



**LUND UNIVERSITY**

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**Master programme in Economic Growth,  
Innovation and Spatial Dynamics**

## **Innovation in the Automotive Sector**

Revealing and Comparing Innovative Performance of  
Major Car Manufacturers in the Years 2000 – 2015.

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*Abstract:* The automotive industry, a matured and vital global sector, is currently facing the biggest upheaval so far in the necessity to emancipate itself from fossil fuels. This moment before technical revolution is used for a detailed comparison of innovative performance of the sector in the last 15 years. With innovation being interpreted along the lines of technical progress in key variables, this thesis uses a technometric approach along the idea of trajectories of technological development to gather a comprehensive database, a descriptive and empirical set of data on innovation in the sector is shown, revealing the direction of technical change and the stable nature of innovation overall, but also surprising performances by the manufacturers. Furthermore, the technometric approach and the focus on the manufacturers' perspective of this descriptive study aims at closing a gap to previous research on innovation in the automotive sector, focussing on the public sector perspective and mechanisms to externally influence innovation..

*Key words:* innovation, automotive sector, technometric data

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# 1 Introduction

## 1.1 Background

When Karl Benz set out to take his new invention, the 'Patent-Motorwagen', for a first small trip in the streets of Mannheim in 1886, he most likely was not aware of the success story that would unfold from this initial impulse (von Fersen, 1986). In the following decades, a vast surge in development characterised the evolving automotive industry, transforming it from a group of small experimental backyard workshops to a ubiquitous global industry of major importance nowadays. It is safe to say that only few other innovations have shaped and influenced the twentieth century in the way the car has. Along its path, the automotive industry has been pioneering in major industrial innovations and its products, shifting from luxury goods for the rich towards affordable utilities for the general public, became icons for generations, resulting in an unprecedented individual mobility, therefore laying one of the cornerstones of today's lifestyle. Today, the automotive sector globally generates a total revenue of USD 3.5 trillion and in the European Union alone provides jobs for 12 million people and accounts for 4% of the GDP (European Commission, 2012; McKinsey, 2016).

Despite this 130 years of remarkable success so far, the industry is now facing what probably is the biggest transformation process since its invention, and just as in 1886, we can only speculate on how the next decades will shape the automotive sector. Although studies indicate a potential to almost double the revenue in the industry, they also emphasise the necessity of the industry to transform vastly in order to achieve this (McKinsey, 2016). Considering the environmental problems resulting from an ever-growing population using cars that burn increasingly scarce fossil fuels, there is a growing pressure within the industry to adapt to these changing conditions. The problem with clean, renewable alternatives so far has mainly been the resulting cutbacks in performance data, operator friendliness and especially affordability. A modern fossil-fuelled car can go at high speeds for several hundreds of kilometres and conveniently be refuelled in a close-knit network of petrol stations within minutes, whereas for example electric cars can only high travelling speed or range or quick recharge, but not all three at once. This, in combination with a rather pronounced pressure to consolidate led to a situation where it evidently did not seem economically appealing for the established manufacturers to take the lead in a radical technology shift towards alternative propulsion methods and develop and offer an appropriate product, as sales would suffer from its inadequacies and it is only recently that this is apparently changing, due to the pressure of new innovative pioneers such as Tesla. Instead, the answer of the automotive industry to the changing circumstances has for many



years been to stick with conventional propulsion and channelling efforts in increasing efficiency. This special situation, with an imminent paradigm change in drive technology ahead and a preceded competition in further innovating conventional technologies, offers an interesting opportunity to compare the performance of the automotive manufacturers with each other on a larger scale, before the industrywide conversion towards alternative drive technologies sets in and will distort the picture.

The selection of this worthwhile period to look into the innovative performance of an interesting key industry will furthermore be combined with the goal to attempt insights from a new perspective to complete the overall picture of innovation in the sector. So far, research on innovation in the automotive sector has been dominated by providing the perspective of the public sector in an attempt to understand the theoretical connections allowing innovative processes to be influenced and guided. This extensive theoretical research in understanding the mechanisms occurring before the 'black box' of innovation processes, i.e. input, so far lacks an appropriate counterpart of understanding the results, i.e. the 'black box' output. In using a technometric approach and providing comprehensive data on innovative performance along the lines of technical improvement, this work can provide a much clearer picture in terms of actual outcomes. While patenting data or database-resting indicators can map major leaps innovation activity, it lacks the ability to show actual progress in terms of outcomes. Similarly, R&D data only provides the amount of input, merely allowing a rough estimation of resulting innovation. Here, given the technical nature of the automotive industry and cars possessing a clear set of vital technical characteristics to be considered, in applying a technometric approach, a more accurate insight based on technical figures being the actual outcomes of innovative processes can be provided. In doing so, this work contributes to closing the gap to the more inaccurate indicators previously used to capture innovation in this sector.

## 1.2 Objective

The aim of this study is to identify innovative potential of the major car manufacturers by revealing the progress in technical performance and compare them with each other. The main research question is:

*What was the innovative performance of major international car manufacturers in the period 2000 - 2015 and how did they compare to each other?*

In doing so, innovation will be assessed from a different perspective in this work. As shown in 2.1, previous research on innovation in the automotive sector is primarily based on the public

perspective, focussing on understanding the effects of external factors such as policies on direction and scope of innovation processes within the industry. In this work, however, the perspective of the firms and the provision of historical data prevails. As opposed to previously used indicators to assess innovation in the industry such as patenting data, a technometric approach will be used where innovation is defined along the lines of improvements in specific technological characteristics. With this approach, a comprehensive database is constructed, providing a descriptive and empirical overview of innovation data across the industry from a new angle. This work has to be considered as an initial step towards adding a new perspective to innovation research in this sector, on which further steps of more in-depth analysis of results could follow, which is why the creation of the database, the provision of the data and the resulting descriptive and empirical nature of the work predominates.

For the purpose of answering the main research question, it also has to be answered what progress in product specifications will be considered major innovations by identifying the underlying driving forces that shape the requirements in the products in order to define 'innovation' in this context. This study also compares external factors, such as fuel prices and environmental policies, to the developments in terms of technical performance in order to analyse the determinants of the path of technological progress. Furthermore, the question of comparative performance has to be answered in the construction of a trajectory of technological development of the vital variables in order to obtain a wide comparability across this rather heterogeneous industry. Also, a comparison of the actual observed innovative performance of an individual firm with the patent activity as another indicator of innovative activity will be carried out. This leads to, besides the main research question, to the following three sub-questions:

1. *In terms of technical variables, what core characteristics of cars were targeted by innovation processes in the automotive sector in the relevant period and what was the direction of this technological change in the period?*
2. *How did major external factors shape the technical development of cars in that period?*
3. *To what extent is the observed innovative performance related to the corresponding patenting activity of the manufacturer in this period?*

### 1.3 Outline

After this introductory chapter, the theoretical fundamentals will be covered in Chapter 2, including the main problem with measuring innovation due to the inability to measure innovation in a standardised way. This problem will be addressed in the first part of Chapter 3, where the major parameters to be measured and compared will be determined. These parameters will then be collected and processed to ensure comparability across different car manufacturers and models in order to show the innovative performance based on. Here, the construction of the database is also explained, providing insights into the selection and grouping as well as the initial processing of the data in preparation for the results. From this raw data, a trajectory of technological progress is composed to visualise the innovative performance of the manufacturers. Also, the individual patent activity and major external factors are mapped for a comparison with the observed progress from the technometric approach. The results are collectively presented in Chapter 4, both generally and also manufacturer-specific. According to the nature of this work, the main focus here lies on the data gathered by the technometric approach. Subsequently, the findings will be discussed along with ideas for improvement in further research in Chapter 5. The final Chapter 6 provides a conclusion to sum up the study. In the Appendix, further results in more detail and grouped by the manufacturers are shown.

## 2 Previous Research, Theory and Methodological Framework

In this chapter, a brief overview will be given on the previous research concerning innovation in the automotive industry. Here, it will be revealed that previous research focussed on understanding the mechanisms of external factors influencing innovative processes within the industry. This corresponds to the tendency of previous research in examining innovative processes from the perspective of the public sector, aiming at revealing setscrews to gain influence on the innovation processes occurring detached and internally within the industry. This indeed is a fruitful field of research and to reveal the underlying mechanisms to influence or even steer innovation processes poses an appealing goal for the public, however this leads to a certain bias in research on this topic due to the focus on one perspective. Furthermore, as will be elaborated afterwards, innovation as a process is challenging to capture and measure due to its, broadly speaking, nature as being the emergence of the new and unprecedented. Hence, approaches to measure innovation generally use auxiliary variables to record innovation. These auxiliary variables could either be located before the mysterious process of innovation, such as R&D expenses, or afterwards, such as the analysis of technical data of products. As becomes apparent, in using variables prior to the actual innovation process, a stronger degree of estimation results as to how strong the variable and innovation are connected, whereas analysing variables post-innovation gives a clearer picture of the occurred amount of innovation. Here lies a weakness of previous research concerning innovation in the automotive sector, as the usage of indicators such as patenting data or R&D expenses results in a higher degree of uncertainty. The gap that results from this in combination with the tendency of previous research to aim at understanding the mechanisms prior to the innovation process to reveal measures of influences, will be tackled by this work. Here, the focus will lie on the perspective of the manufacturers and a technometric approach is used to benefit from the technical characteristics of cars to provide a more accurate picture of innovation in relying on actual technical figures of the products instead of more indirect indicators leading to a higher degree of uncertainty.

