Young Researchers Seminar 2015

Research domain: Transport sustainability and environment

Assessment of efficiency-improving technologies for passenger vehicles in the international context

Jens Brokate*, Michael Kofler, Horst E. Friedrich

Institute of Vehicle Concepts, German Aerospace Center (DLR), Stuttgart, Germany

**Corresponding author: jens.brokate@dlr.de*

Abstract

Worldwide CO_2 emission regulations impose a pressure to develop innovative fuel efficient powertrains for passenger cars. The production of passenger cars is expected to grow, whereas growth prospects for electrified powertrains remain uncertain. Meanwhile manufacturers seek to maximize the utilization of their production capacities for electric and conventional efficiency-improving technologies. Thus, a competition for production capacities between fuel-saving technologies arises. Technology assessment has a major influence on the stakeholders´ decision making process on which technology to produce and where to deploy it. The commonly used greenhouse gas abatement cost curve (ACC) provides a methodology to evaluate the cost-benefit potential of new technologies. It allows a ranking of all efficiency-improving technologies according to their cost abatement ratio. However, this approach neglects various other requirements in the decision making. These requirements can be numerous and vary across markets. This article aims at improving the ACC methodology in the context of the deployment of fuel-saving technologies on international markets. A multi-attribute decision-making (MADM) model is constructed that combines the abatement cost potential with the consideration of market-specific criteria. As a preceding result, fuel-saving technologies are derived from a meta-analysis. Applied in the MADM model, the results show that market-specific criteria can be reflected in the assessment of a technology portfolio.

Keywords: CO2 emission reduction, technology assessment, efficiency-improving technologies

1 Introduction

CO_2 emission regulations worldwide impose a pressure to develop electrified powertrain technologies on the whole automotive industry [Liebl et.al. 20014]. Alongside public funding, the development process demands a significant investment by the industry itself. In recent years, the number of electrified powertrain options available to consumers has increased significantly [Klötzke et.al. 2015]. However, the sales of these vehicles remain at a relatively low level [IEA-HEV 2014]. Growth prospects are currently uncertain, which associates a risk with the development and production of electrified vehicles. At the same time, the global production of passenger vehicles is expected to grow by 50% from 2010 to 2020 [Frost&Sullivan 2012]. This leads to a situation in which established manufacturers seek to maximize the utilization of their production capacities for electrified and conventional efficiency-improving technologies. Thus, a competition for production capacities between efficiency-improving technologies arises [Gassmann and Kobe 2006].

The selection of technologies to be used in products is based on a decision-making process that usually considers a number of indicators [Ardillo and Laib 2008]. Technology assessment can deliver such indicators. Commonly used methods to assess technologies on qualitative or quantitative terms are the Delphi method, the cost-benefit-analysis and the cost-utility analysis [VDI 2000]. Another commonly used method is the abatement cost curve (ACC), which enables a comparison of technologies by their ability to reduce CO_2 emission in relation to their cost [McKinsey 2015]. This approach has been used extensively in order to evaluate the impact of efficiency-improving technologies on the tank-to-wheel emission of passenger cars [Hill et.al. 2012; ICCT 2013; IKA 2012; IKA 2014]. Yet, only little is known about the relationship between technological change and the associated consumer behavior [Tran et.al. 2014]. Each efficiency-improving technology underlies market-specific uncertainties that need to be analyzed in the appropriate context. In order to improve a fact-based decision for the global use of various technology alternatives, a technology’s cost-abatement relation needs to be combined with the risk involved to its introduction in a specific market. This article aims at improving the ACC methodology in the context of the deployment of efficiency-improving technologies on international markets.

Multiple-attribute decision-making (MADM) models provide the opportunity to combine the abatement cost curve approach with the consideration of market specific criteria. Originally, they have been developed to overcome drawbacks of conventional optimization models that are usually based on only one economical measure [Oberschmidt 2010]. Such a model and its input data are described in the following chapter (chapter 2). Afterwards, the results of exemplary model calculations for three technologies (discrete variable valve lift, turbocharging in combination with a downsizing by 30% and mild-hybrid in a medium sized gasoline car) in three markets (China, Germany and USA) are shown (chapter 3). Conclusions and the discussion of future work are presented in chapter 4.

2 Methodology

In a first step, a meta-analysis of the efficiency-improvement and cost potential of future passenger car technologies is used to derive an abatement cost curve. The analysis is based on published literature and differentiated in vehicle segments and powertrains. In a second step, a MADM model is constructed that combines the abatement cost potential with the consideration of market-specific criteria into a score. The score is then used to produce a market-specific ranking of the considered fuel-saving technologies.

