Analysis of the CO₂ and energy demand reduction potentials of passenger vehicles based on the simulation of technical improvements until 2030

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Abstract: In Europe, passenger cars use over 65% of total transport fuel energy and produce around 12% of total EU carbon emissions. Under such circumstances advanced technologies and modifications in multiple powertrain technologies in passenger cars hold an important key to reduce emissions and energy demand into future. This study compiles a set of efficiency improvement technologies and makes use of a 'Bottom-up simulation' to assess the effects of introduction these technologies on total energy demand and CO₂ emission from passenger cars up to 2030 in the EU-27. The integration of improvement technologies in vehicle will serve the purpose of increasing fuel efficiency, enhancing performance and provide further technical and environmental benefits, but it will also result in incremental costs over the vehicle baseline prices. This research also assesses changes in specific driving costs, cost of CO₂ avoidance and the payback period of incremental costs on the vehicle's economic performance. The technical improvement potentials' options considered in this study show that a 5% to 22% increase in fuel economy of car is possible. And based on assumed diffusion of technologies across total gasoline and diesel vehicles, this study infers a potential of 19% to 34% savings in energy demand and CO₂ emission by 2030.

Keywords: Low carbon vehicles, Vehicles innovation, Energy efficiency, Bottom-up modelling, Technology market diffusion

1. Introduction

Across Europe cars have given the public greatest mobility that is adjustable to different usages, driving locations and preferences, and this trend will continue to grow into future. Over the last few years, increasing environmental concerns, rising oil prices and continuous urge for technological developments have stimulated industries and nations across the world to move towards better efficiency and sustainable practices in the transport sector. To tackle the problems associated with constantly increasing transport fossil fuel demand and greenhouse gas (GHG) emission, it has become very important to consider the alternative fuels and alternative cars for meeting environmental benefits.

In the last few years, the European car manufacturers have invested significant amount of money in the technology R&D, and have introduced more than 50 advanced technologies into the cars for the purpose of efficiency gain and emission reduction. 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 the existing conventional vehicles through technical improvements. The core analysis of this paper is based on such 'technical improvement potentials'. This paper is an extension of an ongoing research under the project ALTERMOTIVE, contracted under Intelligent Energy Europe.

Currently, a huge diversity of fuels and advanced powertrain technologies are available in Europe. Table 1 states various alternative automotive mobility technologies (AAMTs) mapped under different developmental stages along the technology curve (Research, Demonstration and/or Commercial state). In Table 1 it can be seen that in addition to the conventional diesel and gasoline cars, few other AAMTs like Natural Gas Vehicles and Flexi

Fuel Cars already exist in the European market on commercial level. These technologies also show continuous process of developments for achieving higher vehicle efficiency and better customer satisfaction. The technologies included under Demonstration phase are not at commercial scale yet, but depending on the speed of progress and overcoming market and cost barriers these may come to commercial phase in next few years. The technologies exhibiting the R&D phase will continue to progress to overcome technical challenges and incompatibilities, and will come to commercial phase no sooner than 2020-2025.

Table 1: Alternative Automotive Mobility Technologies - State of the Art in Europe (2010)

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

Source: (Toro, 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

2. Methodology

The method implemented for this study starts with the review of various technical improvement potentials in the European passenger cars along with their potentials in enhancing the vehicle efficiency. In next step, this study selects two sets of innovative improvement technologies called as ‘Technology Option 1 & 2’ and assesses the impacts of their integration on vehicle’s energy demand, CO₂ emission, and economic performance. The main assessments applied in this study with the bottom-up simulation and economic estimations are:

1. Assessing the improvements in the vehicular energy consumption and consecutive CO₂ emission as a result of integration of Technology Options – Techno-Environmental assessment.
2. Assessing the changes in economic performance of the car as a result of incremental costs and technical improvements – Economic assessment.
3. Assessing the potentials of technologies in overall energy demand and emission reduction at assumed diffusion rates across EU-27 car fleet – Techno-Environmental assessment.

2.1. Techno-Environmental assessment:

The techno-environmental assessment carried through the bottom-up simulation is done to assess the energy demand and CO₂ emission by the total European passenger cars (including all types’ such as gasoline, diesel, hybrid, bioethanol etc.) for a fixed annual driving distance. For setting up an energy demand baseline, energy demand projections and car fleet size

forecasts in EU-27 until 2030 were derived from Fiorello, et al., (2009). Then the bottom-up simulation tool was built up by using different vehicular data and other input values (like fuel economy, average annual traveling etc.) to assess the overall energy demand and CO₂ emission up to 2030. The general formula for the assessment is:

$$ED_t = \sum (F_{i,t} \times D_{i,t} \times FE_{i,t}) \quad [PJ] \quad \text{Eq. 1}$$

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 running in year t .