Hence, after giving a brief overview of the previous research on innovation in the automotive sector, a fundamental overview on the problems and approaches on measuring innovation is provided, also explaining the advantages and drawbacks of the different approaches more detailed. From this, the technometric approach and Dosi's concept of technological trajectories, used in this work as the basis to reveal the direction of technological change and hence as a measure to reveal and compare the innovative performance of the manufacturers, is introduced.

## 2.1 Previous Research concerning Innovation in the Automotive Industry

As mentioned in 1.2, the previous research concerning innovation in the automotive industry is primarily concerned with the public perspective and the understanding of externally influencing innovation processes in the industry. The relation between external factors and innovative processes within the industry, providing the public sector with leverage to partially influence the path of innovation dominates the research. In this work however, both an unusual angle and approach are chosen. Neither the focus on the manufacturers nor the technometric approach to gather technical data in a database carried out in this work are the typical approaches in this field. Hence, the previous research shows no direct predecessor on which this work could build in terms of methodology or perspective, but rather a list of research that approached the topic innovation in the automotive sector from the more conservative point of view. Nevertheless, although not using the same approaches as this work, it still will be briefly discussed here to provide an overview of the current research on this matter.

Probably due to its interesting nature as an industry that saw its growth from the gentle beginnings at the start of the significant twentieth century via the transformation to one of the key industries shaping this century – while continuously relying on the same fundamental technical principle – towards the major player of today facing fundamental restructurings, the automotive industry can be considered a fruitful field for academic research. Parallel to the maturing of the academic understanding of innovative processes and concepts, the automotive industry grew up, providing an interesting research field. It primary a technical sector, but with strong influences of softer factors such as design, it is subject to a vast catalogue of public influences in shape of policies and strong demand forces, while satisfying the basic need for mobility and, as a symbol of individual mobility, being attributed to the democratisation of wealth from the post-war period onwards. Yet, more recently, it is also strongly being attributed with the malign man-made effect on global climate, leading to an increasing outside pressure on the industry to change. This interplay of various factors, from internal, rather individually economically motivated, to external, rather aiming at public welfare, in shaping the development of the industry, is a prime opportunity to reveal the mechanisms of innovation.

It comes as no surprise that a large portion of the research on innovation in the automotive sector is aiming at understanding the effectiveness of externally influencing or even controlling the innovative path of the industry. The public side has a substantial interest in revealing how to guide an industry with adverse effects such as the carbon-based automotive sector towards an ecologically sustainable alternative. The fundamental setscrews that are agreed to be at the public's disposal by most

researchers in this field can be grouped into policies, which directly affect the producers in setting immediate limits in certain factors, or indirect measures, resulting in effects such as increases in fuel prices, channelling the pressure via the consumer and his demand forces. A comprehensive overview of the different approaches of recent research in terms of induced innovation in the automotive sector can be found in the informative work of Sauchanka (2015) that will briefly be explained here. Crabb and Johnson (2010) examined the relation of patent data and oil prices in the period of 1980 – 1999, i.e. after the oil crises of the 1970s and the beginning of the formation of an ecologic consciousness and also consider the role of American emission standards (CAFE). While they indeed found empirical evidence for high oil prices affecting innovation, hinting towards the induced innovation theory, they also revealed the emission policies of having no empirical influence on the innovation. Haščič, de Vries, Johnstone and Medhi (2009) conducted a study focussing on the patenting behaviour in developed countries and the effects of external factors fuel prices and policies on the innovation processes. As opposed to Crabb and Johnson, they distinguish innovation between the two groups of internal, i.e. technology within the internal combustion engine itself, and technologies post-combustion, such as emission control measures. Their aim was to reveal possible differences in external measures affecting innovation in both technologies and indeed, they found that fuel prices had a strong influence on the internal technologies, whereas policies had a significant effect on external, or post-combustion technologies. What seems surprising at first is proposed by them in the difference in benefits: while internal technologies, aiming at consuming lower fuel, might also lead to a reduction in attributed costs such as maintenance, they result in both public and private benefit, while external technologies, mainly focussing on transforming the same amount of fuel used to an environmentally cleaner emission will only result in public benefit. The intriguing thought here is that by consciously selecting the right set of measures, either direct ones through policies or indirect ones through taxation and resulting rise in fuel prices, the different benefits could be selectively used to focus innovation in specific, desired technologies and thus be used to steer industrial development. These findings however are challenged by the work of Vollebergh (2010), who himself examined the effect of both policies and fuel prices on innovation relating to the internal combustion engine, however even further subdividing the different areas of technical innovation. While he shows an effect of policy measures on all areas at a different extent, most notably he registers a negative effect of rising fuel prices and innovation in certain areas. This surprising result of an increase in fuel price decreasing innovative activity is the opposite of Haščič et al.'s findings. A possible explanation delivered by Vollebergh to this phenomenon is his argumentation that an increase in fuel prices would lead to consumer demand dropping and subsequently adapted consumer behaviour in switching to either more environment-friendly products or decreasing the use of their existing products, both leading to a decrease in overall

emissions. He argues that the drop in overall emissions also decreases the incentives to innovate in these areas, resulting in the findings he registered.

Taking a slightly different approach and focussing more on further elaborating the subdivision of the technical areas being objective of the innovative processes, Aghion, Dechezleppêtre, Hemous, Martin and van Reenen (2012) analyse the innovative activity on firm level while distinguishing between 'dirty' and 'clean' technologies. Here, 'dirty' means technologies being related to the fossil fuelled internal combustion engine, while 'clean' technologies are related to eco-friendly alternative propulsion systems and both are perceived by them as substitutes and the effects of tax-included fuel price changes. Their work shows the path dependency of a firm in proving that firms tend to stick to former decisions, which is corresponding to the focussing effect mentioned in Dosi's work, meaning a firm with a long history of development in 'dirty' technologies will tend to remain with these technologies. They also find evidence for an influence of fuel price changes on both dirty and clean technologies, leading them to their conclusion of fuel prices not being high enough to entirely discourage the further innovation in dirty technologies.

Bergek, Berggren and the KITE Research Group (2013) of Sweden's Linköping University take a more pronounced look at the various forms of environmental policy instruments and their effect on the innovative processes based on the example of the automotive and the energy sector. After defining main types of policy instruments, they find evidence that general economic instruments promote incremental innovation, whereas radical innovation is enforced by technology-specific instruments. This adds to the results of the other mentioned papers, revealing the potential power in skilful policy making as a steering device of an industry as important as the automotive sector. Whether all specific results from the papers are considered final and universally accurate or not, they still indicate the strong dependency of the industry on external factors. Therefore, in this paper, a look into the major external factors already mentioned in these papers, namely fuel prices and emission policies will be taken in order to elaborate the influence of these factors on the observed innovative performance.

Finally, Zapata and Nieuwenhuis (2010) analyse the origins of major automotive innovations as well as the causes for their industry-wide spread. While they elaborate that most fundamental innovations have their roots in motorsports applications, they find evidence that at least since the 1960s the spread of innovations to broad road car usage has been influenced by governmental policymaking, further stressing the importance of policies in influencing innovations in the automotive sector. However, they also point out the time span that this spreading process is taking in several examples such as the turbocharger: while it saw its origins in aeronautical applications from the 1930s onwards and post-war saw applications in motorsports, it took pioneers such as SAAB

in the 1970s that introduced this technology in regular, yet unusual road cars, it is only now and due to strict emission regulations that turbocharged engines see a broad spread across the industry in an attempt to lower emissions. This might indicate a very extensive delay between actual invention and broad and successful commercialisation that should always be taken into account when considering innovation within the automotive sector.

