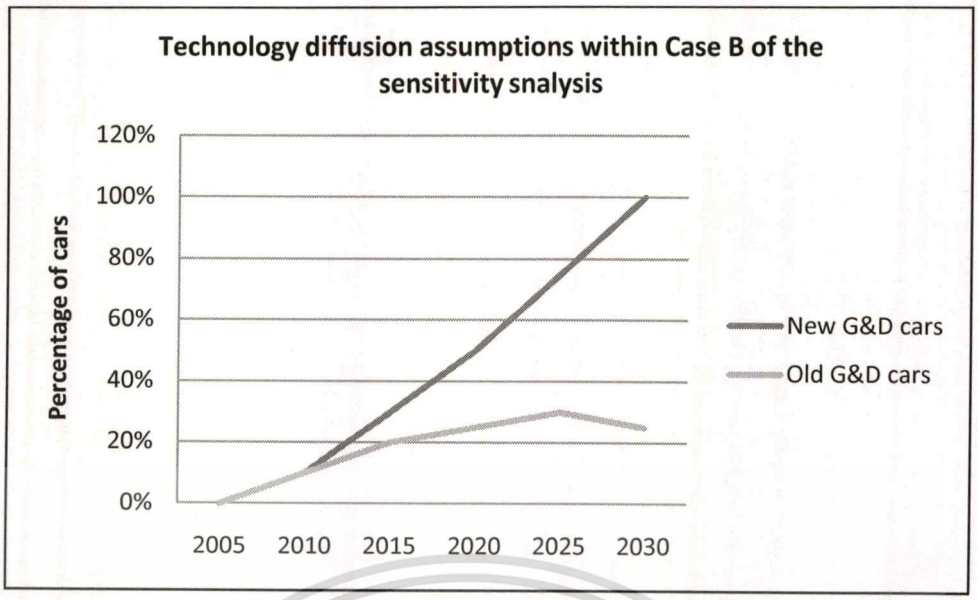


Figure 36: Technology diffusion assumptions within Case B

Source: Created by the author

Abbreviations: G = Gasoline Car, D = Diesel Car

5.4.1.3 Results of the sensitivity analysis: Cases A and B

The results of the sensitivity analysis presented in Table 32 show the potential changes after 2010. Both cases show a potential reduction in energy demand and CO_2 emission by around 46% to 47% by 2030. Evidently, these potentials are higher than the potentials inferred by this study for question 4. The reason for this is, to answer the question 4, only the efficiency increase (%) offered by *'Technology Options'* was taken into account. However, in the sensitivity analysis, the efficiency increase offered by different technologies is taken higher, and the efficiency increase in the vehicle as an impact of integrated approach is also assumed. Moreover, the percent increase in the efficiencies of old vehicles as a result of autonomous efficiency growth is also taken higher.

The results of the sensitivity analysis presented Table 32 infer a potential reduction of around 46%-47% in energy demand by all EU-27 passenger cars up to 2030. These results can be inferred as an impact of multiple technological developments, consideration of the integrated approach and a strong autonomous efficiency growth.

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Table 32: Results of the sensitivity analysis at the level of fleet

Results - Energy Demand Changes	**2010**	**2015**	**2020**	**2025**	**2030**
Baseline (PJ)	9,253	9,439	9,630	9,959	10,300
Case A	9,253	7,195	7,099	6,735	5,579
Case B	9,253	7,747	7,396	6,898	5,427
Case A/Baseline	0.0%	-23.77%	-26.27%	-32.37%	-45.83%
Case B/Baseline	0.0%	-17.93%	-23.20%	-30.73%	-47.31%
Results – CO_2 Emission Changes	**2010**	**2015**	**2020**	**2025**	**2030**
Baseline (Mil.tonnes)	684	698	712	736	761
Case A	684	532.01	524.74	497.69	412.06
Case B	684	572.87	546.67	509.76	400.80
Case A/Baseline	0.0%	-23.74%	-26.28%	-32.34%	-45.85%
Case B/Baseline	0.0%	-17.88%	-23.19%	-30.70%	-47.33%

Source: Created by the author

5.4.2 Sensitivity Analysis – At the vehicular level

For the sensitivity analysis at the vehicular level, two varying parameters namely 'average yearly driving distance' and 'average vehicle technical lifetime' were chosen. These parameters were selected for the analysis, because these two vehicle characteristics differ significantly across different European countries. For example, the average vehicle lifetime for the EU-27 stands around 9-10 years, but the same can be to a minimum of 6-7 years for the UK, Austria and Belgium, or a maximum of 14-16 years for East European countries like Latvia, Slovakia and the Czech Republic (ACEA, 2008). Therefore, assuming, if the input values of the assessment change as expected from the real world observations, the results can be interpreted similar to the real on-road assessment.

The main steps involved in the sensitivity analysis are following:

- Select the input parameter of the model to be analyzed i.e. average yearly driving distance or average vehicle technical lifetime.

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- Change one of the input parameters to the variation range (+ or - %), while keeping the other constant.
- The model computes the results by assessing the relative influence of the input parameters on the output results.
- In the last step, compile and analyze the results.

Table 33 summarizes the parameters involved in the sensitivity analysis and the way they were calculated. The top two rows "Changing input parameters" show the input values that were changed in the sensitivity analysis.

Table 33: Parameters involved in the sensitivity analysis

Assessment	Category	Description	Way of calculation
Changing input parameters	Yearly travelling distance	How much does the car drive in a year? Assumed 18,000 km for gasoline vehicle and 20,000 km for diesel car	Assumed
	Vehicle life time	Assumed as 10 years	Assumed
Energy demand and Emission saving assessment	Fuel economy	Fuel consumed by the car for a certain distance	Derived from Concawe (2008)
	Specific CO_2 emission	CO_2 emitted by combustion of per MJ of fuel	Derived from Concawe (2008)
	Yearly energy demand	Fuel demand for a fixed yearly driving cycle	Calculated
	Total CO_2 emission	CO_2 emitted as per the yearly energy demand	Calculated
Economic assessment	Fuel expenses	Fuel demand × Fuel price	Calculated by using fuel price projections from Fiorello, et al., (2009)
	Specific driving costs	Technology cost of vehicle driving	Calculated
	CO_2 abatement cost	How much does it cost to save 1 tonne of CO_2?	Calculated
	Payback period	The time period in which the incremental costs can be reimbursed through the monetary savings by enhanced fuel economy	Calculated

Source: Elaborated by the author

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Table 34 summarizes the cases considered for the sensitivity analysis. As stated earlier, after selecting one input parameter to be analyzed, the other one was kept constant. In 'Case C', it was considered that after the implementation of *'Technology Options'* into the car, the vehicle lifetime stays constant at 10 years, but the yearly travelling distance changes between 15% higher or lower range than the baseline value. Similarly, in 'Case D' the yearly average travelling distance was considered constant, but the vehicle lifetime was considered varying between +/- 30%.