Changes in fuel economy: It was considered that when the technical improvements occur into the car by implementation of ‘*Technology Options*’, the fuel economy increases by a certain %. The equation used to assess changes in the fuel economy is:

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

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 vehicle efficiency.

2.2. Economic assessment:

The fuel efficiency of the vehicle can be enhanced by implementation of advanced innovative technologies, but the introduction of new technologies in vehicle will cause extra upfront investments and additional costs to the manufacturers and these costs will add extra price over the vehicle price (McKinsey, 2009). Thus, it is technically feasible to reduce the fuel consumption of new vehicles, but additional costs will be incurred. In this study, following assessments were done.

Incremental Cost of technology options: The concept of Retail Price Equivalent Multiplier (RPE factor) that represents the average additional price consumers would need to pay for an advanced technology was used to assess the incremental costs of technologies.

$$IC_{TO} = C_M \times RPE \text{ factor} \quad \text{Eq. 3}$$

Where IC_{TO} is the incremental cost of Technology Option, C_M is the manufacturer cost of technologies (derived from AEA, 2009) and $RPE \text{ factor}$ is the retail price equivalent multiplier (derived from Vyas, et al., 2000; NRC, 2010).

Specific Driving Costs: the cost of driving per kilometer of vehicle. This cost in the analysis was interpreted as an aggregate construct of vehicle investment costs linked to 8% annual O&M costs, fixed annual driving distance and the vehicle lifetime of 10 years.

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

Where, SC_d is the specific driving cost, I_a is the annual investment cost, $O\&M$ is the operation and maintenance cost and D_{annual} is the annual distance travelled by the car.

Average payback Period: It is the time period in which the incremental costs can be compensated by the monetary savings that occur as a result of decreased fuel demand by technical improvement.

$$PB_{avg} = \frac{C_i}{YS_{\text{€a}}} \quad [\text{Years}] \quad \text{Eq. 5}$$

Where, PB_{avg} is the average payback period, C_i is the incremental cost and $YS_{\text{€a}}$ is the annual monetary saving (€a) per year through reduced fuel expenditure.

Cost of CO₂ avoidance or CO₂ abatement costs: It is assumed that for a technically improved vehicle the driver has to bear extra investment costs over the vehicle price. So, how much does it cost (in €) to the driver for saving each tonne of CO₂ is called the cost of CO₂ avoidance. It is calculated by the following formula.

$$CO_2 \text{ abatement cost} = \frac{C_i}{\text{Tonne } CO_2 \text{ saved}} \quad [\text{€tonnne}] \quad \text{Eq. 6}$$

Where, C_i is the incremental cost and Tonne $CO_{2\text{saved}}$ is the CO₂ saved within vehicle life time.

2.3. Sources, Data and Assumptions:

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

This report was chosen for fleet characteristics and energy demand projections as it delivers the quantified data in Europe until 2030 and more importantly the assessment carried in the study does not consider any technical improvements of the cars after 2008. Table 2 states the data and values extracted from Fiorello, et al., (2009).

Table 2 : Baseline values and assumptions (EU-27 passenger car fleet)

	Unit	2005	2010	2020	2030
Total no.of cars-EU-27	1,000 vehicles	211,062	228,120	265,628	294,220
Total Energy Demand	PJ	8,435	9,251	9,630	10,301
CO ₂ emissions*	Million tonnes/year	624	684	712	761
Emissions	MillionTonnes/year	793	760	833	840
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), *Calculated by Authors

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

Average characteristics and data for the European passenger cars like vehicle price, engine power, fuel economy, fuel specific emission factor of the fuel etc. were derived from the Concawe reports mentioned above. Table 3 states the data derived for gasoline and diesel cars.