## 2.2 Measuring Innovation

In order to reveal and compare innovation across the manufacturers in the automotive sector, it is necessary to measure innovation beforehand. When trying to measure something accurately, it is necessary to know in advance what to look for. Measuring includes the selection of a specific set of tools, which themselves are being capable of only capturing a certain group of variables. As this selection process and the subsequent inevitable restriction on variables to monitor is the initial step in a measuring cycle, it is of vital importance to possess at least a suspicion of what variables to measure in order to gain the desired information as result. It becomes obvious that subjects from the fields of the natural sciences are generally easier to measure due to their specific definitions. Other fields of science – also the one underlying this work – lack the formulated strictness in their definitions and are characterised by rather conceptual definitions with broader leeway. Nevertheless, as becomes apparent, the more exact a subject is defined, the more satisfying and accurate it can be measured. This chapter will offer the theoretical fundamentals necessary to define what has to be gathered and evaluated in the following chapters.

As mentioned above, the vital key for any measurement is an initial definition of the subject to be measured in order to know what set of tools to pick for measuring. In this work, innovation in the automotive sector is to be demonstrated, so the first step is to establish a definition for innovation itself. Even before actually diving into the theoretical fundamentals of research on innovative processes, an elementary problem can instantly be identified. As deduced above, the success of measuring and therefore demonstrating something is dependent on a certain kind of knowledge about what to look for, or in other words, properties of the subject to be demonstrated. This necessity of ex ante knowledge seems to contradict the commonplace perception of the concept of innovation as something new and unpredicted. Today's scientific understanding of innovation has its origins in the works of Schumpeter (1913), who provided the initial definition of innovation as a new and unprecedented combination of materials and forces and their commercial realisation.



In more detail, Schumpeter's understanding of innovation can be divided into 5 different cases (Borbély 2008, Schumpeter 1913):

1. Production of new products
2. Introduction of new production methods
3. Exploration of new sources of supply
4. Development of new markets
5. Reorganisation of business

From these cases, in addition to his provided characterisation of innovation originating from the economy in a discontinuous manner, it becomes apparent that Schumpeter's initial understanding of innovation was focussed rather on the commercialisation than the invention of new technologies and ideas, as in his eyes, it is only the successful commercialisation of an invention that could act as a proof of value of the invention and simultaneously provide the new impulse to the economy (Schumpeter 1913, Kiss 2004 as cited by Borbély 2008). In Lazonick's (2006) words, innovation requires firms to learn about how technologies can be transformed and markets be accessed in generating products with a higher quality and lower costs. He also stresses the uncertain nature of the innovation process, since the required knowledge for transforming technologies and accessing new markets, by definition, can only be revealed during the learning process itself. There is a vast amount of research on the question what makes a firm innovative, ranging from social, historical or managerial factors, not least by Lazonick (2006), who tries encircling the underlying question from several directions, but here, the initially preponderating question will not be why certain firms innovated, but rather quantifying their innovative performance. Therefore, after establishing the fundamental meaning of innovation, it has now to be decided how to measure it – a field of research that is of equal complexity as that of why firms innovate. As becomes apparent from the initial definition of innovation by Schumpeter, which might be considered long alphabetically, but lacks the clear precision of a mathematical formula, a universal and reliable method of measuring innovation appears impossible, even more so as the definition of innovation depicts the characteristics of a third party, the product or technology, which is unpredictable and unique in every case. This is also pointed out by Smith (2006), who in his works on how to measure innovation explicitly points out the underlying problem when trying to measure the uncertain. Although he tends to agree on certain aspects of innovation being immeasurable, he still believes this to not be true in its exclusiveness. Instead, he subsumes, the solution lies in breaking down the multidimensional aspect of novelty creation into bits that can convincingly be measured, therefore, by concentrating on what can be measured, and circumventing the fundamental paradox of being forced to measure novelty. The formation of these innovation indicators is vastly influenced by the works of Kline and Rosenberg

(1986) and their creation of the so-called chain-link model of innovation, stressing the following aspects of innovation:

1. Instead of a linear process, innovation involves numerous feedbacks and interactions concerning knowledge creation
2. Innovation is a multi-dimensional learning process with various inputs
3. Innovation is not dependant on inventive processes, in terms of discovery of new principles, with such processes by trend being considered as problem-solving within an existing innovation process rather than an initiating event.

As Smith (2006) points out, this leads to two major implications in terms of innovation indicators, one being novelty implying not only creating entirely new products, but also changes in a relatively small scale, that however add up over time and may lead to major implications economically or technologically. A successful indicator, he adds, has therefore to be able to capture not only radical changes, but also gradual and subtle advancements. The second implication according to him is the importance on innovation of factors besides usual R&D, such as design activities or exploration of new markets, leading to the necessity of an indicator to being able to record those inputs besides mere R&D spending. In his work, Smith (2006) distinguishes between five groups of major indicators, which will briefly be described here.

### 2.2.1 R&D Data

The traditional approach to attempt to measure innovation is using an R&D indicator in putting R&D expenses in relation to total sales (van der Panne, 2007). After establishing the fundamental problem of innovation measurement described above, in picking R&D indicators as the initial base of innovation mapping, several of the aforementioned problems could be solved and meaningful results be obtained. The most obvious reason for R&D indicators being the initial and longest-standing area of data collection lies in their simplicity (Smith, 2006). R&D data on corporate level has not only been recorded for a long time span, but also in a rather standardised way, allowing for comparisons between firms, industries or countries, making it a readily available and easily evaluable source of data to circumvent the problem of immeasurability of innovation itself (van der Panne. 2007). However, this simplicity comes at a price. Monitoring the R&D expenses can give an impression of the activity of the R&D department of the respective entity, especially when put in comparison with the expenses of competing entities, but eventually, even this is a deduction. Furthermore, this activity in R&D could at most be translated to inventive activity, but, as according to Schumpeter's concept stated above, it is not invention defining innovation, but rather the successful

commercialisation of inventions. This imbalance of focussing only on inputs (i.e. R&D expenses), discounting outputs (i.e. sales) as a measure of commercialisation is raised by Kleinknecht, van Montfort, and Brouwer (2002). Furthermore, this indicator implies an exclusiveness of R&D activities in innovation processes, which contradicts the aforementioned assumptions by Smith. Indeed, as a work by Brouwer and Kleinknecht (1997) shows, only 25 percent of the total innovation expenses can be attributed to mere R&D, the rest flowing into, inter alia, market evaluations or design processes. Another problem raised by Smith (2006) is the difficulty in finding a sharp definition of R&D as opposed to related processes.

### 2.2.2 Patent Data

The importance of the small states in 15<sup>th</sup> century Italy with their increasing focus on mercantilism, technology and advance in the formation of a basis for the rise of the further development of Europe, can exemplarily be seen in the example of patent systems. It was in these pioneering days that innovation was made desirable within a market situation in linking it to a rewarding system. Venice introduced a licensing system in 1474, granting those who could prove the feasibility of their inventions through demonstration a protection from imitation for ten years, as a location measure to attract engineers and boost progress (Granstrand, 2006). These beginnings of patent systems further developed in a pattern that can be characterised by increasing spatial spread: was the initial licensing limited to Venice and meant as a measure to recruitment, the current intellectual property rights systems are in effect almost globally and focus rather on protection of the invention rather than attraction of the inventor (Granstrand, 2006). Yet, the connection between innovation and patenting is still valid and is used by researchers as a measure to detect innovation. The patenting system is helpful here as it can make innovation visible: in order to successfully file a patent, the applicant has to disclose his invention, prove its feasibility and agrees to have it publicly registered and roughly explained in order to benefit from the promised protection from imitation (Smith, 2006). Through public patent databases, innovations are publicly announced and therefore made measurable. However, as with R&D indicators, the simplicity of patents as an indicator comes at a price. As with R&D, patent data maps invention rather than innovation, as it is lacking the Schumpeterian requirement of commercialisation (Smith, 2006). On a more complex level, the underlying trade-off for the applicant has also to be considered: the protection by the patent system is only achieved by previously disclosing the invention. This could trigger various considerations by firms, as a firm could decide the resulting protection does not compensate the disclosure of internal details, possibly revealing major strategic decisions beyond the actual patent itself, or, in contrary, using the patent

system as a strategic measure to seize key technologies without actually intending to commercialise on them (Smith, 2006, Kleinknecht et al., 2002). Nevertheless, patent data can give an idea of innovative activity and will in this work be used as a comparator to the main approach.

### 2.2.3 Bibliometric Data

In a more scientific approach, bibliometric data can also be used as an indicator for innovation. Here, scientific publication and citation are analysed for composition and dynamics, with the Science Citation Index and the database of the Institute for Scientific Information (ISI), founded in 1958, being the most integral parts (Smith, 2006). Although those databases contain statistics for more than 170 countries and a vast variety of subfields, the major problem with this approach lies in the focus on scientific dynamics rather than innovation (Kaloudis, 1998; Moed, de Bruin, & van Leeuwen 1995; Smith, 2006).