Table 34: Conditions for the sensitivity analysis

Case name	**Assumption**
Case C (1)	*'Technology Option 1'* integrated into the car, vehicle lifetime constant at 10 years, yearly travelling distance varying between + / - 15%
Case C (2)	*'Technology Option 2'* integrated into the car, vehicle lifetime constant at 10 years, yearly travelling distance varying between + / - 15%
Case D (1)	*'Technology Option 1'* integrated into the car, yearly travelling distance constant, vehicle lifetime varying between + / - 30%
Case D (2)	*'Technology Option 2'* integrated into the car, yearly travelling distance constant, vehicle lifetime varying between + / - 30%

Source: Created by the author

Table 35 and Table 36 show the results of the sensitivity analysis for Case C (1) and Case C (2) respectively. And Table 37 and Table 38 show the results of the sensitivity analysis for Case D (1) and Case D (2) respectively.

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Table 35: Results of the sensitivity analysis, Case C (1)

***'Technology Option 1'* integrated into the car, vehicle lifetime constant at 10 years, yearly travelling distance varying between + / - 15%**														
Sensitivity category	Yearly travelling distance	% change	Yearly energy demand	% change	Fuel expenditure[17]	% change	Sp. Driving costs	% change	Payback period[18]	% change	Total CO_2	% change	CO_2 abatement cost	% change
Unit	km/year		MJ/yr		€/year		€/100km		Years		Tonnes/yr		€/Tonne	
Gasoline car	18,000		37,620		1,624		24.62		4.1		2.79		238	
Gasoline car - high case	20,700	+15%	43,263	+ 15.0%	1,867	+15%	21.41	-13%	2.2	-46%	3.21	+ 15.0%	207	- 13.0%
Gasoline car - low case	15,300	-15%	31,977	- 15.0%	1,380	-15%	28.97	+17.7 %	5.9	+46%	2.37	- 15.0%	280	+ 17.7%
Diesel car	20,000		36,100		1,259		23.30		5.3		2.65		250	
Diesel car – high case	23,000	+15%	41,515	+ 15.0%	1,446	+15%	20.26	-13%	2.9	-45%	3.05	+ 15.0%	217.5	- 13.0%
Diesel car – low case	17,000	-15%	30,685	- 15.0%	1,069	-15%	27.42	+17.7 %	7.6	+45%	2.25	- 15.0%	294	+ 17.7%

[17] Calculated by considering 2010 fuel price derived from Fiorello, et al., (2009)
[18] Calculated by considering 2010 fuel price derived from Fiorello, et al., (2009)

Table 36: Results of the sensitivity analysis, Case C (2)

***'Technology Option 2'* integrated into the car, vehicle lifetime constant at 10 years, yearly travelling distance varying between + / - 15%**														
Sensitivity category	Yearly travelling distance	% change	Yearly energy demand	% change	Fuel expenditure[19]	% change	Sp. Driving costs	% change	Payback period[20]	% change	Total CO_2	% change	CO_2 abatement cost	% change
Unit	km/year		MJ/yr		€/year		€/100km		Years		Tonnes/yr		€/Tonne	
Gasoline car	18,000		30,888		1333		27.74		7.4		2.29		432	
Gasoline car - high case	20,700	+15%	35,521	+ 15.0%	1533	+15%	24.12	- 13.1%	3.9	-46%	2.64	+ 15.0%	923	+ 113.6 %
Gasoline car - low case	15,300	-15%	26,255	- 15.0%	1133	-15%	32.63	+ 17.7%	10.8	+46%	1.95	- 15.0%	282	-34.8%
Diesel car	20,000		29,640		1032		25.71		8.4		2.17		398	
Diesel car – high case	23,000	+15%	34,086	+ 15.0%	1187	+15%	22.36	- 13.1%	4.6	-45%	2.50	+ 15.0%	850	+ 113.7 %
Diesel car – low case	17,000	-15%	25,194	- 15.0%	878	-15%	30.25	+ 17.7%	12.18	+45%	1.85	- 15.0%	260	- 34.7%

[19] Calculated by considering 2010 fuel price derived from Fiorello, et al., (2009)
[20] Calculated by considering 2010 fuel price derived from Fiorello, et al., (2009)

5.4.2.1 Results of the sensitivity analysis: Cases C (1) & C (2)

Fuel Economy: This parameter is not affected by any of the changes considered in the sensitivity analysis. The Fuel economy is a vehicle characteristic and it depends on technological features of the car, so it does not change with change in the average travelling distance. However, as an impact of integration of *'Technology Option 1 and 2'*, an increase of 5% and 22% in fuel economy was considered over the baseline values.

One important point to be considered is, that, in the real world conditions, when the travelling distance increases, the wear and tear of the engine and other motor parts also occurs, hence the fuel economy may confront changes.

Specific CO_2 emission: It is a technical feature of the car and it does not change in the sensitivity analysis. Similar to the fuel economy, as a result of integration of *'Technology Option 1 and 2'*, a decrease of 5% and 22% in the specific CO_2 emission was considered over the baseline values.

Yearly energy demand: There is a direct proportionality relationship between car travelling distance and the energy demand. As the travelling distance changes within the range of +/- 15%, the energy demands change proportionally.

Annual expenditure on the fuel: These costs were calculated by considering 2010 fuel price derived from Fiorello, et al., (2009). As an impact of +/- 15% changes in the energy demand, the yearly expenditure on the fuel changes in the same proportion.

Specific driving costs: The cost of driving per km of the vehicle, but it does not include fuel expenditure. It is calculated as total annual costs divided by annual driving distance (see equation 4, section 4.3 for details). In case of 15% increase in travelling distance, the specific driving costs reduce by 13.1% (hence a negative sign). The reason is, when the *'Technology Options'* are integrated into the car there are incremental costs involved, and hence the specific driving costs increase in the equal proportion. But after the technical improvements have been achieved, as a result of increase in traveling distance by 15%, the specific driving costs decrease,

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thus showing a net -13.1% change. Similarly, when the travelling distance decreases by 15%, the specific driving costs increase by +17.7%.

Payback period: The concept of payback period and its relation to conventional fuel prices is discussed in section 5.2.6. In Case C (1), the results vary between -45 and +46%. The reason for negative values of the results is, that, the driver drives more kilometers per year, and hence he saves more money through reduced fuel expenditure. Therefore, with an increase in driving distance, the payback period reduces.

In addition to the driving distance, the payback period also shows a direct proportionality relationship with conventional fuel price. It means, that, whenever driver is driving the car, there is always saving of the fuel due to enhanced efficiency, but the amount of money being saved on the fuel, depends on the market price of the conventional fuel. The evidence of this concept can be seen in Case C (2) where with a 15% decrease in the travelling distance, the payback period goes as high as +46%. And as low as -45%, in case of 15% increase in the travelling distance.

Yearly total CO_2 emission: This relates to the amount of CO_2 emitted per year during the driving cycle. There is a direct relation between the energy demand and total emission from the car, hence, as a direct impact of the changing yearly travelling distance, the results vary between +15% and -15%.

CO_2 abatement cost: This cost is related to the incremental investment costs occurring on the vehicle for technical improvements. The amount of CO_2 generated during a year depends on the amount of fuel combusted during the travelling distance. Within the sensitivity analysis, the incremental costs are fixed for *'Technology Option 1&2'*. But, with a decrease in travelling distance, the fuel demand and the consecutive CO_2 emission decrease, and therefore, the CO_2 abatement cost decreases. The same concept is applicable is case of increase in traveling distance as well. Within the sensitivity analysis, the results vary between -13 and +17.7% for *'Technology Option 1'* [in Case C (1)], and -34.7% and +113.7% *'Technology Option 2'* [in Case C (2)].