2.1 Meta-analysis

The meta-analysis of the cost-efficiency of advanced fuel-saving technologies for passenger cars is clustered in the areas of improvements of conventional engines, improvements of the transmission, the (partial) electrification of conventional powertrains, the reduction of the consumption of auxiliaries and the reduction of the driving resistances. The analysis is focused on gasoline (spark ignition) and diesel (compressed ignition) powertrains, as they are the most commonly produced. Three segments (small, medium, large) are considered to allow for a differentiation of different vehicle sizes. For each of the considered technologies, median cost and efficiency-improvement values are derived from the gathered information (see Figure 1). The cost values refer to the additional production cost when only this technology is applied to a vehicle.

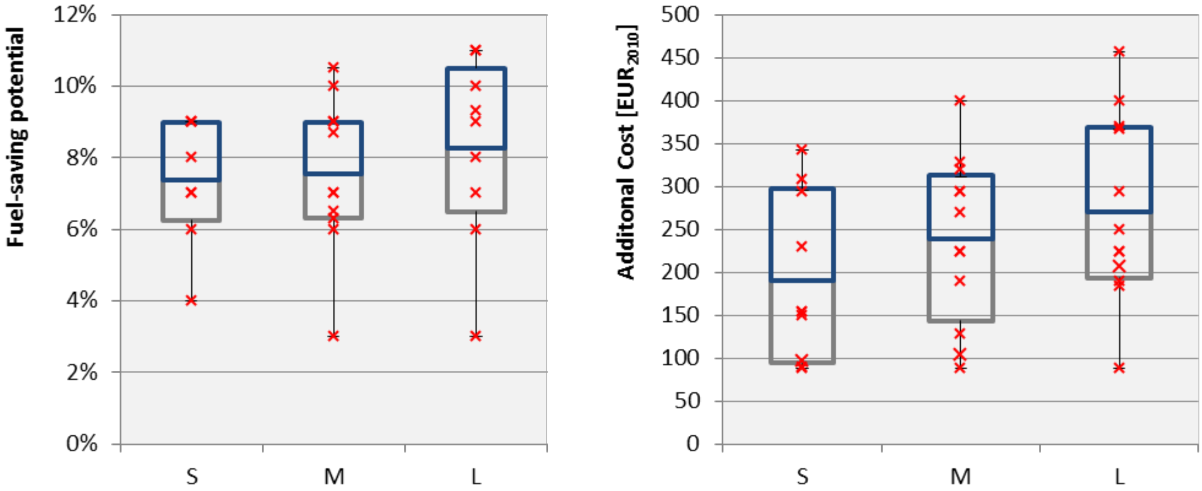

Figure 1: Boxplot illustrations of fuel-saving potential and cost of discrete variable valve lift for gasoline engines in small (S), medium (M) and large (L) passenger cars. The bottom and top of the box indicate the first and third quartiles. The band inside the box indicates the median. The whiskers indicate the outliers outside the quartiles (own illustration, data source: [EEA 2006, EPA 2008, EPA 2008a, EPA 2012, EPA 2012a, FEV 2012, Hill et.al. 2012, ICCT 2012, IKA 2012, TNO 2006, TNO 2011]

2.2 Multi-attribute decision-making model

The decision of which efficiency-improving technology to introduce on a certain market is based on various factors. They can be aggregated to three dimensions (see Figure 2): the legal requirements for the manufacturer of a technology, the technological potential and the consumers' needs [Kieckhäfer 2013].

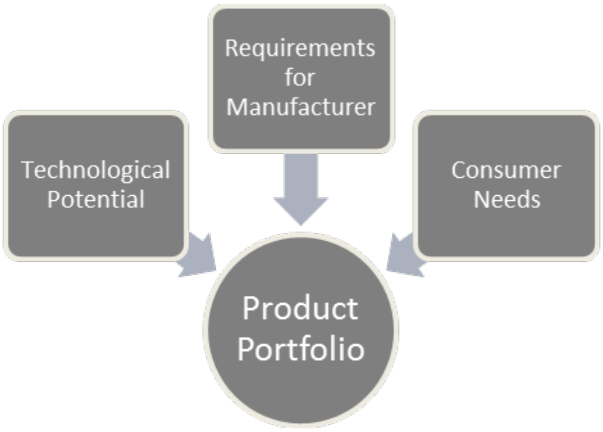

Figure 2: Factors influencing a manufacturer's product portfolio of fuel-saving technologies (own illustration based on Kieckhäfer 2013).