### 2.2.4 Database-resting Indicators

In an attempt to overcome the aforementioned problems of the more simplistic indicators, the development of more sophisticated indicators was pursued and led to the emerging of database-resting indicators. According to Archibugi and Pianta (1996), these can be divided into two different approaches, the one being called the subject approach, since the focus lies on the innovating entity, i.e. the subject that is innovating, whereas the other is being called the object approach, as, accordingly, the focus here lies on the output of the innovation process.

The most famous example for the object-based approaches in accordance with Smith (2006) is the SPRU database developed by the University of Sussex, which bundles the major technical innovations in British industry post-war up until 1983. As Smith adds, the advantages of such an approach lie in the focus on the technological aspects in combination with a quality assurance mechanism through the upstream panel of experts acting as gatekeepers. On the other hand, he points out, there is an inherent weakness through the combination of the expert panel acting as gatekeepers of significance and their sources being press releases or journals, i.e. published information, leading to a bias towards more revolutionary progress, whereas the usual incremental progress might not be journalistically noteworthy and therefore avoids being recorded by the panel in the first place.

Another form of object-based approach uses literature as the source of data. The so-called literature-based innovation output method (LBIO) stems on the works of Edwards and Gordon (1982) and have

been refined and further developed most notably by Kleinknecht (see: Kleinknecht & Bain, 1993). Here, the information on the release of new products is taken from professional trade and technical journals to map innovative processes in the industry, having the advantage of using an independent source and being able to also capture innovations from smaller firms that in other indicators such as patenting data tend to be missed, with the drawback already mentioned above of only capturing innovation that is decided to be published (Coombs, Narandren, & Richards, 1996; Kleinknecht & Bain, 1993). A recent example of a profound LBIO database is the Swedish SWINNO, covering data of Swedish manufacturing firms between 1970 and 2007, providing unprecedented insights into the development of the Swedish manufacturing sector (Sjöö, Taalbi, & Ljungberg, 2014; Taalbi, 2014).

The subject-based approach is characterised by an initiative by the OECD in the early 1990s to harmonise earlier survey results and laying the cornerstone of a uniformed approach, resulting in a manual that is today known as the Oslo Manual (OECD, 1992; Smith, 2006). This initiative was taken up by the European Commission and led to the formation of the Community Innovation Survey (CIS), being a large scale attempt to collect international and comparable data on direct measures of innovation output, inter alia incorporating data not only on R&D, but also on the associated fields mentioned in chapter 2.2.1, or sales figures of both radically and incrementally changed products, tackling the mentioned problems with incremental change disappearing in previous approaches (Smith, 2006). Due to the survey-based approach, where the information is centrally gathered after being compiled by the subjects themselves, it calls for a clear definition of figures to be stated on the one hand, and on the other hand, in order to achieve an indicator as versatile and comparable as possible, definitions cannot be too narrow in order to fit all different sectors and companies, resulting in a constant trade-off between universality and complexity and criticism arises, whether the CIS approach is feasible beyond its native area of application in manufacturing (Smith, 2006).

### 2.2.5 Technometric Data

Most of the aforementioned indicators focus strongly on either the input side of the innovation processes, as in expenses flowing into R&D, or try to visualise the processes happening inside the innovation black box through auxiliary by-products such as citations or patent applications. At least for technical products, however, there is the possibility of actually assessing the degree of product improvement through innovation processes by observing the improvements in technical specifications in the products (Smith, 2006). In order to close the informational gap between the analysis of mere R&D input at the beginning of the chain and market results at the end, Grupp (1994)

suggests bridging the gap through addition of analysing technical performance of the products to gain the opportunity for a more specific insight. Here, he suggests an initial stage of data collection, but also raises the necessity of an evaluation of the data, which he suggests to be achieved through a board of experts. The importance of this becomes apparent when considering the variety of different performance data of products from which those have to be determined that should be considered crucial for the product's commercialisation. When remembering Schumpeter's understanding of innovation, it is not the improvement in random technological parameters that constitutes innovation, but rather the improvement in those technological parameters that have the biggest effect on the product's commercialisation. Grupp's (1994) solution is to survey a board of expert as an authority of appraisal, but as shown in 2.3, other approaches exist as well. Nevertheless, given a functional appraisal mechanism insuring significance, the usage of an indicator based on technometric data in assessing innovation is a tempting alternative or addition to the aforementioned, as it approaches various raised problems. It is more precise than an indicator based on inputs, such as R&D expenses, as measures the data of actual post-innovation process output. Furthermore, it is immune to the behavioural trade-off present in the patent data indicator, as it measures product characteristics independently from a possible patenting status. Additionally, it is also capable of measuring both incremental and revolutionary progress in focussing on pure data, avoiding the problems of journal-based bibliometric data, being prone to overlooking incremental progress due to the lack of reference in these journals. Finally, as mentioned, the necessary consideration of commercialisation is achieved through the appraisal mechanism. Simultaneously, however, this does not only emphasise the importance of this integral part for the successful functioning of this indicator, but also reveals it as the weakest link of this approach: it is only a reliable, profound and careful selection of the significant technical parameters that enables the potential of this approach. It is needless to say that the biggest drawback of this approach lies in its inherent limitation on technical products, while the other indicators show a higher degree of universality, compensating the alluded disadvantages. However, as in this work the focus will lie on the automotive sector and the concerning products are heavily revolving around technical data, this drawback is of no relevance, while the benefits of the indicator fully apply. Therefore, a technometric approach is chosen in this work, including, as suggested by Grupp (1994), a supportive glance into patent data.

## 2.3 Technological Paradigms and Trajectories

As mentioned above, the technometric approach according to Grupp (1994) includes an appraisal entity to determine the technical variables of relevance. This can be considered a solution to Schumpeter's prerequisite of factoring in commercialisation into successful innovation. However, based on the premise of this mechanism serving the main purpose of identifying those technical aspects that will be of significance in terms of later commercialisation of said product, it becomes apparent that this mechanism can be substituted if the knowledge of what technical aspects will be of importance can be acquired elsewhere through another, preferably easier method. The fundamental question is therefore how to determine the importance of a product's various technical variables and the direction of their future development.

This question of possibility to determine the direction of innovation has been tackled by Giovanni Dosi, who in his work (1982) evaluates a corresponding concept of technological paradigms and trajectories. While not trying to provide a general theory, his concept tries to tackle the question of why certain directions in technological change emerged and others did not, which would be a crucial information for evaluating innovation in an industry. Originating in the classic approach of technical change being either forced by the market (demand-pull) or quasi-autonomous (technology-push), he argues that there is the possibility of knowing the direction of technological development being pulled by the market before the actual innovation process. In approaching technology in a rather microeconomic way, he describes it as a limited set of pieces of knowledge and possible technological alternatives a firm can use to achieve its goals and meet notional developments. From this, his concept derives the idea of *technical paradigms*, which analogous to scientific paradigms, are defined as models or patterns in order to solve certain technological problems, based on specific principles or technologies. This means that in the beginning, there is the identification of a technological problem, i.e. the definition of a goal for the further development of a product, based on notional future development. Then, in a second step, as the goal is established, the actual set of tools in terms of technological approach is chosen, which is what he defines as the technological paradigm and of which there might exist several at the same time. In a crude example, the goal to produce electricity could be achieved by either nuclear power, coal power or wind power, each symbolising a different technological paradigm. Based on the chosen technological paradigm, Dosi (1982) in the next step states that there is the possibility of defining the direction of regular progress, meaning problem solving activity to achieve the aspired goal, as a chosen technological paradigm will determine the direction of technological change. This direction is called *technological trajectory* by him. This trajectory on one hand allows the identification along which route technical progress will

be pursued, on the other hand, it stands for the focussing effect of the choice of technological paradigm, as following the trajectory with the chosen paradigm further enhances the blindness towards other paradigm alternatives due to a growing momentum of the initial paradigm, called *natural trajectory* (Dosi, 1982; Nelson & Winter, 1977a; Nelson & Winter, 1977b; Rosenberg, 1976). Technical progress would then be defined as a movement in the multi-variable space along this trajectory, leading to an improvement in the inherent variable trade-offs that comprise the trajectory, which itself is nothing else than a series of possible technological combinations with the underlying paradigm defining the outer boundaries (Dosi, 1982; Martino, 1980; Sahal, 1978). This boundary is called the technological *frontier* and can be considered the highest possible level to be reachable along the technical trajectory considering the technological paradigm, while also affecting the probability of future advances along the trajectory of the concerning entity according to the distance between entity and technological frontier, consistent with Nelson and Winter's understanding of technical progress based on Markovian chains (Dosi, 1982; Nelson & Winter, 1977a). As mentioned, the trajectory can contain strong focussing forces, which can impede the switching to an alternative one due to the new trajectory being far behind the existing one, leading to the necessity of starting new when switching the paradigm (Dosi, 1982). In his model, Dosi finds evidence for the aforementioned market-induced evidence, however with the limitation of it rather affecting incremental, or normal technological progress, instead of the radical, discontinuous advances (Dosi, 1982; Schmookler, 1966).