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Table 37: Results of the sensitivity analysis, Case D (1)

***'Technology Option 1'* integrated into the car, constant yearly travelling distance, vehicle lifetime varying between + / - 30%**														
Sensitivity category	Car lifetime	% change	Yearly energy demand	% change	Fuel expenditure[21]	% change	Sp. Driving costs	% change	Payback period[22]	% change	Total CO_2	% change	CO_2 abatement cost	% change
Unit	Years		MJ/yr		€/year		€/100km		Years		Tone/yr		€/Tonne	
Gasoline car	10		37,620		1,624		24.62		4.1		2.79		238	
Gasoline car - high case	13	+30%	37,620	0.0%	1,624	0%	22.20	-9.8%	4.1	0%	2.79	0%	183	-23.0%
Gasoline car - low case	7	-30%	37,620	0.0%	1,624	0%	29.25	+18.8%	4.1	0%	2.79	0%	442	+85.6%
Diesel car	10		36,100		1,259		23.30		5.3		2.65		250	
Diesel car – high case	13	+30%	36,100	0.0%	1,259	0%	21.01	-9.8%	5.3	0%	2.65	0%	192	-23.1%
Diesel car – low case	7	-30%	36,100	0.0%	1,259	0%	27.68	+18.8%	5.3	0%	2.65	0%	464	+85.6%

[21] Calculated by considering 2010 fuel price derived from Fiorello, et al., (2009)
[22] Calculated by considering 2010 fuel price derived from Fiorello, et al., (2009)

Table 38: Results of the sensitivity analysis, Case D (2)

***'Technology Option 2'* integrated into the car, constant yearly travelling distance, vehicle lifetime varying between + / - 30%**														
Sensitivity category	Car lifetime	% change	Yearly energy demand	% change	Fuel expenditure[23]	% change	Sp. Driving costs	% change	Payback period[24]	% change	Total CO_2	% change	CO_2 abatement cost	% change
Unit	Years		MJ/yr		€/year		€/100km		Years		Tone/yr		€/Tonne	
Gasoline car	10		30,888		1,333		27.74		7.4		2.29		879	
Gasoline car - high case	13	+30%	30,888	0.0%	1,333	0%	25.01	-9.8%	7.4	0%	2.29	0%	676	-23.1%
Gasoline car - low case	7	-30%	30,888	0.0%	1,333	0%	32.95	+18.8%	7.4	0%	2.29	0%	1257	+43.0%
Diesel car	10		29,640		1,032		25.71		8.4		2.17		975	
Diesel car – high case	13	+30%	29,640	0.0%	1,032	0%	23.18	-9.8%	8.4	0%	2.17	0%	750	-23.1%
Diesel car – low case	7	-30%	29,640	0.0%	1,032	0%	30.54	+18.8%	8.4	0%	2.17	0%	1394	+43.0%

[23] Calculated by considering 2010 fuel price derived from Fiorello, et al., (2009)
[24] Calculated by considering 2010 fuel price derived from Fiorello, et al., (2009)

5.4.2.2 Results of the sensitivity analysis: Cases D (1) & D (2)

Fuel Economy: As seen in previous cases, the fuel economy of a car is not affected by any of the changing parameters of the sensitivity analysis.

Specific CO_2 emission: This a technical feature of the car and it does not change with the changing parameters of the sensitivity analysis.

Yearly energy demand: As the yearly travelling distance does not change, the energy demand remains unchanged.

Annual expenditure on the fuel: As the traveling distance is constant, the fuel demand does not change, and therefore the yearly fuel expenditure does not change. However, the total lifetime fuel expenses change as per the variations in the lifetime of the vehicle.

Specific driving costs: The cost of driving per km of the vehicle, but it does not include fuel expenditure. It is calculated as the total annual technology costs that include O&M, depreciation and other costs. In case of 30% increase in the vehicle lifetime, the specific driving costs reduce by 9.8% (hence a negative sign) and with a 30% decrease in the vehicle lifetime, the specific driving costs increase by 18.8%.

Payback period: In Case D (1), the results vary between -22.7% and +45.5%. The reason for negative values of the results is, that, with increase in the lifetime of the vehicle, the total lifetime fuel and monetary savings are higher. In other words, the driver now travels for more years, and therefore more kilometers in the total lifetime. So, the money saved on reduced fuel expenditure is also higher. Therefore, as a result of increase in the lifetime of the vehicle, the payback period decreases. In Case D (2), with a 30% increase in the vehicle lifetime, the payback period decreases to around -20% for the gasoline car, and around -23.8% for the diesel car. And with a 30% decrease in the vehicle lifetime, the payback period increases to around +46.7% for the gasoline car and around +38.1% for the diesel car.

Yearly total CO_2 emission: This relates to the amount of CO_2 emitted per year during the driving cycle, and is dependent on yearly fuel demand. As there is no change in the yearly fuel demand, the level of total CO_2 emission does not change.

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However, the total lifetime CO_2 emission changes as per the variations in the lifetime of the vehicle.

CO_2 abatement cost: This cost is related to the incremental investment costs occurring on the vehicle for technical improvements. With the implementation of *'Technology Options'* into the car, the fuel efficiency increases, and hence, the CO_2 emission decreases. In Case D (1) and (2) as the lifetime of the car decreases by -30%, the lifetime fuel and CO_2 savings decrease in comparison to the baseline values. The reason is, that, within the sensitivity analysis, the incremental costs are always fixed at 10% and 30% higher than the baseline vehicle price. But, with a decrease in the vehicle lifetime, the total amount of CO_2 that could have been saved decreases, and therefore, the abatement costs increase. As a result of shorter lifetime of the car, the cost of CO_2 avoidance increases between +43% and +85.6% for *'Technology Option 2 and 1'* respectively. Moreover, when the technical lifetime of the vehicle increases, the total amount of CO_2 that can be saved throughout life increases, hence, at the fixed incremental cost it becomes cheaper to save per tonne of CO_2. This effect can be seen in the results that show a -23% decrease in the CO_2 abatement costs with 30% increase in the vehicle lifetime.

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6. CONCLUSIONS AND DISCUSSION

All four of the research questions for this study are answered until the completion of chapter 5 (ANALYSIS AND RESULTS) and this chapter concludes the results and findings of the thesis.

The aim of **research question 1** was to carry out an assessment of various technical improvement potentials in European passenger cars and their potentials in the vehicle efficiency increase. In addition to the industrial studies and literature referred for this assessment, the European Commission and European car manufacturers consider a leading role of innovative technologies in reducing transport energy demand and GHG emissions. While all the technologies stated in section 3.3 are capable of enhancing the vehicle efficiency, they demonstrate varying degrees of production and maturity in Europe. Currently, a huge diversity of innovative technologies is available in the European market, but the integration of those technologies into the vehicle may add an incremental cost over the baseline vehicle price. Given the diversity of technologies and dynamically changing RD&D, it is not possible to say which particular technology or technology mix will be the winner of the solution for vehicle efficiency increase. Most likely, the future will see a number of technology combinations entering the market, tailored for different usages, driving circumstances and customer preferences.