Table 3: Data and values derived from Concawe reports

	Unit	Gasoline	Diesel
Vehicle Price	€	19,000	20,000
Capacity Fuel/Engine Power	kW	77	74
Av. Travelling distance*	Km/yr	18,000	20,000
GHG emission	gm CO ₂ eq.per km	165	140
Specific driving costs*	€100 km	24.18	22.90

Source: (Concawe, 2008); *Authors' assumption/calculations

2.4. Efficiency Improvement Technologies

There are many efficiency improvement technologies that can be introduced in today's vehicles without changing the vehicle's basic type, general size, or performance. Virtually all of the technologies are capable of increasing vehicle efficiency and reducing fuel demand, but they all are not equally ready for the commercial production. The technologies grouped as Technology option 1 and 2 in Table 4 were chosen based on their readiness as they are applicable into the conventional diesel and gasoline passenger cars within 2010-2012 timeframe.

Table 4: Technology Options considered for the study

	Technology Option 1	Technology Option 2
Technology Combination	<ol style="list-style-type: none"> 1. Reduced engine friction losses 2. Improved aerodynamics 3. Low rolling resistance tyres 	<ol style="list-style-type: none"> 1. Improved aerodynamics 2. Vehicle Weight reduction 3. Optimized transmission 4. Mild downsizing with Turbo Charging 5. Start-stop-system 6. Use of advanced devices (tyre pressure monitoring system, gear shift indicator etc.)
Expected efficiency increase	Around 5%	Around 22%
Source - eff. Increase	(EPA, 2008)	(McKinsey, 2009)
Tech. cost assumption*	10% over car baseline price	30% over car baseline price
Status in Europe	Integrated into new cars by most manufacturers	High consideration for application

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

2.5. Technology Diffusion Assumption

The term technology diffusion in this study refers to the widespread integration of Technology Options into the new European gasoline and diesel cars up to 2030. 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 size or performance of the car. Moreover, gasoline and diesel cars represent the biggest share in the total EU-27 car fleet and this trend of majority will continue to increase at least until 2030.

To build the stock of new cars in EU-27 until 2030, a review of historical vehicle registration data and socio-economic developments was done. Then the review was complemented with the expected GDP growth to establish the expected trend of new car registrations in EU-27.

The two scenarios considered for this study are:

Scenario 1: Technical Potential - Assessment of the maximum energy demand and CO₂ emission reduction potential offered by the technologies under the assumption that Technology Option 2 diffuses extensively across the fleet.

Scenario 2: Autonomous Potential - Assessment of the reduction potential from the technologies under the assumption that the Technology Option 2 diffuses to a limited extent within the new fleet, however followed by autonomous technological progress the Technology Option 1 diffuses widely across the fleet.

Table 5: Technology Diffusion Assumption

		2010	2015	2020	2025	2030
Scenario 1 (Tech.Pot)	Diffusion of Tech. Op 2 into new cars	10%	30%	50%	75%	100%
	Diffusion of Tech. Op 2 into old cars	10%	20%	25%	30%	25%
Scenario 2 (Auto.Pot)	Diffusion of Tech. Op 2 into new cars	10%	15%	20%	30%	35%
	Diffusion of Tech. Op 2 into old cars	10%	15%	18%	20%	20%

3. Results

The results presented in Table 6 are derived by considering the integration of Technology Options into the vehicle. The assessment methods for the techno-environmental and economic assessment take into account all the salient aspects like baseline vehicle price, additional investment costs Technology Options, engine size and fuel capacity, yearly driving distance, diesel and gasoline fuel price projections until 2030 from (Fiorello, et al., 2009).

Table 6: Results of techno-environmental and economic 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
Sp. 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 emissions	Tonnes CO 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	7.4	-	5.3	8.4

Source: Assessed by authors, * considering 2010 fuel price from (Fiorello, et al., 2009)

The energy demand and emission potential results presented in Table 7 show as what could be achieved when technologies are implemented into the assumed percentage of the EU-27 new gasoline and diesel cars. The scenarios developed within this study show that 19% to 34% reduction in total energy demand and subsequent CO₂ emission can be achieved by 2030.

Table 7: Results of total energy demand and emission saving potential

Results	2010	2015	2020	2025	2030
Baseline – Energy Demand (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%
Baseline - CO ₂ emission (Mil.tonne)	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: Own calculations

It is important to note that diffusion assumptions explained here are based on authors' views supported by technology readiness and expected technical developments. In reality there may be several interactions and measures (like EU policies, market behavior, cost of technologies, consumers' preference etc.) that will affect the relative effectiveness of technologies and their deployment within industry (Skinner, Essen, Smokers, & Hill, 2010). To summarize the results, Figure 1 shows the overall potentials in energy demand and CO₂ emission savings assessed within this study. The figure is converted in % savings for the ease of understanding and combining the energy demand and emission changes until 2030.