The multi-attribute decision-making model is realized as a three-dimensional score that is calculated for each fuel-saving technology incorporating the aforementioned dimensions. Equation 1 illustrates the calculation of the market-specific score. Hence, the score of each individual dimension can be interpreted as a coordinate in a three-dimensional Cartesian coordinate system. The calculation of each dimension is explained in the following subsections.

$$S_{i,j} = \sqrt{(Man_{i,j})^2 + (Tec_j)^2 + (Con_{i,j})^2} \qquad (1)$$

where

i	Market
j	Efficiency improving technology
$S_{i,j}$	Score for technology *j* in market *i*
$Man_{i,j}$	Requirements for manufactures for *j* in *i*
Tec_j	Technological potential of *j*
$Con_{i,j}$	Consumer needs in *i* for *j*

Requirements for Manufacturers

The cost-benefit relation, as depicted in the abatement cost curve, still plays a central role in the presented score. It is assumed that technologies with the least cost abatement ratio (cost per percentage of efficiency improvement) contribute most to a manufacturer's compliance with CO_2 regulation. Additionally, the difference in the severity of CO_2 regulations on different markets is included in the score. The more strict emission regulation is, the less effective are technologies with low emission reduction potential. Therefore, the on average required annual emission reduction and the absolute level of the fleet emission target are taken into account.

$$Man_{i,j} = \alpha_1 \frac{C_j}{R_j} + \alpha_2 \left(\frac{R_j}{1 + \frac{Imp_i}{Limit_i}} \right) \qquad (2)$$

where

C_j Production cost for technology j [EUR_{2010}]

R_j Consumption reduction of j [%]

Imp_i Required average annual consumption reduction in market *i* [%]

$Limit_i$ Absolute level of CO_2 target in *i*

$\alpha_{1,2}$ Weighting factor, [0…1]

Technological Potential

In the context of the development of future automotive fuel-saving technologies, a singular evaluation of consumption reduction falls too short. A technology's potential also depends on the maturity of development and the ability to produce the technology. The Technology Readiness Level (TRL), developed by NASA, is used to assess technological maturity [Mankins 1995]. However, it concentrates on the early stages in the development process. Technologies assigned with highest TRL must have been qualified in "mission operation" [Mankins 1995]. Yet, the TRL does not include information on the complexity and the effort to produce a technology on large scales. The presented score combines the TRL with a factor resembling the production capability. It is assumed that manufacturers seek to maximize the utilization of their current production capacities. Technologies that can be effortlessly integrated in the existing manufacturing process are rated higher than those creating a large effort or even affording completely new techniques, processes or capacities. Different measures for production capability have been developed [Steiner et.al. 1997]. These afford process-specific indicators that vary across manufacturers, making them futile in the presented application. For the purpose of this article, the production capability is assessed by expert rating.

$$Tec_j = \beta_1 \, TRL_j + \beta_2 \, PC_j \qquad (3)$$

where

TRL_j Technology Readiness Level for j, [0…1]

PC_j Production capability for j, [0…1]

$\beta_{1,2}$ Weighting factor, [0…1]

Consumer Needs

The cost of automotive technologies (investment and operation) is one of the most important criteria influencing a consumer's purchasing decision [Peters and de Haan 2006; Herberg 2008]. However, the importance of the cost criterion differs across markets [Frühauf 2011]. The presented score includes the market-specific purchasing power in order to resemble this difference. It is assumed that less capital intensive technologies become more attractive with decreasing purchasing power. For the purpose of this article, the purchasing power is approximated with the gross national income (GNI) per capita based on purchasing power parity. Furthermore, it is assumed that the demand in passenger cars is elastic. That means that the demand in cars decreases disproportionately when prices increase.

Additionally, the influence of the engine displacement on taxation is considered in the score. Vehicle taxation is based on engine displacement in a multitude of countries [ACEA 2012]. The introduction of technologies reducing engine displacement can therefore affect the demand in these markets.

Besides the monetary purchasing criteria, environmental awareness constitutes another important factor in the context of fuel-saving technologies. It varies across markets, analogue to the cost criteria [Frühauf 2011]. For the transport sector, environmental awareness can be estimated by a market's modal split [Bodenstein et.al. 1997]. It is described by the relation of the amount of trips travelled by public transport, foot and bicycle to the trips travelled by car. The ratio is then multiplied with consumption reduction potential. Consequently, technologies with a high consumption reduction potential are valued more in markets with a larger environmental awareness.

$$Con_{i,j} = \gamma_1 \left(1 + \left(\frac{C_j}{I_i} * E\right)^{2-\frac{GNI_i}{GNI_{max}}}\right) + \gamma_2\, ED_{i,j} + \gamma_3 * EA_i * R_j \qquad (4)$$

where

I_i	Average vehicle purchase price in market *i*
E	Price elasticity for passenger cars ($E < 0$)
GNI_i	Gross National Income of market *i*
GNI_{max}	Maximum GNI_i
$ED_{i,j}$	Influence of engine displacement of j on taxation in *i*, [0…4]
EA_i	Environmental awareness factor in *i*
$\gamma_{1,2,3}$	Weighting factor