Overall, Dosi's concept of technological paradigms and trajectories serves as a fruitful addition to the fundamental technometric approach. Not only does it enable identifying the relevant technical aspects of the product for successful product innovation, but even allows plotting a path of the direction of desired innovation due to the concept of technological trajectories, while also illustrating the underlying problem of technological frontiers depending on the chosen technological paradigm and the possibility to defining the position of the entity within this multi-variable space, enabling a qualitative assessment. The major drawbacks of Dosi's concept stem from the fundamental drawbacks of the technometric approach in general, in being rather limited to technical products instead of services and, more specifically, due to the concept of paradigms and the resulting difference in trajectories, being more suited for small, incremental progress instead of revolutionary.

However, given that in this work the subject of interest is the automotive sector and their products and therefore the characteristics of these products have to be matched with a suitable indicative approach, Dosi's concept can be considered a suitable approach. In order to determine innovation in the automotive sector, the focus will lie on the main product of this sector, namely cars. These in itself are a perfect example of a technical product and despite their diversity, all revolve around the



same fundamental technical concept and subsequently a similar set of technical aspects to provide. This, in combination with the special situation mentioned in the introduction that all major automotive firms can momentarily be considered on still being on the same page in terms of the fundamental conceptual approach of problem solving in still focussing on internal combustion engines, while simultaneously future research, development and announcements suggest an imminent change towards alternative forms of drive systems within the coming years, leads to a promising possibility of applying Dosi's ideas. The current situation with major changes in terms of drive train concepts to be expected is a critical point of time in Dosi's concept, as it shows the imminent transition from one technological paradigm towards another, hinting a technological frontier to be reached with the current paradigm internal combustion engines. Simultaneously, as currently, due to their adherence to conventional drive systems, the manufacturers can be considered adhering to the same technological paradigm. This therefore enables a broad comparison both along the industry and along the years, as the current paradigm has been the vastly predominant approach for products in the automotive sector, resulting in a high level of overall technical sophistication, and the imminent change in paradigms will lead to a rather frayed field of competitors at various stages of technological transfer towards the by comparison rather embryonic alternative technologies. As Dosi elaborates, the switching towards an alternative, new technological paradigm will initially lead to a deterioration in terms of position along the technological trajectory and therefore, the heterogenic switch towards new technologies along the industry will lead to fragmentation, preventing a reasonable comparison both along the industry but especially chronologically. So as the internal combustion engine will see its inevitable demise, it still does provide the optimal occasion for a broad comparison of the industry's past innovative performance before the cards are being reshuffled.

## 3 Data and Methods

In order to answer the underlying questions of this work in a satisfactory manner, several sets of questions have to be raised. In this chapter, it will be explained what data is gathered and how it is composed. According to the target and nature of this work, a strong focus will lie on the technical data that is gathered and compiled to the database. Due to the mentioned focus of previous research on innovation in the automotive sector on the role of external factors and innovation indicators such as innovation data, both the main external factors and patenting data are also included to provide a brief comparability with the newly-gathered technometric data and thus enabling a better linkage of the results from this work to previous findings. Nevertheless, this does not raise the claim to provide a complete and in-depth statistical or econometric analysis of the results from the different approaches, as the underlying main objective of this work is to provide the possibility to add a new perspective on innovation in this sector by gathering a new set of data.

### 3.1 Innovation in the Automotive Sector

Any measurement of innovation requires prior identification or definition of what to perceive as innovation. In order to map the direction of innovation in the automotive sector, Dosi's fundamental concept of technical paradigms and trajectories will form the basis. In exploiting the underlying notion of technological trajectories showing the desired direction of development, this revealed path can be assumed as the target direction and hence goals of innovation. Therefore, and in order to be able to answer the follow-up question of innovative performance of the individual manufacturers, along the lines of Dosi's concept, an initial trajectory of technological change will be generated from the average values of two selected key variables. This resulting industry-wide trajectory will reveal the direction of innovative development of the industry in terms of technical progress and enables a subsequent performance comparison.

In order to construct a trajectory to reveal the direction of technological change for the automotive sector, it beforehand needs to be identified, what technical variables are to be considered crucial. Despite this in general being a rather difficult task, in this specific case, several characteristics of the automotive sector alleviate the process. With small exceptions such as electrically powered cars at the beginning of car manufacturing or occasional experimental vehicles fathoming the potential of alternative drive technologies, from the beginning up until today, virtually the whole automotive industry is concentrating on building cars around the same basic concept of the internal combustion

engine. The whole progress of over a hundred years of technical advancement in car manufacturing, the transformation from crude, mechanically controlled engines towards electronically optimised high-performance engines and the ever-increasing complexity of a car's internal system does not belie the fact that beyond all these auxiliary systems, physically both engines work the same. This is insofar remarkable and helpful for the underlying question of identifying variables, as it means that the automotive sector is facing the same fundamental problems for over a hundred years in engine development.

Naturally, these problems and their underlying technical variables have been prioritised and therefore tackled differently, as for example power optimisation seemed more important than fuel consumption in motoring's early days, not least because of the lack of environmental awareness due to the lack of large-scale environmental influence of cars at that time. However, when considering at least the last quarter of a century, the same fundamental properties of an engine stand out. Here, it is important to make a clear distinction. The factors or reasons of a consumer to buy a certain car over another are as diverse as with other consumer goods. Car manufacturers succeeded in segmenting the car market into different parts, each incorporating another demand, be it premium cars, pragmatic cars, or design cars. Despite all being based on the same basic principle, car manufacturers emphasise their image management in order to diversify what is based on an identical functional basis. The technical component building the fundament of each car is covered with an enormous range of emotional aspects in order to market the product successfully. However, these marketing-based *soft skills* are irrelevant when assessing the innovative performance, where mere technical data and functionality ought to be identified. It is therefore necessary to concentrate on the technical factors that are of importance for a consumer to buy a car.

Here, only a few properties of a car remain and of these, even without thorough examination, two could reasonably be considered the most important. Whereas most car owners would not be able to state the weight, the dimensions or the emitted noise of their cars in numbers, most have a rather clear idea of the car's fuel consumption and its power. Obviously, these two variables should not be considered exclusive technical purchasing arguments, but most other prominently advertised aspects of an engine, be it CO<sub>2</sub> emission, range or the sprint time to 100 km/h, inevitably result in affecting either or both figures of an engine. Therefore, as in previous works, it can be considered a viable choice to focus on these two aspects in order to evaluate the technical development and hence innovation performance. In this work, the technical nature of cars prevails, hence the reduction of cars to their key technical characteristics and a subsequent rather technical definition of product innovation. How these variables are processed in order to make them comparable is illustrated in 3.2.

## 3.2 Technical Performance

The most important task in order to being able to record and evaluate innovative performance within the automotive sector in a technometric approach is to build a suitable database. This database has to meet several requirements in order to provide viable results. As mentioned before, the biggest problem when trying to assess innovation is the difficulty to measure something as heterogeneous and intangible as innovation. However, even after having identified a suitable set of tools to measure the subject to be examined as elaborated in the previous chapter, the main obstacle to tackle is to enable a comparability along the measured data both chronologically and spatially. The automotive sector is characterised, despite the tendencies of consolidation and the demise of numerous companies within the last decades, by a rather heterogeneous range of products. Car models alone differ in sizes, features, and demands and that does even disregard the different motorisations, further adding to a vast variation among cars from both different manufacturers but even intracompany. This is reflected in the technical data to be collected and in order to establish a comparability, it demands of a high degree of pre-organisation and arrangement of the data. The initial problem is that despite the advanced level of globalisation in the automotive sector, with major groups such as Ford, Toyota or Volkswagen being active on virtually all global markets, due to differing consumer preferences, a rather high degree of market segmentation exists. The Volkswagen Golf, ubiquitous in Europe, is less common in Japan or even the United States. Vice versa, the American preference for large pickup trucks is unrequited by Europe, as is the Japanese fondness of so-called Kei Cars, that can be considered small even by more moderate European standards. The manufacturers responded to these differences in preference in offering especially tailored models for major markets and omitting an 'one size fits all'-approach that could be observed in consumer electronics for example. As a result, a global market comparison is threatening to produce skewed results, as it would mean comparing a normal car (e.g. VW Golf) with a truck (e.g. Ford F-150) and a four-wheeled motorbike (e.g. Suzuki Wagon R). As one aim of this work is to provide a possibility to compare innovative performance not only chronologically along a model, but also spatially across the industry, there is the need of harmonising the data starting point.