Figure 1: Total energy and CO₂ emission saving potentials

Source: Own calculations and elaboration

4. Discussion and Conclusions

The results and analysis detailed in this paper show the potentials of energy demand and CO₂ emission reduction; however, there are certain limitations in the analysis. The technologies considered in the study are based on the theoretical values and potentials for vehicle efficiency increase, but the results may vary significantly during vehicle segment applications (e.g. small, medium or large cars) and under different on-road driving conditions. Secondly, the technologies included in this study are not the only options that European car manufacturers are considering. There are many other technologies and measures that have varied degree of technology readiness and implementation within cars for the purpose of efficiency increase.

An important aspect regarding the aforementioned results is the compliance of the emission values with the EU regulations on average gCO₂/km emission. The European Commission has established the emission limiting targets 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 EC targets then this does not imply that all the cars drive at the same mileage and emit same amount of CO₂. All car models across the Europe possess varying mileage range, therefore different vehicle models, car segments and the fuel used in them contribute differently to the average on-road CO₂ emission.

Technical improvement technologies can result in substantial improvements in new car fuel economy and subsequent GHG emission. While virtually all of the technologies are capable of enhancing vehicle efficiency, they are not equally ready for production and integration into the vehicle. Technologies included in Technology Option 1 have been widely introduced into the market until now. And, the technologies included in Technology Option 2 possess high

degree of technology readiness and high consideration by the manufacturers for integration within the current production lines.

Results stated in this study (in Table 6) have shown the increasing pattern of fuel economy in gasoline and diesel cars. Technology Options 1 & 2 have the potential to enhance vehicle efficiency by 5% and 22% respectively, which can save between 0.14 and 0.64 tonneCO₂/year per car for a fixed driving cycle. Results of economic assessment show the decreasing pattern of fuel expenditure in terms of €/100km or €/Year. The assessment shows that both the Technology Options may increase vehicle cost by 10% and 30%, but as a result of increased fuel economy and reduced fuel expenditure, the additional investment can be reimbursed within the certain time period considered 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 because the cumulative fuel expenditure savings offset the higher incremental costs. The results of technology diffusion based on bottom-up simulation show that there is a potential of between 19% and 34% reduction in the energy demand and CO₂ emission in the EU-27 up to 2030.

References

- [1] Toro, F. A., Jain, S., Reitze, F., Ajanovic, A., Hass, R., Furlan, S., et al. (2010). State of the art for alternative fuels and alternative automotive technologies. Karlsruhe, Germany: Project ALTERMOTIVE: Deriving effective least cost policy strategies for alternative automotive concepts and alternative fuels.
- [2] Fiorello, D., De Stasio, C., Koehler, J., Kraft, M., Newton, S., Purwanto, J., et al. (2009). *The iTREN-2030 reference scenario until 2030: Deliverable 4 of iTREN-2030*. Milan, Italy: Project co-funded by European Commission 6th RTD Programme.
- [3] McKinsey. (2009). Der Trend zu energie - effizienten Pkw, Implikationen für die deutsche Automobilindustrie. McKinsey&Company.
- [4] Concawe. (2008). *Wheel to Wheel Analysis of Future Automotive Fuels and Powertrains in the European Context*.
- [5] EPA. (2008). *EPA Staff Technical Report: Cost and Effectiveness Estimates of Technologies Used to Reduce Light-duty Vehicle Carbon Dioxide Emissions*. United States Environmental Protection Agency. US-EPA.
- [6] AEA. (2009). *Assessment with respect to long term CO₂ emission targets for passenger cars and vans*. AEA - Deliverable D2: Final Report.
- [7] TNO. (2006). *Review and analysis of the reduction potential and costs of technological and other measures to reduce CO₂-emissions from passenger cars*. Delft: TNO Science and Industry.
- [8] Skinner, I., Essen, H. v., Smokers, R., & Hill, N. (2010). *Towards the decarbonisation of the EU's transport sector by 2050*. London, UK: AEA.
- [9] TNO. (2006). *Review and analysis of the reduction potential and costs of technological and other measures to reduce CO₂-emissions from passenger cars*. Delft: TNO Science and Industry.
- [10] Skinner, I., Essen, H. v., Smokers, R., & Hill, N. (2010). *Towards the decarbonisation of the EU's transport sector by 2050*. London, UK: AEA.