2.3 Data

The production cost (C_j) and fuel reduction potential (R_j) of each technology is shown in chapter 3 (see Table 1). The average of the required emission reduction (Imp_i) for the years 2015 to 2020 is 6.2% p.a. in China, 6.1% p.a. in the member states of the European Union (EU) and 6.0% p.a. in the USA [EU 2009;

EPA 2010; Yang 2014]. The baseline year for the consideration of the absolute level of CO_2 targets ($Limit_i$) is 2020. The average fleet target is 117 g_{CO2}/km in China, 95 g_{CO2}/km in the EU and 121 g_{CO2}/km in the USA [EU 2009, EPA 2010, Yang 2014]. Due to the importance of the cost abatement ratio given in prior studies [Hill et.al. 2012; ICCT 2013; IKA 2012; IKA 2014; McKinsey 2015], the weight of this criterion is chosen greater (α_1=0.6) than the weight of the level of CO_2 regulation (α_2=0.4).

The Technology Readiness Level (TRL_j) of all three technologies in the exemplary calculation is on the highest level, as the chosen technologies are already applied to vehicles in series production. For the purpose of this article, an expert rating for the production capability (PC_j) was conducted. On a scale from 0 to 1, discrete variable valve lift is rated 1, meaning that the new technology can be integrated in current production without any additional effort. Turbocharging and downsizing by 30% is rated with 0.9 and mild-hybrid with 0.6. Downsized engines are assumed to cause only a minor change in the production process, such as adaptions in the pre-assembly. The production of vehicles equipped with mild-hybrid powertrains implies a major change to the production of conventional powertrains. New processes (i.e. for high voltage systems) are needed, different tools are necessary and there is an additional effort in the training of the workforce. The aforementioned factors are weighted equally ($\beta_{1,2}$=0.5).

The GNI values are applied as ratio to that of the USA $\left(\frac{GNI_{USA}}{GNI_{max}} = 1\right)$. The GNI ratio of China amounts to 0.22, that of Germany to 0.84 [World Bank 2015]. The price elasticity is based on a literature average [Diez 2011; EFTEC 2008; Goodwin et.al. 2009; Simon and Fassnacht 2009] (E=-2.5). All three factors for the consumer needs are weighted equally ($\gamma_{1,2,3}$=⅓). The influence factors of engine displacement on vehicle taxation are based on the actual tax calculation [ACEA 2012] and the average engine displacement. There is no taxation based on engine displacement in the USA ($ED_{USA,j}$=0). The average engine displacement for medium sized passenger cars is 1,600 cm³ in Germany and 1,800 cm³ in China [IHS 2014]. For Germany, the influence factor of technologies reducing the engine displacement is 1 ($ED_{Germany,j}$=1), that of China is 2 ($ED_{China,j}$=2). As mentioned above, the environmental awareness is taken into account by a factor (EA_i) based on a country's modal split [Bodenstein et.al. 1997]. It is 2.49 in Germany, 1.07 in China and 2.13 in the USA, which means that Germany is the most conscious market with regard to the environment. For the purpose of this article, the average medium sized vehicle gross price (without taxes, incentives, etc.) is assumed to be equal in China, Germany and the USA. This neglects the manufacturers pricing policies on different markets. Yet, the simplification is made to avoid an asymmetric relation to the costs of the fuel-saving technologies, as they are not differentiated.

3 Results

Table 1 shows the results of the meta-analysis on efficiency improving technologies for gasoline and diesel powertrains.

Table 1: Results of meta-analysis of efficiency-improvement potential and cost of gasoline and diesel technologies.