To answer **research question 2**, *'Technology Options 1 & 2'* were identified from (EPA, 2008) and (McKinsey, 2009) respectively. Both the *'Technology Options'* can have significant positive impact on the vehicle efficiency and fuel economy. The technologies included in *'Technology Options'* demonstrate varied state of development towards production. For example, on one hand, *'Technology Option 1'* contains technologies (reduced engine friction losses, improved aerodynamic efficiency and low rolling resistance tires) that are followed by the latest developments, approved test-drive results and reliability by manufacturers. Therefore, these technologies show high degree of market readiness, and are considered as the most promising option for early integration into vehicles. On the other hand, *'Technology Options 2'* contains advanced technologies that show medium to high degree of technology readiness, and their broad scale application

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into vehicles may take some time, primarily due to the additional costs and investments involved.

Results of the energy demand and emission saving assessment stated in section 5.1 show the changing pattern of the car fuel economy and CO_2 emission. *'Technology Options 1 & 2'* have the potential to enhance the fuel efficiency by 5% and 22% respectively. The results show, that, *'Technology Options 1 & 2'* offer the potential of annual energy savings of around 2,000 MJ (~60 l fuel) and 8,500 MJ (~250 l fuel) and consecutive CO_2 emission of around 0.14 tonnes and 0.64 tonnes per car for a fixed driving cycle. Techno-economic assessment results presented within the same section show the decreasing pattern of expenditure on fuel, and the relationship between increased specific driving costs and enhanced fuel economy.

To answer **research question 3**, the results of assessment presented in section 5.2 show the changes that occur in the economic performance of a technically improved car against the baseline car's economic indicators. The *'Technology Option 1 & 2'* will increase the vehicle cost, but as a result of increased fuel economy and fuel expenditure savings, the additional investment can be reimbursed within a certain time period defined as the payback period. The *'Technology Options'* are projected to result in a net cost benefit to the owner over a 10 year vehicle lifetime. This is because the cumulative fuel expenditure savings offset the higher incremental costs of the vehicle. Showing the customer the benefits of their decreased fuel expenditure and additional monetary benefits after the completion of payback period can be an important strategy to motivate them to buy an expensive but efficient car.

To answer the **research question 4**, the *'Technology Options'* were identified as per their market readiness. The results of the analysis stated in section 5.3 represent what potential reduction in the total EU-27 energy demand and CO_2 emission could be achieved when the *'Technology Options'* are integrated within a specific percentage of the total number of cars. This effect of assumed technology diffusion was assessed through the bottom-up simulation. The scenarios defined within the analysis show, that, a 19% to 34% reduction in total energy demand and subsequent CO_2 emission can be achieved in Europe up to 2030.

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The results and analysis detailed in this thesis show the potentials of technologies, although there are certain limitations of this study. The potentials of efficiency increase by advanced innovative technologies are based on the theoretical values, so the results may vary significantly during different vehicle applications and under varying on-road driving conditions. Investment costs, fuel economy, fuel efficiency improvements etc. stated in this study are average values derived from published data and studies, but different vehicles like SUVs and large cars from different manufacturers exhibit unique characteristics, therefore, the inputs values need to be revised if the assessment is to be applied to diversified variety of vehicles.

Moreover, the technologies included in *'Technology Option 1 & 2'* are not the only options that manufacturers are considering. There are many other technologies and measures that have varied degree of technology readiness and implementation within cars. The European automotive manufacturers have identified multiple categories of innovative car technologies and other measures that will ensure further progress in the efficiency of cars, systems and components.

Noting the limitations, the research contained in this thesis has potential to be extrapolated upon. The results and scenarios discussed in the assessment are confined to the application of technical improvement potentials on conventional gasoline and diesel cars. Most of the technologies stated in this thesis are not only restricted to conventional passenger cars, but are also applicable into other AAMTs. Therefore, a broader analysis of technology diffusion in different vehicle classes and segments can give wider illustrations of the future energy and emission saving potentials. In addition to this, the assessment has been done for the EU-27, but given the availability of datasets, this analysis can be extended to the level of EU member states.

The results produced in this thesis have shown the quantitative effect of combined technologies on the vehicle's energy demand and economic performance. The findings of this study show that the advanced and innovative technologies can have significant positive impacts in reducing the EU-27 energy demand and subsequent CO_2 emissions in future.

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APPENDIX I

Technical Improvement Potentials in European Cars

1. Body Technologies

1.1 Vehicle weight reduction – Technical and construction measures for vehicle load reduction include utilizing advanced lightweight construction & designing material, reducing unnecessary and low-use vehicle features (like seat heating or electrical devices), and using smaller capacity fuel tanks to avoid additional weight. The automotive industry has already put several efforts into reducing the vehicle weight by using a higher share of plastics in the car and aluminium in the car bodies. Different studies suggest that an improvement of 4 to 6% in fuel economy can be achieved by use of advanced weight reduction technologies (AEA, 2009) (Greenpeace, 2008). Further features like downsizing the engine and suspension can also help to reduce the vehicle weight by 11-13%. In contrast to the vehicle weight reduction, safety measures and luxury features add to the vehicle weight and followed by the same reason during last 10 years a 10-20% increase in the average vehicle weight has been noticed in UAS and Japan (Kobayashi, Plotkin, & Ribeiro, 2008).

1.2 Aerodynamic drag – Aerodynamic drag holds an average of around 30% in total tractive forces and this increases further during high speed driving (especially on highways). The measures to improve aerodynamic drag include better streamlining, reduction of vehicle frontal resistance areas, optimization of car body shape, construction of under-body covers for smoother flow and lowering the car. This kind of improvement can increase the efficiency by around 2-4% (AEA, 2009). Technically there is a relation that a 10% decrease in the aerodynamic drag coefficient can lead to fuel savings of about 0.2-0.3 l/100km depending on the driving cycle (Elena, 2001).

2. Engine Technologies

To reach the objectives of CO_2 reduction and increased efficiency, the future will to depend on a combination of multiple vehicle technological developments entering the market, customized for different usage, driving circumstances and consumer

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preferences etc. However, the internal combustion engine (ICE) and its modifications will remain the dominant source of power for at least in the coming decade, mainly because of the high cost of alternatives (ACEA, 2009). This subsection describes some important engine technologies for efficiency improvements. The sources used for technologies stated here are Alson, Ellis, & Gnass (2005); IMPRO-car (2008); TNO (2006); EPA (2008); Kobayashi, et al. (2008); US-ITA (2009); and AEA (2009).

2.1 Variable Valve Timing & Lift (VVT&L) – this technology improves the engine efficiency by optimizing the flow of fuel and air into the engine for various engine speeds. It is also referred as variable valve actuation (VVT), variable-cam timing or variable valve timing and lift electronic control. Valves control the flow of air and fuel into the cylinders and exhaust out of them. When and how long the valves open (timing) and how much the valves move (lift) both affect engine efficiency and VVT&L systems automatically alter timing and lift to the optimum settings for the engine speed.

2.2 Cylinder Deactivation – The concept of this technology targets reducing pumping losses by switching off half of the engine cylinders. This technology deactivates some of the engine's cylinders when the vehicle load is low or constant speed is maintained. This temporarily turns an 8 or 6 cylinder engine into a 4 or 3 cylinder engine. By deactivating half the cylinders, the remaining active cylinders are operating at twice the load that the engine would normally operate at if all cylinders were active. By definition therefore, those active cylinders have the throttle further open, thereby reducing the pump losses and improving fuel consumption. This technology is not used on 4-cylinder engines since it would cause a noticeable decrease in engine smoothness. Cylinder deactivation is called as displacement on demand (DOD), or Multiple Displacement Systems (MDS); developed by Chrysler, or Active Fuel Management (AFM); developed by GM, or Variable Cylinder Control (VCM): from Honda or Active Cylinder Control (ACC) by Mercedes Benz.