In order to achieve this, the focus in this work will be set on the European car market. Firstly, for the majority (2000-2012) of the period to be examined, the combined European car market surpasses the other major markets USA and China in annual sales, while secondly providing a degree of comparability across its countries and being characterised as a stable, mature market not prone to the chaotic growth of the catching up Chinese market and resulting distortions in chronological order (Gomes, 2016). Based on this market decision, 15 major automotive groups were chosen, accounting

for over 97% of the European market (EU + EFTA, car registrations in 2015), with a focus on the largest sub-brand of each group according to market share figures (ACEA, 2016). The range of products of each of the 15 chosen sub-brands was classified according to the car classification scheme developed by the European Commission (2002). From this classification scheme, the following fringe classes and belonging products have been omitted:

- A mini cars
- F luxury cars
- S sports cars
- M multi-purpose cars
- J sport utility cars

As marginal differences even within the EU internal market exist in terms of offered motorisation, models or dates of introduction, in order to create a standardised database, technical data has been gathered based on the biggest of the European car markets, Germany (Gomes, 2016). For this purpose, the technical data has been centrally gathered from the database of Europe's biggest motor club, the German Allgemeiner Deutscher Automobil-Club (ADAC, 2016). This club possesses a publicly accessible, closed and professionally maintained automotive database, gathering numerous information and data on virtually all cars offered on the German car market for at least the last 25 years. Besides data from its own in-house tests, the database also provides an extensive amount of manufacturer specifications and technical data on all models and all respective engine variants in the relevant period. It is the combination of the vast extent of the data, the closed and professional characteristic of the database, the good reputation of the data owner as a reputable club and car insurance company, and the contained technical data being used for both insurance and fiscal calculations, that makes this database a both comfortable and reliable source of data in this work.

In the next step, each offered model of the brands within the period 2000 – 2015 is classified to the relevant classes B – E. As mentioned, the heterogeneous nature of the automotive firms resulted in not all manufacturers offering cars in every class examined, or at least only partially over the period of time. In order to maintain both comparability and consistency, sporadic models have been omitted in the case of it being the only model the manufacturer is offering in this class and only for a reasonably short time. The main goal has been to achieve timelines as complete as possible for each class and each manufacturer. As a result, especially the high-end-oriented manufacturers are lacking models at the lower end of classes and vice versa budget-oriented do not offer models within the higher classes. This imbalance also is the reason for a priori dropping the most remote classes, while including classes B and E is a compromise between adding diversity without causing too many data holes. As a result, 148 models by 15 manufacturers are being analysed, with most manufacturers on

average having 2.5 or more models per each class, including those not covered by product range and at least two up to 4 models per each class covered.

This list of models is now categorised and enriched by different motorisation. In order to achieve comparability, a selection of engines per each model is selected and according data gathered. Fundamentally, engines comparable in performance data can be expected in each class due to the competitive forces within the industry. However, due to the heterogeneity of the automotive market, several manufacturers aim at different niches within the market and the one standardised engine per class cannot realistically be expected. Instead, certain manufacturers aim for the higher end of performance, whereas others concentrate on the lower end. Secondly, certain manufacturers offer a wide range of different motorisation for their model, while others might content their selves with only a couple different engines. To overcome this striking imbalance, a standardised approach proves impossible and data selection is rather based on individual choices. In the selection approach, the aims were firstly to map the span and average of technical performance in the engines offered in settling for engines from both ends and possibly a mid-tier engine. Secondly, great care has been taken to achieve continuity over the whole time span, so engines only appearing for a couple of years have been omitted in favour of engines being offered along the entire model history. Also, extremes and artificially created gap fillers, meaning engines being decreased in power to fill in the model range, have been omitted, as both would distort the results, the first in being niche products hardly being comparable to other manufacturers, the second being artificially decreased in performance, therefore distorting the manufacturer's overall technical performance in an undesirable manner. When in doubt, the more potent of two variants of the same engine has been selected. In terms of continuity, the revision and improvement of the engines over the years sometimes led to a switch with the possibility of either adopting a new smaller engine with comparable power or remaining with the new equal sized engine that gained performance. In general, for the sake of continuity and the mapping of development, an engine has been tracked as far as reasonable, in most cases, the designation by the manufacturers acted as a guiding post and allowed identification of intended heir. As in the end, the technical data of each engine is standardised, these decisions are only of minor importance in terms of impacting the result. The same applies to the differences in nominal data for the selected engines of the different manufacturers.

A general distinction has been made between petrol and diesel engines, with the aim of covering a sound sample of engines for each fuel type in each class. Due to the lower distribution of diesel engines at the end of the 1990s as compared to today (ca. 30 % as compared to over 50 % in EU 15, AAA 2015), the starting point in 2000 saw a significantly lower number in diesel engine variants for each manufacturer, resulting in an overall smaller sample of diesel engines, as the engine sample is

set in the first years. Where necessary and reasonable, the first data has been recorded in 2001 or 2002, when engines were only introduced then, but for the sake of avoidance of larger data holes, later initially introduced engines were omitted. Nevertheless, for most models, the sample of diesel engines might be smaller but is still informative. This eventually leads to a sample of 724 engines in total for analysis. In order to standardise the resulting data and achieve comparability, for each engine, the engine output per unit of displacement (standardised power output in kw per 1000 ccm) and specific fuel consumption (standardised fuel consumption in l/100 km per 100 kw) have been calculated. Further data can be found in the appendix, providing a more in-depth insight of the results of each manufacturer in each class of cars, thus revealing the performance across the different classes.

### 3.3 External Factors

As revealed in the previous chapter, there is evidence of recognisable influence of external factors on the innovative processes within the automotive industry. In previous approaches, these external factors have commonly been divided into policies and fuel prices as the major influencers. In order to provide information on how the proven innovative processes in the automotive sector might be influenced by these external factors, they need to be captured. Due to the selection of the European car market as the standard for the collection of technical data as explained in 3.2, both external factors themselves will be focussing on the European market.

#### 3.3.1 Emission standards

Cars offered on the joint market of the European Union and the European Economic Area have to comply with an extensive set of emission standards. This sequence of emission standards, the Euro stages, will be taken into account in this work in order to map the policy side of the external factors affecting the car industry. A timeline will be compiled, showing the emission standards and the industry-wide fuel consumption to reveal connections. The data on the European Emission Standards (Euro 3 – 5) have been gathered from the Official Journal of the European Community / European Union (European Communities, 1998; European Union, 2007).

Besides this European emission standards system, the European Union also decided to implement a mechanism in order to decrease carbon dioxide emission in setting an upper limit for manufacturer's fleet consumption. This mechanism was agreed upon in 2008 and although it will only be fully applicable in 2015 and therefore by the end of the period covered here, due to the phasing-in

mechanism since 2012 and generally the forerun needed in the automotive sector, the effects of this mechanism will also be examined (BMU, 2009).

### 3.3.2 Fuel prices

In previous research, one of the main factors of influence were the prices for fuel. In this work, the according data has been gathered from the European Environment Agency (2016) for the period 2000 – 2015. Furthermore, the data is subdivided into two subsets. The first shows the average prices within the European Union for *Diesel*, *Petrol* and *All Fuel* including taxes, i.e. final price. Due to the different grades of petrol, the numbers for *Petrol* are consumption-weighted averages of both leaded and unleaded petrol, corrected according to energy content to result in an equivalent amount of unleaded petrol. *All Fuel* data is compiled according to the same principle, but also takes into account the *Diesel* figures. These figures are all nominal. Therefore, in a second set, the *nominal All Fuel* numbers are set aside *real All Fuel* numbers, prices corrected for inflation and using 2005 as base year, in order to achieve a comparability and take skewing inflation effects into account.

## 3.4 Patenting Data

Furthermore, it will be examined whether the observed technical innovation within the automotive sector derived from the technometric data can be confirmed from the patent data of the manufacturers in the same period of time. In order to this, the patenting activity of each manufacturer will be recorded. A fundamental theoretical problem is the approach to patenting data. As mentioned in 2.2.2, patenting activity cannot necessarily be translated into innovative activity as there might be behavioural trade-offs in both directions: it could be perceived advantageous to waive patenting an innovation in order to avoid public attention for example, and it might also be that the patenting system is rather used as a defensive mechanism to exclude competitors from promising technologies in blocking key technologies that do not allow direct feedback to actual innovation activity in the firm. Furthermore, it has also to be considered that modern car manufacturers are offering a wide set of products and services and are involved in a vast span of activities that go far beyond the actual technology contained in an internal combustion engine. The car itself as the main product does include know-how from a plethora of fields in all its different parts, without taking into consideration the multitude of other activities a manufacturer finds himself involved in today. Patents of a car manufacturer might include work process optimisations or even innovation related to its staff catering. This calls for a clear definition of what patents to consider. Therefore, in this work, the patent classification according to the IPC classes is



used in selecting these areas that can be considered directly affecting technical performance of the car in terms of the variables chosen to be relevant. These classes focus on the engine itself and the following components involved in delivering the generated power towards the road and transform the engine power into movement, as these influence the driving characteristics and technological potential of the engine itself. Patenting data of the manufacturers is gathered centrally from DEPATISnet, the central research gateway of the German Patent and Trade Mark Office (DPMA), offering a database of almost 90 million data entries from all major patent registers, including the European, the American, the Japanese and the Korean and therefore covering all countries of origin of the manufacturers covered in this work (DPMA, 2014).