			Small		Medium		Large	
	Technology	**N =**	**Efficiency Gain**	**Additional Cost [EUR$_{2010}$]**	**Efficiency Gain**	**Additional Cost [EUR$_{2010}$]**	**Efficiency Gain**	**Additional Cost [EUR$_{2010}$]**
	Gasoline							
Engine	Engine Friction Reduction	9	3.0%	50	3.0%	70	3.0%	70
	VVT - Dual Cam Phasing (DCP)	12	3.5%	75	4.0%	125	4.0%	150
	Cooled Exhaust Gas Recirculation (EGR)	3	4.0%	150	4.0%	175	4.0%	175
	Thermal Energy Recovery (Rankine Cycle)	5	2.0%	300	2.0%	300	2.0%	300
	Turbocharging and Downsizing 15%	9	5.5%	300	6.0%	250	6.0%	200
	Turbocharging and Downsizing 30%	9	8.0%	350	9.0%	400	10.0%	500
	Turbocharging and Downsizing 45%	9	14.0%	500	15.0%	550	16.0%	600
	Cylinder Deactivation	12	6.0%	100	6.0%	150	6.0%	200
	Variable Compression	5	6.0%	500	6.0%	550	6.0%	600
	Discrete Variable Valve Lift (DVVL)	15	7.0%	200	8.0%	250	8.0%	275
Transmission	Downspeeding	9	2.5%	40	2.5%	45	2.5%	50
	7/8/9-Speed Auto Transmission	9	3.0%	300	3.0%	300	3.0%	300
	Dual Clutch Transmission	14	6.0%	400	7.0%	450	7.0%	500
	Continuously Variable Transmission (CVT)	9	5.0%	500	5.5%	500	5.5%	500
Electrification	Micro Hybrid (Start-Stop)	12	6.0%	350	6.0%	400	6.0%	450
	Mild Hybrid	10	12.0%	1400	12.0%	1550	12.0%	1700
Auxiliaries	Electric Power Steering	10	1.5%	100	1.5%	100	1.5%	100
	Thermal Management	3	2.5%	150	2.5%	150	2.5%	150
	Electrified Auxiliaries	15	3.0%	200	3.0%	250	3.0%	300
Driving resistances	Low Rolling Resistance Tires	10	2.0%	25	2.0%	30	2.0%	35
	Aero Drag Reduction	8	2.0%	50	2.0%	50	2.0%	50
	Diesel							
Engine	Engine Friction Reduction	9	3.0%	50	3.0%	70	3.0%	70
	Combustion Control	3	1.0%	100	1.0%	120	1.0%	150
	Cooled Exhaust Gas Recirculation (EGR)	3	2.5%	150	2.5%	175	2.5%	175
	Thermal Energy Recovery (Rankine Cycle)	5	2.0%	300	2.0%	300	2.0%	300
	Turbocharging and Downsizing 30%	4	5.0%	350	6.0%	400	6.5%	500
	Turbocharging and Downsizing 45%	4	10.0%	500	11.0%	575	12%	675
	Cylinder Deactivation	13	3.0%	150	3.0%	200	3.0%	250
	Variable Compression	5	4.0%	500	4.0%	500	4.0%	600
	Discrete Variable Valve Lift (DVVL)	14	4.0%	250	4.0%	300	4.0%	300
Transmission	Downspeeding	4	2.5%	40	2.5%	45	2.5%	50
	7/8/9-Speed Auto Transmission	4	3.0%	300	3.0%	300	3.0%	300
	Dual Clutch Transmission	4	6.0%	400	7.0%	450	7.0%	500
	Continuously Variable Transmission (CVT)	2	5.0%	500	5.5%	500	5.5%	500
Electrification	Micro Hybrid (Start-Stop)	4	6.0%	400	6.0%	450	6.0%	500
	Mild Hybrid	3	11.0%	1450	11.0%	1600	11.0%	1750
Auxiliaries	Electric Power Steering	9	1.5%	100	1.5%	100	1.5%	100
	Thermal Management	3	2.5%	150	2.5%	150	2.5%	150
	Electrified Auxiliaries	3	3.0%	200	3.0%	250	3.0%	300
Driving resistances	Low Rolling Resistance Tires	5	2.0%	25	2.0%	30	2.0%	35
	Aero Drag Reduction	3	2.0%	50	2.0%	50	2.0%	50

The constructed abatement cost curve ranks the technologies by their cost-benefit ratio (see Figure 3). In the example of discrete variable valve lift (DVVL), turbocharging and downsizing by 30% and mild hybrid, the cost-benefit ranking differs for gasoline and diesel powertrains. DVVL (*a* in Figure 3) is ranked first of the three examined technologies for gasoline powertrains, whereas it is only ranked second for diesel powertrains. The ranking of downsizing (*b* in Figure 3) corresponds vice versa. Mild hybrid (*c* in Figure 3) is ranked last for both powertrains.