Example: GM's Displacement on Demand, it automatically turns off half of the cylinders during light load operating conditions, enabling the working cylinders to achieve a higher fuel efficiency through better thermal, pumping and mechanical

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efficiency. The deactivation technology under a light load closes both the intake and exhaust valves for half of the cylinders.

Technical challenges: The integration of cylinder deactivation into the vehicle is challenging as active engine mounts are needed to run deactivated engine at idle. Also the noise produced due to the intake and exhaust is problematic. Deactivation can be used in the highest two gears only, because it may be difficult to maintain the vehicle in a deactivated mode at around 100 Kmph, which can lead to customer dissatisfaction with higher fuel consumption.

2.3 Engine Downsizing, Turbochargers & Superchargers – this technology increases the engine power by downsizing engines (the use of a smaller capacity engine operating at higher specific engine loads) without sacrificing performance. Turbochargers and superchargers are fans that force compressed air into engine's cylinders; the resulting increased mass of air creates extra power. A turbocharger fan is powered by exhaust from the engine, while a supercharger fan is powered by the engine itself. Both technologies allow more compressed air and fuel to be injected into the cylinders, generating extra power from each explosion to increase performance with increasing fuel economy. A turbocharged or supercharged engine produces more power than the same engine without the charging; hence the technology makes it possible to use smaller engines without sacrificing the power or performance of the vehicle.

2.4 Direct Fuel Injection (with or without turbocharging or supercharging) - Also called fuel stratified injection or direct injection stratified charge. This technology delivers higher performance with lower fuel consumption. In conventional multi-port fuel injection systems, fuel is injected into the port and mixed with air before the air-fuel mixture is pumped into the cylinder. In direct injection systems, fuel is injected directly into the cylinder so that the timing and shape of the fuel mist can be precisely controlled. This allows higher compression ratios and more efficient fuel intake, which ultimately delivers higher vehicle performance with lower fuel consumption.

2.5 Homogeneous Charge Compression Ignition (HCCI) - In the HCCI systems the fuel-air mixture is ignited simultaneously throughout the entire volume of the cylinder, rather than being centralized at the fuel injector. HCCI combines homogeneous

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charge spark ignition (gasoline engines) and stratified charge compression ignition (diesel engines) such that well-mixed fuel and the oxidizer are compressed to the point of auto-ignition. The combustion through HCCI systems occur on a faster rate than conventional combustion. This results in the generation of a higher peak pressure (which results in a leaner fuel-air mixture for achieving higher efficiency) and a relatively lower peak temperature (that reduces NOx emissions) within the combustion chamber (Norris, Stones, & Reverault, 2010). Currently, HCCI engines are in R&D or early demonstration, the estimated commercialization of this application is foreseen after 2015 (strategyanalytics.com, 2007). Currently few motor manufacturers, including General Motors, Volkswagen, Honda, and Mercedes-Benz are all believed to have fully operating prototypes. Within one of the earliest demonstrations, few test drives of Vauxhall Vectra 2.2 HCCI engine showed a fuel efficiency increase of around 15% resulting the consumption from 37 miles per gallon (mpg) to 43 mpg (ETSAP-1, 2010).

Technical challenge: During HCCI operation, engine control can be difficult as the ignition timing is not under direct control. This is different to conventional gasoline or diesel engine where ignition is controlled directly by sparks or injectors. So, to achieve an effective operation in HCCI mode, fast and precise control may be required, for example with sensors.

2.6 Optimised / advanced cooling and electric water pump – Engines generate mechanical power by extracting energy from heat flows, so more heat energy enters the engine than what is produced in mechanical power. This difference of waste heat in the vehicle is removed by the intake of cool air, hot exhausts gases, or by cooling the engine. Optimised/advanced cooling technologies use coolant (as water) and oil thermal inertias to help in reducing fuel consumption and avoid engine damage through extra heat. During engine operation, the system is integrated into the cooling loop of the engine. After the engine's shutdown, the residual heat is carried away by means of a small cooling circuit, which is driven by a thermostatically controlled electric water pump (ETSAP-1, 2010).

2.7 Reducing Engine Friction – These technologies are considered very important by manufacturers and almost every engine manufacturer is researching options to reduce engine friction losses, therefore these technologies have already been implemented in

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many of the new engines. The technologies for reducing engine friction include system components and materials that minimize the friction between moving metal parts in the engine and the use of better heat resistant lubricating agents. Currently, a significant amount of work has been done in this field, for example advanced outlining of the crank with the cylinder concepts has been proposed by researchers and manufacturers in which the friction of the piston can be lowered. Advanced coating techniques for the cylinder and piston have also been considered. Few other examples include friction reduction for piston surfaces and rings, crankshaft design and improved roller cam followers.

2.8 Heat Recovery Systems – A lot of heat is wasted during propulsion, hence recovering the heat lost during engine operation and exhaust gas of the internal combustion engines has been recently investigated. The recovered heat can be converted into mechanical work or electrical power or direct warming-up of the engine. In fact, immense fundamental research is currently being done in the field of thermoelectric power generation for better heat recovery systems. Few examples of such technologies include mechanical, 'electrical turbocompounding' and 'rankine bottoming cycles'. Another important technology is to utilize the exhaust gas for driving the engine turbine, which then delivers the power to the crankshaft, resulting in the increase of engine power output without increasing the fuel consumption. One important point to be noted about heat recovery technologies is that compared to other technologies heat recovery is a complex technique and contains a large number of mechanical components.

3. Transmission Technologies

3.1 Continuously Variable Transmissions (CVTs) – This kind of systems have an infinite number of "effective gears" that provide seamless acceleration through continuous shifting. Other conventional transmission systems control the ratio between engine speed and wheel speed using a fixed number of metal gears. However, CVT technologies facilitate a pair of variable-diameter pulleys connected by a belt or chain that can produce an infinite number of engine/wheel speed ratios. This system offers few unmatched advantages over conventional transmission designs i.e. seamless acceleration without the jerk or jolt from changing gears and no frequent downshifting or "gear hunting" on up-hills.

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3.2 Automated Manual Transmission (AMT) - An Automated Manual Transmission (AMT) is mechanically similar to a conventional manual transmission, but shifting and launch functions are controlled by the vehicle. Manual transmissions are lighter than conventional automatic transmissions and suffer fewer energy losses. The gearbox in a car is optimized for power output as per the type of car and the installation of more gear ratios for further optimization (gearbox optimization) can increase fuel efficiency by as much as 9%. AMT operates similarly to a manual transmission except that it does not require clutch actuation or the shifting of gears by the driver. Automatic shifting is controlled electronically (shift-by-wire) and performed by a hydraulic system or electric motor. In addition, technologies can be employed to make the shifting process smoother than conventional manual transmissions.