## 4 Results

### 4.1 Innovation in the Automotive Sector

The collection of the data of the engines and the subsequent standardisation to a comparable unit allows the rendition of two graphs, showing the development of each manufacturer in terms of fuel consumption (Figure 1 and Table 1) and power (Figure 2 and Table 2). These initial graphs do neither distinguish the different car classes nor the different types of fuel, but they conveniently show the overall performance of each manufacturer. As becomes apparent, despite a certain degree of deviation especially concerning the development of fuel consumption, in both cases there exists a clear tendency upward or downward respectively.

Furthermore, it can be noted that the differences between the manufacturers in terms of power are not as pronounced over the whole period as the differences between the manufacturers regarding fuel consumption. Instead, after showing a remarkable homogeneity especially in the first three years, with only BMW and Jaguar significantly deviating from the rest, the overall tendency here appears to be towards a stronger scattering towards the end of the time period with remarkable outliers in form of Volvo and Jaguar.

Fuel consumption however, shows a stronger scattering overall, with most turbulence in the middle of the period, characterised by significant deflections from Nissan. Towards the end of the period, a tendency towards approximation on an overall lower level can be observed. In addition, due to the stronger overall deviation within the industry, the individual developments can be identified more easily, with certain manufacturers such as Peugeot showing a more gradual improvement, whereas others, such as Volvo, are characterised by sudden steep steps.

Overall, it can be noted that each manufacturer, even Nissan, regarding its unusual spikes in fuel consumption mid period, eventually achieved an improvement in both variables. Furthermore, at least in fuel consumption, a certain set of leaders can be identified. Jaguar, Mercedes, BMW and Volvo show a rather isolated group at an overall lower level of consumption throughout the whole period, characterised by a strong approximation towards the end of the period.

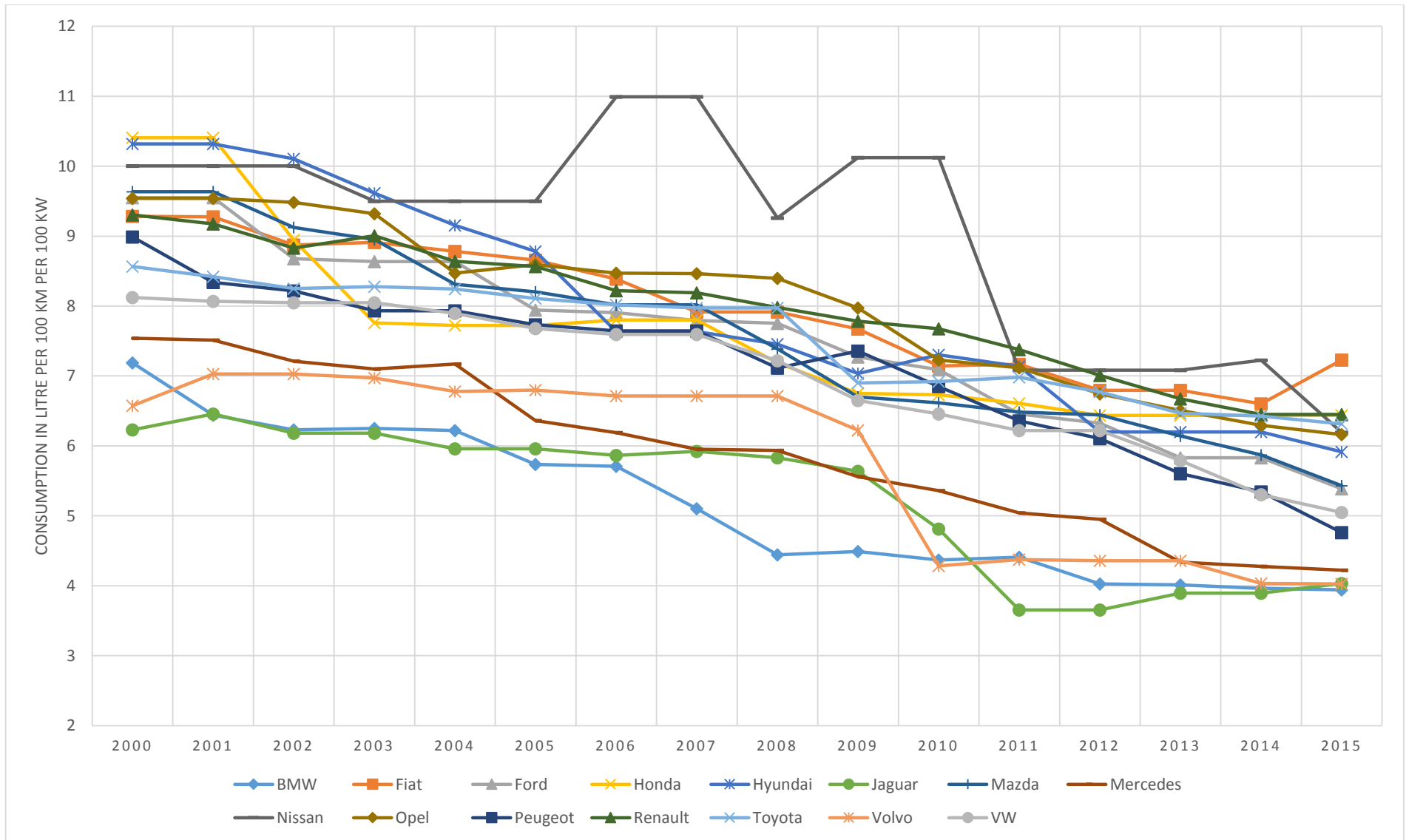


Figure 1: Fuel consumption in litre/100 km per 100 kW engine power per manufacturer, 2000 - 2015