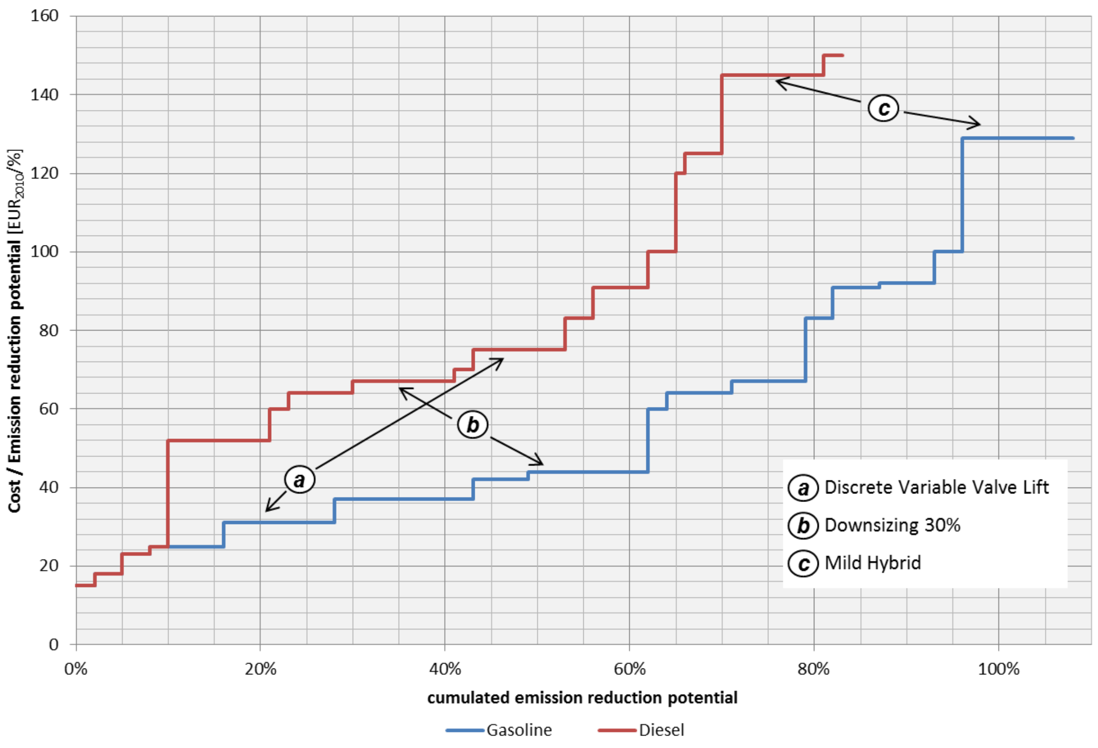

Figure 3: Abatement cost curves for efficiency improving technologies of a medium sized gasoline and diesel vehicle. The figure illustrates the ranking of technologies and the comparison of cost curves. Technologies cannot be aggregated as depicted.

The scoring shows that the ranks change only slightly when compared to their cost abatement ratio. In China, the purchasing power and the influence of engine displacement on taxation causes a change in the ranking.

Table 2: Scoring results for discrete variable valve lift (DVVL), turbocharging and downsizing by 30% and mild hybrid for a medium sized gasoline vehicle. Ranking by the abatement cost curve (ACC) is shown in comparison.

		DVVL	Downsizing	Mild Hybrid
ACC	Cost-Benefit [EUR/%]	31	44	129
	Rank	1	2	3
China	Score	1.24	1.26	1.01
	Rank	2	1	3
Germany	Score	1.24	1.22	1.02
	Rank	1	2	3
USA	Score	1.24	1.18	1.02
	Rank	1	2	3

The influence of the engine displacement is not as significant in Germany and non-existent in the USA. Additionally, the purchasing power in both countries is substantially higher than in China. Hence, the score is less affected by these factors. The fulfilment of environmental awareness, as realized in the model, does not show significant impact on the score. This also applies to a technology's contribution to achieve CO_2 emission limits and the Technology Readiness Level. Furthermore, the rank of the cost benefit ratio and the production capability show the same tendency for the examined technologies.