3.3 Dual Clutch Transmission (DCT) – DCT is a kind of alternative automatic transmission that contains combined features of mechanical efficiency from manual transmission system and shift control from an automatic transmission system. The DCT consists of two power transmission paths in parallel, each with its own clutch. A change in gear ratio is achieved by disengaging one clutch while simultaneously engaging the other. Currently available DCTs use 2 different types of clutches i.e. wet-clutch DCT and dry-clutch DCT. A wet multi-plate clutch requires a hydraulic system to clamp and cool the clutches as well as for gear shifting, while a dry-clutch DCT does not. Dry-clutch DCTs thus have an advantage over wet-clutch DCT as dry ones do not need oil to cool down (unlike wet clutches) and chances of hydraulic pumping losses and churning losses in the transmission due to a lower oil volume are also lower in the dry-clutch DCT systems.

4. Hybrid Technologies

4.1 Start stop systems and regenerative braking - These systems automatically turn the engine off when the vehicle comes to a stop and restart it instantaneously when the accelerator is pressed, so the fuel is not wasted during idling. This system is also called as Integrated Starter/Generator (ISG) Systems and is widely used in current manufactured battery hybrid vehicles. In some of the advanced hybrid motor technologies, start-stop systems are coupled with regenerative braking where the mechanical energy lost in braking is converted into electricity. This electricity can be

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stored in a battery and used for driving or for powering the automatic starter systems. With this technology efficiency can be increased between 0.5 to 8%.

Stop-Start, or idle-off operation also reduces fuel consumption caused by friction and pumping losses by turning the engine off while stationary. The advantages of the Stop-Start technology are highly dependent on control strategy and drive cycle. The benefits of this system will be higher in a drive cycle that has frequent stops; city driving may yield significant savings from idlestop operation but on long highway drives, none or very low savings will be made because the vehicle remains in motion.

5. Other Technologies

5.1 Overcoming rolling resistance – These modifications include measures for the reduction of mechanical resistance and friction of tires. The frictional forces between the tires and the road are very much affected by vehicle weight and driving speed, and they are of equal importance for both urban or highway driving. These forces account for around 30% of the total tractive force and can be reduced by redesigning the tires & tire material, bearings & seals, regular tire pressure monitoring etc. These measures can result in an enhanced fuel efficiency but the potential losses in traction or tire durability shall not be overlooked (Kobayashi, Plotkin, & Ribeiro, 2008) (Greenpeace, 2008). Tire characteristics such as materials, construction, and tread design etc. influence durability, traction control and comfort of a car to a large extent. Low rolling resistance tires are considered very important by the automotive industry to increase vehicle efficiency increase and are seen as an option that can be readily applicable to a large number of vehicles without changing and vehicle characteristic or configuration.

5.2 Use of advanced accessories – Use of advanced accessories like gear shift indicators, GPS navigation systems, power steering can be very important in achieving a lower fuel consumption rate. A gear shift indicator is a simple light-signal fitted on dashboard and reminds the driver to change the gears whenever required and consequently helps in avoiding unnecessary engine revolutions. Use of power steering in vehicles can result in reducing the fuel use by 3% and providing better handling and safety. Storage of latent heat (which gets wasted otherwise) into the batteries can result in 3-5% fuel usage reduction. This stored heat can be used to heat

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the system and catalytic converter during the start-up (Greenpeace, 2008). Other accessories like air conditioners, windshield wipers etc. that can use the energy generated from the engine can make the car systems more efficient. Few other advanced measures to improve the efficiency of cars are; use of advanced computer chips for the monitoring of auto and driving conditions, use of advanced navigation systems, better maintenance and driving habits, monitoring of traffic conditions through satellite or radio to avoid traffic jams etc.

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APPENDIX II

COMPARISON BETWEEN DIFERENT STUDIES

In addition to the studies considered for this study like (TNO, 2006), (EPA, 2008), (Kobayashi, Plotkin, & Ribeiro, 2008), (IMPRO-car, 2008), (AEA, 2009) and (McKinsey, 2009)[25], there are many other studies that have examined the technological potentials to improve the fuel economy and emission reduction by passenger cars as well as other vehicles (like light trucks). Most of these studies have considered technology and/or cost analysis by implementing several analytical methods from various disciplines of economics and automotive engineering. After a brief review of these recent studies mainly from Europe and USA, following main points of comparison between the studies can be drawn:

- Different institutions and organizations have carried different studies and sometimes there are many similarities with respect to the methodology and data used for the analysis. For example, (TNO, 2006) (AEA, 2009) and (Eichhammer, et al., 2009).

- Technical options are expected to have a major share in the emission reductions. Almost all of the studies considered a leading role for technologies in reducing emissions. An important reason for the analysis in these studies can be, that, for these technical options more data is available than for non-technical options.

- All studies have considered that higher levels of the fuel economy can be achieved through technical innovation, but that will also add an incremental cost to vehicle.

[25] **(TNO, 2006)** = Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars, **(EPA, 2008)** = EPA Staff Technical Report: Cost and Effectiveness Estimates of Technologies Used to Reduce Light-duty Vehicle Carbon Dioxide Emissions, **(Kobayashi, Plotkin, & Ribeiro, 2008)** = Energy efficiency technologies for road vehicles, **(IMPRO-car, 2008)** = Environmental Improvement of Passenegr Cars, **(AEA, 2009)** = Assessment with respect to long term CO2 emission targets for passenger cars and vans, Deliverable D2: Final Report, **(McKinsey,2009)** = Der Trend zu energie - effizienten Pkw, Implikationen für die deutsche Automobilindustrie.

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- The majority of the technologies discussed in reports/studies are available today, either in the United States, Japan, or Europe (like aerodynamic drag improvement, vehicle weight reduction, low rolling resistance tires). However, few others have only recently been introduced into the market (tire pressure monitoring system, strong downsizing). In a few cases, estimates are done on the technologies which are not currently in the production, but are expected to be so in the next few years (for example, homogeneous charge compression ignition-HCCI).

- In general, the estimates and assessment presented in studies may be conservative as they rely on data sources from the past one to six years, which in some cases, can be relatively old. The automotive industry is a technology-driven industry and new technologies keep developing over the time. A number of technologies which have been introduced recently or will be introduced in the next few years will sow improvements in their effectiveness and cost reductions which can be over the values than the studies estimate today.

- The important distinction between all technology/cost analyses is the assumption of the vehicle and technical characteristics. Behavior of real markets, consumer acceptance, political impacts etc. are often taken in a limited perspective.

- Nearly every technology and/or cost analysis presented in the studies shows at least some potential to increase fuel economy beyond current market baseline levels. However, cost-effective integration of technologies remains questionable.

- Reviewed studies limit the time horizon of proven technologies about 10 years. It suggests, that, the passenger car fuel economy improvement potentials are seen mainly in near term. Future implementation and technology changes are subjected to several factors like success of technology, costs, political support etc. However, in some cases for longer-term analyses, considering the possibility of technological changes, studies suggest varied level of technology potentials and cost reductions.

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- A significant degree of variation in potential efficiency of technologies exist between studies, therefore the differences in assumptions across analyses lead to widely divergent conclusions across different studies. The largest area of divergence about data is the efficiency potential and costs of technologies.