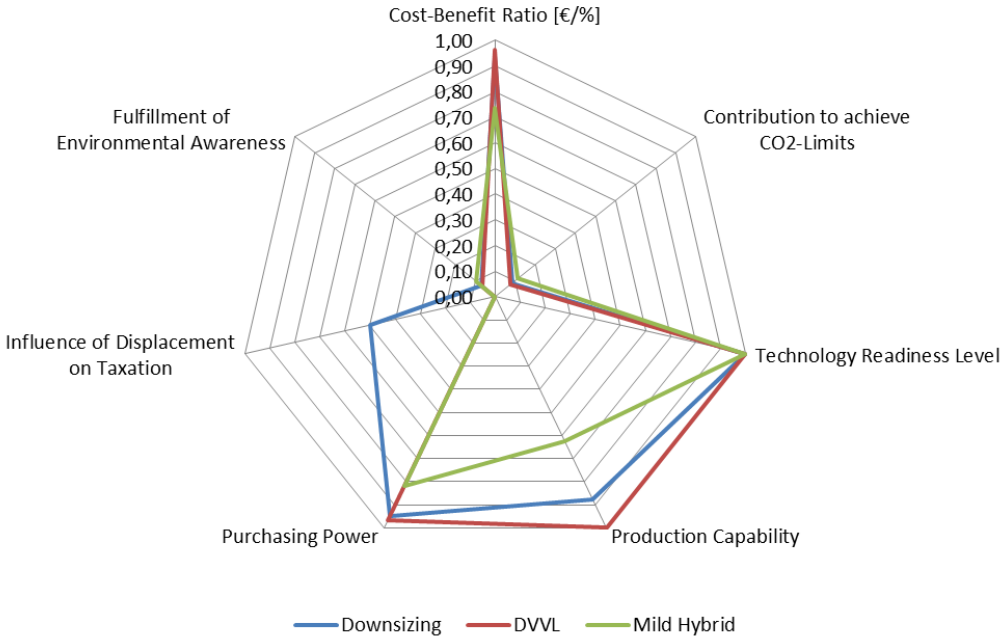

Figure 4: Illustration of scoring results for discrete variable valve lift, turbocharging and downsizing by 30% and mild hybrid for the Chinese market.

The ranking suggests the deployment strategy of the three examined technologies should differ for China from that for Germany and the USA. In accordance to the exemplary results, a vehicle with downsizing by 30% should enter the market before a vehicle equipped with DVVL. In Germany and the USA a vehicle with DVVL enters the market before that equipped with a downsized engine. The results also suggest that the two conventional efficiency-improving technologies are more likely to be applied earlier in new vehicles than the mild hybrid system. However, the absolute level of CO_2 regulation may require additional efficiency improvement in the vehicle's powertrain (i.e. mild-hybrid).

4 Conclusion and outlook

The results show the possibility to rank fuel-saving technologies based on MADM modelling. The approach can be used to select efficiency-improving technologies based on market specific criteria. The created ranking supports decision makers in the evaluation of specific demands for fuel-saving technologies. When calculated for an entire product portfolio, the ranking may support a market-specific strategic product planning. The product portfolio can be applied to vehicle market data in order to derive market-specific reference vehicles. These can be used in vehicle market models to increase the accuracy of predictions on the fulfilment of CO_2 emission regulation of a market's vehicle fleet.

The selection of the evaluated criteria is a central challenge in MADM modelling. From the chosen criteria in the assessment of the three presented technologies, the Technology Readiness Level and the production capability show a large improvement potential. Besides identifying the proper decision criteria, the challenge lies within the operationalization of the criteria in the model. Thus, future work could identify other criteria. Concurrently, it should focus on the implementation of these criteria in the presented model framework. Examples could be the usage of a technology attractiveness factor instead of the Technology Readiness Level or an improved operationalization of the environmental awareness. Moreover, a differentiation of market data could show an improvement of the model results (i.e. price elasticity, average vehicle cost and production cost of the fuel-saving technologies).

References

ACEA (2012). ACEA Tax Guide. European Automobile Manufacturers Association, Brussels.

Ardillo, A. and Laib, S. (2008). Technologiepotentialanalyse. In: Bullinger, H.-J. (ed.). Fokus Technologie: Chancen erkennen – Leistungen entwickeln. Hanser, München

Bodenstein, G., A. Spiller and H. Elbers, 1997: Strategische Konsumentscheidungen: Langfristige Weichenstellungen für das Umwelthandeln – Ergebnisse einer empirischen Studie. Diskussionsbeiträge des Fachbereichs Wirtschaftswissenschaft der Gerhard-Mercator-Universität, Gesamthochschule Duisburg, Nr. 234.

Diez, W. (2011). Preispolitik in der Automobilwirtschaft. Vorlesung Wintersemester 2011/2012. Institut für Automobilwirtschaft.

EEA (2006). Technologies to Reduce Greenhouse Gas Emissions from Light Duty Vehicles; Report to Transport Canada. Energy and Environmental Analysis, Inc., Ottawa.

EFTEC (2008). Demand for Cars and their Attributes. Final Report. Economics for the Environment Consultancy, London.

EPA (2008). A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies; Revised Final Report. U.S. Environmental Protection Agency

EPA (2008a). Cost and Effectiveness Estimates of Technologies Used to Reduce Light-duty Vehicle Carbon Dioxide Emissions; EPA Staff Technical Report. U.S. Environmental Protection Agency.

EPA (2010). Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule. U.S. Environmental Protection Agency

EPA (2012). Proposed Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Draft Joint Technical Support Document. U.S. Environmental Protection Agency.

EU (2009). Verordnung (EG) Nr. 443/2009 des Europäischen Parlaments und des Rates zur Festsetzung von Emissionsnormen für neue Personenkraftwagen im Rahmen des Gesamtkonzepts der Gemeinschaft zur Verringerung der CO2-Emissionen von Personenkraftwagen und leichten Nutzfahrzeugen.

FEV (2012). Light Duty Vehicle Technology Cost Analysis – European Vehicle Market; Analysis Report. FEV, Inc.

Frost & Sullivan (2012). 2020 Vision of the global automotive industry. Megatrends, platform standardization, new-mobility model to change the global automotive industry.