Feasibility and functionality of technologies in a car is a key point to decide the application of technology or technology sets into a vehicle. When improvement technologies are integrated into the car, there theoretical efficiency increase potentials or cost values cannot be simply added. First reason for variation in technical efficiency is, that, while estimating, the aggregate effectiveness of multiple technologies may depend on the level of integration into the vehicle and functioning of one technology may significantly impact on the other technology. For example, a variable valve train system (VVT system) and a six speed automatic transmission, both act to shift the engine operating points to a fraction of the engine speed where pumping losses are less significant, and it is therefore there can be a negative synergy, or dis-synergy, between such technologies (EPA, 2008). Similarly, the second reason for variation in cost of technologies is, that, when car manufacturers introduce technologies into the car or production line, there will be several technological and infrastructure changes, which will cause higher investments to the manufacturer, ultimately, resulting in the price increase more than the theoretical cost.

Many studies provide numerical data for costs and % impacts of technologies. But in general, there are somewhat uncertainties or differences between the costs of technologies (USD or €), and their impacts on efficiency increase (in %). For example, between (TNO, 2006), (EPA, 2008) and (Kobayashi, Plotkin, & Ribeiro, 2008). Therefore, variations into the final results and estimations of technology potential occur, as explicit state of the impact and cost of such technologies vary between studies. These wide variations in technology costs and potentials show, that, there is a substantial divergence on the assumptions used in analysis.

In this study, the technical improvement technologies and expected efficiency increase from them is stated in Table 6 on page 31. In addition to *'Technology Options'* stated in this thesis, there are a number of other technologies and clusters,

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that can be implemented into European cars for achieving reductions in greenhouse gas emissions, and to improve the vehicle fuel economy. (TNO, 2006), (IMPRO-car, 2008), (AEA, 2009) and (McKinsey, 2009) have explained and compared few technology sets and evaluated the theoretical values of efficiency increase by them, along with the expected incremental costs. Following tables summarize the potentials of different technologies in % efficiency increase or % CO_2 reductions, and the cost estimates stated in the aforementioned studies.

- Table 39: CO2 reduction potential and additional manufacturer costs of technical options in petrol passenger cars
- Table 40: CO2 reduction potential and additional manufacturer costs of technical options in diesel passenger cars
- Table 41: Different technology options for petrol passenger cars selected by (TNO, 2006) and (AEA, 2009) for the analysis
- Table 42: Different technology options for diesel passenger cars selected by (TNO, 2006) and (AEA, 2009) for the analysis
- Table 43: Potential CO2 reduction and additional costs for different technology combinations (petrol cars)
- Table 44: Potential CO2 reduction and additional costs for different technology combinations (diesel cars)
- Table 45: Fuel efficiency measures, potential efficiency and incremental costs

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Table 39: CO_2 reduction potential and additional manufacturer costs of technical options in petrol passenger cars

Source: (TNO, 2006), (AEA, 2009)

	Small Cars			Medium Cars			Large Cars		
Petrol Passenger Cars	**CO2 reduction (%)**	**Costs (€)**	**Attributable costs (€)**	**CO2 reduction (%)**	**Costs (€)**	**Attributable costs (€)**	**CO2 reduction (%)**	**Costs (€)**	**Attributable costs (€)**
Engine technologies									
Reduced engine friction losses	3	40	40	4	50	50	5	60	60
DI / homogeneous charge (stoichiometric)	3	125	125	3	150	150	3	175	175
DI / Stratified charge (stoichiometric)									
DI / Stratified charge (lean burn / complex strategies)	10	320	320	10	400	400	10	480	
Mild downsizing with turbocharging									
Medium downsizing with turbocharging	8.5	225	225	10	300	300	10	375	375
Strong downsizing with turbocharging	12	390	390	12	450	450	12	510	510
Variable Valve Timing	3	100	75	3	150	113	3	200	150
Variable valve control	7	300	225	7	350	263	7	400	300
Cylinder deactivation							4.3	68	68
Variable Compression Ratio									
Optimised cooling circuit*	1.5	35	35	1.5	35	35	1.5	35	35
Advanced cooling circuit + electric water pump	3	120	120	3	120	120	3	120	120
Transmission technologies									

Petrol Passenger Cars	Small Cars			Medium Cars			Large Cars		
	CO2 reduction (%)	Costs (€)	Attributable costs (€)	CO2 reduction (%)	Costs (€)	Attributable costs (€)	CO2 reduction (%)	Costs (€)	Attributable costs (€)
Optimised gearbox ratios	1	50	50	1.5	60	60	1.5	70	70
Piloted gearbox	4	300	300	4	350	350	3	120	120
Continuous Variable Transmission	2.9	127	127	2.1	148	148	2.1	148	148
Dual-Clutch	4	600	450	5	700	525	5	900	675
Hybrid technologies									
Start-stop function	4	220	220	4	250	250	4	280	280
Start-stop + Regenerative braking	7	515	515	7	600	600	7	685	685
Mild hybrid (motor assist)	11	1,200	900	11	1,600	1,200	11	2,000	1,500
Full hybrid (electric drive)	22	2,800	2,100	22	3,500	2,625	22	4,200	3,150
Body technologies									
Improved aerodynamic efficiency	1.5	75	75	1.5	75	75	1.5	75	75
Mild weight reduction	0.9	22	22	1	28	28	0.9	34	34
Medium weight reduction	2.2	57	57	2.3	90	90	2.2	115	115
Strong weight reduction	5.5	212	212	5.8	294	294	5.4	418	418
Other technologies									
Low rolling resistance tires	2	25	25	2	30	30			
Electrically assisted steering (EPS, EPHS)*	3	100	100	2.5	100	100			
Advanced after treatment	-1			-1					
Homogeneous direct injection	1	100	100	2	400	400	2	400	400

Table 40: CO_2 reduction potential and additional manufacturer costs of technical options in diesel passenger cars

Source: (TNO, 2006), (AEA, 2009)

	Small Cars			Medium Cars			Large Cars		
Diesel Passenger Cars	**CO2 reduction (%)**	**Costs (€)**	**Attributable costs (€)**	**CO2 reduction (%)**	**Costs (€)**	**Attributable costs (€)**	**CO2 reduction (%)**	**Costs (€)**	**Attributable costs (€)**
Engine technologies									
Reduced engine friction losses	3	40	40	4	50	50	5	60	60
4 valves per cylinder	NA	NA	NA						
Piezo injectors	NA	NA	NA						
Homogeneous charge compression ignition (HCCI)	18	775		21	1165		21	1165	
Mild downsizing	3	120	120	3	150	150			
Medium downsizing	5	160	160	5	200	200	5	240	240
Strong downsizing	NA	NA	NA	7	300	300	10	375	375
	NA	NA	NA						
Cylinder deactivation	NA	NA	NA						
Exhaust heat recovery				1.5	45	45	1.5	45	45
Optimised cooling circuit*	1.5	35	35	1.5	35	35	1.5	35	35
Advanced cooling circuit + electric water pump	3	120	120	3	120	120	3	120	120
Transmission technologies									
6-speed manual/automatic gearbox	NA								
Piloted gearbox	4	300	300	4	350	350	4	400	400
Continuous Variable Transmission	NA								

Diesel Passenger Cars	Small Cars			Medium Cars			Large Cars		
	CO2 reduction (%)	Costs (€)	Attributable costs (€)	CO2 reduction (%)	Costs (€)	Attributable costs (€)	CO2 reduction (%)	Costs (€)	Attributable costs (€)
Dual-Clutch	5	600	450	5	700	525	5	900	675
Hybrid technologies									
Start-stop function	3	180	180	3	200	200	3	220	220
Start-stop + Regenerative braking	6	475	475	6	550	550	6	625	625
Mild hybrid (motor assist)	10	1,200	900	10	1,600	1,200	10	2,000	1,500
Full hybrid (electric drive capability)	18	2,800	2,100	18	3,500	2,625	18	4,200	3,150
Body technologies									
Improved aerodynamic efficiency	1.5	75	75	1.5	75	75	1.5	75	75
Mild weight reduction	1	23	23	1	31	31	1	38	38
Medium weight reduction	2.4	65	65	2.5	101	101	2.4	136	136
Strong weight reduction	5.9	231	231	6.3	333	333	5.9	538	538
Other technologies									
Low rolling resistance tires	2	25	25	2	30	30	2	35	35
Electrically assisted steering (EPS, EPHS)*	3	100	100	2.5	100	100	2	100	100
DeNOx catalyst									

Table 41: Different technology options for petrol passenger cars selected by (TNO, 2006) and (AEA, 2009) for the analysis

	TNO-2006					AEA 2009				
Petrol Passenger Cars	Baseline	1	2	3	4	1	2	3	4	5
Engine technologies										
Reduced engine friction losses	*	*	*	*	*	*	*	*	*	*
DI / homogeneous charge (stoichiometric)		*	*			*				
DI / Stratified charge (stoichiometric)										
DI / Stratified charge (lean burn / complex strategies)				*	*		*	*	*	*
Mild downsizing with turbocharging										
Medium downsizing with turbocharging				*	*			*		
Strong downsizing with turbocharging									*	*
Variable Valve Timing			*	*			*	*		
Variable valve control					*				*	*
Variable Compression Ratio										
Optimised cooling circuit*				*		*	*			
Advanced cooling circuit + electric water pump					*			*	*	*
Transmission technologies										
Optimised gearbox ratios		*	*	*	*	*	*	*	*	*
Piloted gearbox			*	*	*			*	*	*
Continuous Variable Transmission										
Dual-Clutch										
Hybrid										
Start-stop function			*				*	*		
Start-stop + Regenerative braking									*	*
Mild hybrid (motor assist)				*						

Full hybrid (electric drive)					*					
Body										
Improved aerodynamic efficiency	*	*	*	*	*	*	*	*	*	*
Mild weight reduction			*				*			
Medium weight reduction				*				*		
Strong weight reduction					*				*	*
Other										
Low rolling resistance tires		*	*	*	*	*	*	*	*	*
Electrically assisted steering (EPS, EPHS)*								*	*	*
Advanced aftertreatment				*	*					
Homogeneous direct injection										

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Table 42: Different technology options for diesel passenger cars selected by (TNO, 2006) and (AEA, 2009) for the analysis

	TNO-2006					AEA 2009				
Diesel Passenger Cars	Baseline	1	2	3	4	1	2	3	4	5
Engine technologies										
Reduced engine friction losses	*	*	*	*	*	*	*	*	*	*
4 valves per cylinder										
Piezo injectors										
Homogeneous charge compression ignition (HCCI)										
Mild downsizing		*	*				*			
Medium downsizing				*	*			*		
Strong downsizing									*	*
Variable Valve Timing						*	*	*	*	*
Exhaust heat recovery					*				*	*
Optimised cooling circuit*				*			*			
Advanced cooling circuit + electric water pump					*			*	*	*
Transmission technologies										
6-speed manual/automatic gearbox										
Piloted gearbox			*	*	*			*	*	*
Continuous Variable Transmission										
Dual-Clutch										
Hybrid										
Start-stop function			*				*	*		
Start-stop + Regenerative braking									*	*
Mild hybrid (motor assist)				*						
Full hybrid (electric drive capability)					*					

Body										
Improved aerodynamic efficiency	*	*	*	*	*	*	*	*	*	*
Mild weight reduction			*				*			
Medium weight reduction				*				*		
Strong weight reduction					*				*	*
Other										
Low rolling resistance tires		*	*	*	*	*	*	*	*	*
Electrically assisted steering (EPS, EPHS)*								*	*	*
DeNOx catalyst										
Particulate trap / filter	*	*	*	*	*					

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Table 43: Potential CO_2 reduction and additional costs for different technology combinations (petrol cars)

Source: (IMPRO-car, 2008)

Combination	C1	C2	C3	C 4	C 5	C 6	C 7	C 8	C 9	C 10	C 11	C 12	C1 3	C 14	C1 5	C 16
ENGINE																
Reduced engine friction LOSSES	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
DI/stratified charge lean burn/comple x strategies			*	*			*	*			*	*			*	*
Strong downsizing with turbocharg.		*		*		*		*		*		*		*		*
Variable valve control	*				*				*							
Advanced cooling circuit + electric water pump									*	*	*	*	*	*	*	*
TRANSMISSI ON																
Optimized gearbox ratios	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Piloted gearbox	*	*	*	*									*	*	*	*
Dual-clutch				*	*	*	*	*	*	*	*	*				
Total CO2 reduction (%)	15.6	20.1	18.3	28.1	16.5	20.9	19.2	28.9	19	23.3	21.6	31	18.1	22.5	20.8	30.3
Total cost (Euro)	810	910	860	1,310	1,160	1,260	1,210	1,660	1,280	13,80	1,330	1,780	930	1,030	980	1,430

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Table 44: Potential CO_2 reduction and additional costs for different technology combinations (diesel cars)

Source: (IMPRO-car, 2008)

Combination	C1	C2	C3	C4	C5	C6	C7	C8
ENGINE								
Reduced engine friction LOSSES	*	*	*	*	*	*	*	*
Strong downsizing with turbocharging	*	*	*	*	*	*	*	*
Advanced cooling circuit + electric water pump	*	*			*	*		
Exhaust heat recovery	*		*		*		*	
TRANSMISSION								
Piloted gearbox	*	*	*	*				
Dual-clutch					*	*	*	*
Total CO2 reduction (%)	18.1	16.9	15.6	14.3	19	17.7	16.5	15.2
Total cost (Euro)	865	820	745	700	1,215	1,170	1,095	1,050

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Table 45: Fuel efficiency measures, potential efficiency and incremental costs

Source: (McKinsey, 2009) and (McKinsey 'b', 2009)

Measures	Description	Eff. Increase (%)	Incremental cost (2006) (Euro)	Incremental cost (2030) (Euro)
Gasoline ICE Package 1	• Variable valve train • Motor friction reduction • Low tire rolling resistance • Tire pressure control • Low weight reduction	12	340	185
Gasoline ICE Package 2	Gasoline ICE Package 1 plus • Middle downsizing • Middle weight reduction • Electrification (steering system, pumps) • Optimized transmission • Improved aerodynamics • Start-stop-system	27	1,235	673
Gasoline ICE Package 3	Gasoline ICE Package 2 plus • High downsizing • Modified air-conditioning • Start-stop-system /brake energy recovery	32	1,985	1,081
Gasoline ICE Package 4	Gasoline ICE Package 3 plus • Gasoline direct injection (homogeneous) • High weight reduction • Optimized power transmission (double coupling)	40	2,869	1,563

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