Frühauf, K. (2011). Wie sich chinesische Autokäufer entscheiden. Eine vergleichende Studie zum Kaufverhalten in China und Deutschland. Progrenium, Wolfsburg.

Gassmann, O. and Kobe, C. (2006).

Management von Innovation und Risiko. Quantensprünge in der Entwicklung erfolgreich managen. Springer, Heidelberg.

Goodwin, N.; Ackermann, F., Weisskopf, T. and Nelson, J. (2008). Microeconomics in Context. Second Edition. Sharpe, New York.

Herberg, D. (2008). Ein Modell der Diffusion der Technologien zur Senkung des Treibstoffverbrauchs bei Pkw-Ottomotoren in Deutschland. Dissertation, Technische Universität Berlin.

Hill, N., Varma, A., Harries, J., Norris, J., Kay, D. (2012). A review of the efficiency and cost assumptions for road transport vehicles to 2050. AEA technologies plc.

ICCT (2012). Summary of the EU cost curve development methodology. Working Paper 2012-5. The International Council on Clean Transportation.

ICCT (2013). Reducing CO2 and fuel consumption from new cars: Assessing the near-term technology potential in the EU. Briefing. The International Council on Clean Transportation.

IEA-HEV (2014). International Energy Agency, Implement Agreement for Co-operation on Hybrid and Electric Technologies and Programmes, Hybrid and Electric Vehicles – The Electric Drive Accelerates, Annual Report

IHS (2014). Passenger Vehicle Sales Data. IHS driven by Polk.

IKA (2012). CO2 Reduzierungspotenziale bei Pkw bis 2020. RWTH Institut für Kraftfahrzeuge, Aachen.

IKA (2014). CO2 Reduzierungspotenziale bei Pkw und leichten Nutzfahrzeugen nach 2020. Aachen: RWTH, Institut für Kraftfahrzeuge.

Klötzke, M., Frieske, B., Soukup, O., Koska, T., Hüging, H., Bienge, K., Ritthoff, M., Kreyenberg, D., Hillebrand, P., Monscheidt, J., Tenbergen, J. (2015). Begleitforschung zu Technologien, Perspektiven und Ökobilanzen der Elektromobilität - STROMbegleitung.

Liebl, J., Lederer, M., Rohde-Brandenburger, K., Biermann, J.-W., Roth, M., Schäfer, H. (2014). Energiemanagement im Kraftfahrzeug, ATZ/MTZ-Fachbuch. Springer Fachmedien, Wiesbaden.

Mankins, J. (1995). Technology Readiness Levels. A White Paper. http://www.hq.nasa.gov/office/codeq/trl/trl.pdf [Accessed: May 16, 2015]

McKinsey (2015). Greenhouse gas abatement cost curves. http://www.mckinsey.com/client_service/sustainability/latest_thinking/greenhouse_gas_abatement_cost_curves (Accessed: February 26, 2015)

Oberschmidt (2010). Multikriterielle Bewertung von Technologien zur Bereitstellung von Strom und Wärme. Dissertation, Universität Göttingen.

OICA (2014). Sales Statistics. International Organization of Motor Vehicle Manufacturers. http://www.oica.net/category/sales-statistics/ [Accessed: May 16, 2015].

Peters, A. and de Haan, P. (2006). Der Autokäufer und seine Charakteristika und Präferenzen. Berichte zum Schweizer Autokaufverhalten Nr. 11, ETH Zürich.

Simon, H. and Fassnacht, M. (2009). Preismanagment: Strategie – Analyse – Entscheidung – Umsetzung. Gabler.

Steiner, S., Bovas, A., MacKay, J. (1997). Understanding Process Capability Indices. Institute for Improvement of Quality and Productivity, University of Waterloo. http://www.stats.uwaterloo.ca/~shsteine/papers/cap.pdf [Accessed: May 16, 2015]

TNO (2006). Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars; Final Report. Netherlands Organization for Applied Scientific Research.

TNO (2011). Support for the revision of Regulation (EC) No 443/2009 on CO2 emissions from cars; Final Report. Netherlands Organization for Applied Scientific Research.

Tran, M., Brand, C. und Banister, D. (2014). Modelling diffusion feedbacks between technology performance, cost and consumer behaviour for future energy-transport systems. Journal of Power Sources. 251.

VDI (2000). VDI Richtlinie 3780: Technikbewertung – Begriffe und Grundlagen. Beuth-Verlag, Düsseldorf.

Yang, Z. (2014). Factsheet China: Light-Duty Vehicle Efficiency Standards. The International Council on Clean Transportation.

World Bank (2015). GNI per Capita. http://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD/countries [Accessed: May 16, 2015].