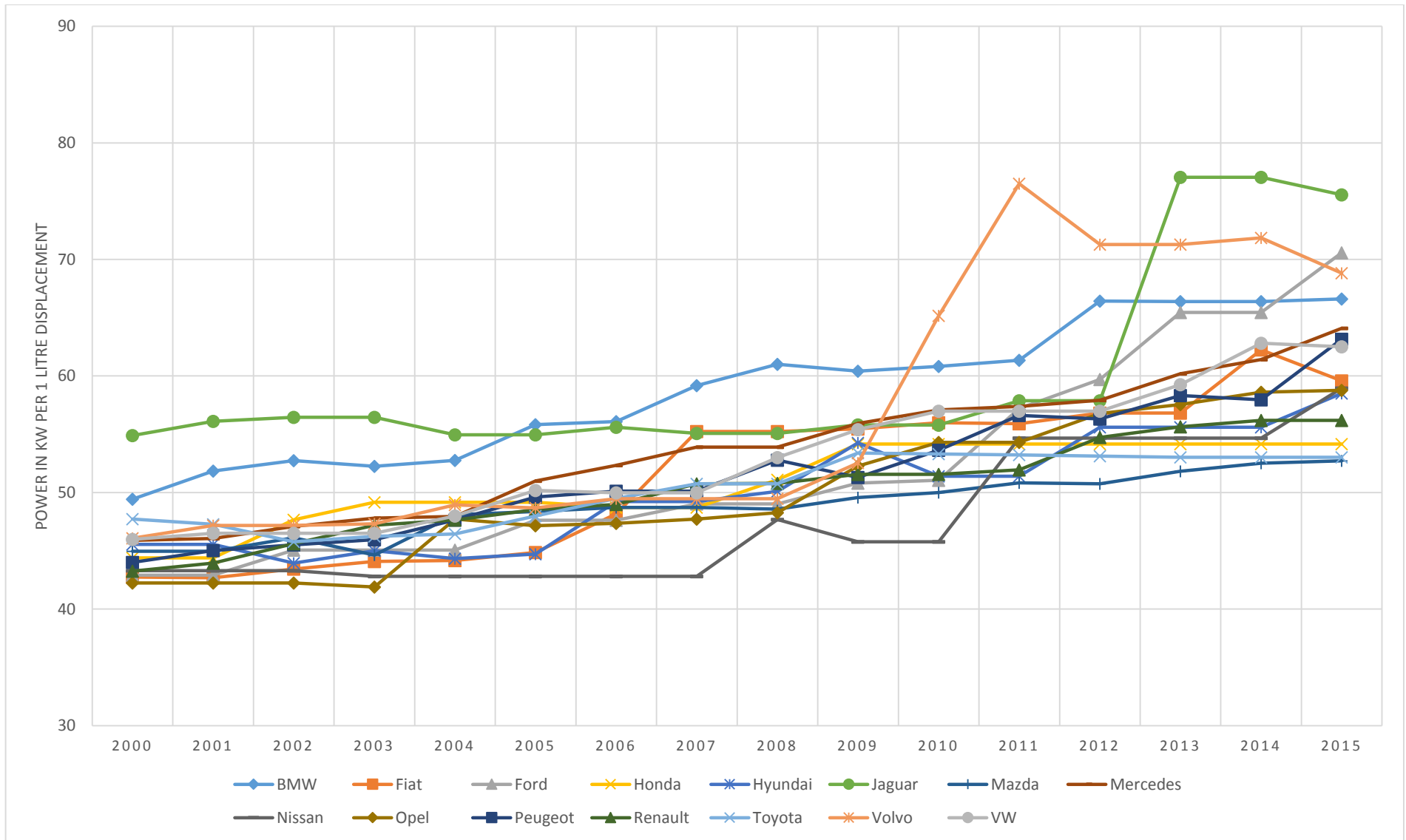


Figure 2: Engine power in kW per 1 litre displacement per manufacturer, 2000 – 2015

consumption manufacturers	years																
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
BMW	7,1894	6,4411	6,2300	6,2492	6,2210	5,7367	5,7081	5,1014	4,4427	4,4900	4,3694	4,4092	4,0280	4,0135	3,9625	3,9407	<b>5,1528</b>
Fiat	9,2842	9,2766	8,8733	8,9109	8,7817	8,6567	8,3871	7,9167	7,9167	7,6702	7,1427	7,1682	6,7938	6,7938	6,6014	7,2293	<b>7,9880</b>
Ford	9,5489	9,5489	8,6786	8,6355	8,6355	7,9438	7,9055	7,7920	7,7545	7,2712	7,0886	6,4552	6,3241	5,8317	5,8317	5,3883	<b>7,5142</b>
Honda	10,4052	10,4052	8,9429	7,7596	7,7217	7,7217	7,7996	7,7996	7,1893	6,7523	6,7295	6,6087	6,4374	6,4374	6,4374	6,4374	<b>7,4850</b>
Hyundai	10,3182	10,3182	10,1068	9,6128	9,1535	8,7815	7,6350	7,6350	7,4554	7,0339	7,3027	7,1386	6,1995	6,1995	6,1995	5,9167	<b>7,6107</b>
Jaguar	6,2296	6,4562	6,1828	6,1828	5,9589	5,9589	5,8639	5,9212	5,8293	5,6383	4,8128	3,6560	3,6560	3,8954	3,8954	4,0320	<b>5,4405</b>
Mazda	9,6334	9,6334	9,1234	8,9499	8,3118	8,2024	8,0170	8,0170	7,3883	6,7012	6,6148	6,4840	6,4436	6,1428	5,8705	5,4326	<b>7,4834</b>
Mercedes	7,5392	7,5126	7,2126	7,0990	7,1692	6,3621	6,1889	5,9518	5,9362	5,5591	5,3587	5,0407	4,9493	4,3389	4,2786	4,2235	<b>5,9688</b>
Nissan	10,0039	10,0039	10,0039	9,5007	9,5007	9,5007	10,9920	10,9920	9,2594	10,1237	10,1237	7,0845	7,0845	7,0845	7,2234	6,1934	<b>9,1506</b>
Opel	9,5394	9,5394	9,4826	9,3214	8,4714	8,5915	8,4722	8,4648	8,3957	7,9716	7,2290	7,1177	6,7437	6,5087	6,2929	6,1606	<b>8,0351</b>
Peugeot	8,9890	8,3398	8,2154	7,9338	7,9333	7,7332	7,6437	7,6437	7,1145	7,3580	6,8493	6,3598	6,1053	5,6035	5,3445	4,7617	<b>7,1442</b>
Renault	9,3023	9,1735	8,8302	9,0060	8,6404	8,5640	8,2184	8,1907	7,9788	7,7841	7,6735	7,3784	7,0074	6,6724	6,4512	6,4512	<b>7,9264</b>
Toyota	8,5642	8,4195	8,2503	8,2770	8,2439	8,1075	8,0154	7,9718	7,9718	6,8988	6,9199	6,9822	6,7722	6,4677	6,4266	6,3135	<b>7,4963</b>
Volvo	6,5762	7,0303	7,0303	6,9728	6,7780	6,8002	6,7156	6,7156	6,7156	6,2228	4,2844	4,3740	4,3592	4,3592	4,0322	4,0253	<b>5,8886</b>
VW	8,1220	8,0690	8,0487	8,0487	7,8961	7,6785	7,5952	7,5952	7,2179	6,6511	6,4582	6,2183	6,2183	5,7886	5,3022	5,0498	<b>6,9973</b>
<b>Total</b>	<b>8,6116</b>	<b>8,3837</b>	<b>8,1735</b>	<b>8,0261</b>	<b>7,8625</b>	<b>7,5800</b>	<b>7,4002</b>	<b>7,2647</b>	<b>7,0358</b>	<b>6,6933</b>	<b>6,4908</b>	<b>6,1421</b>	<b>5,9055</b>	<b>5,6386</b>	<b>5,4668</b>	<b>5,2537</b>	<b>6,9926</b>

Table 1: Average consumption (in litre/100 km per 100 kW engine power)

power manufacturers	years																
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
BMW	49,4311	51,8497	52,7311	52,2583	52,7525	55,8363	56,0933	59,1700	61,0092	60,4068	60,8319	61,3526	66,4206	66,3927	66,3927	66,6016	<b>58,7346</b>
Fiat	42,7519	42,6861	43,4402	44,0948	44,1757	44,8602	48,1610	55,2387	55,2387	55,4545	55,9895	55,9133	56,8296	56,8296	62,2385	59,5808	<b>51,2336</b>
Ford	42,9212	42,9212	45,0740	45,0740	45,0740	47,6177	47,6177	49,0191	49,0191	50,8011	51,0575	57,2000	59,7072	65,4527	65,4527	70,5638	<b>52,2778</b>
Honda	44,3840	44,3840	47,6558	49,1561	49,1561	49,1561	48,7258	48,7258	51,0986	54,1614	54,1614	54,1614	54,1614	54,1614	54,1614	54,1614	<b>50,9814</b>
Hyundai	45,5446	45,5446	43,9572	45,0012	44,3232	44,7187	49,2312	49,2312	50,0929	54,2545	51,3991	51,3991	55,5982	55,5982	55,5982	58,5037	<b>50,7441</b>
Jaguar	54,8915	56,1146	56,4625	56,4625	54,9634	54,9634	55,5996	55,0688	55,0688	55,8034	55,7899	57,8690	57,8690	77,0516	77,0516	75,5443	<b>59,2633</b>
Mazda	44,9640	44,9640	46,1116	44,6299	48,0849	48,3707	48,7282	48,7282	48,5682	49,5780	50,0067	50,8309	50,7595	51,8258	52,5177	52,7140	<b>48,9735</b>
Mercedes	45,9042	46,0522	47,0972	47,8104	47,9559	50,9993	52,3333	53,8939	53,8939	55,9343	57,0828	57,3837	57,9217	60,1930	61,4118	64,0918	<b>53,5094</b>
Nissan	43,2927	43,2927	43,2927	42,8007	42,8007	42,8007	42,8036	42,8036	47,6799	45,7771	45,7771	54,6745	54,6745	54,6745	54,6745	58,9503	<b>46,8583</b>
Opel	42,2421	42,2421	42,2421	41,8903	47,7299	47,1579	47,3665	47,7226	48,2789	52,2665	54,3099	54,3099	56,7901	57,5617	58,5988	58,7638	<b>49,9008</b>
Peugeot	44,0140	45,0137	45,5040	45,9611	47,6434	49,6169	50,1230	50,1230	52,7807	51,2998	53,6325	56,6247	56,3160	58,3164	57,9571	63,1493	<b>51,6348</b>
Renault	43,2630	43,9505	45,6054	47,2061	47,6366	48,5379	48,9871	50,7431	50,7853	51,5615	51,5615	51,9502	54,7398	55,6382	56,1931	56,1931	<b>50,4275</b>
Toyota	47,7210	47,2830	45,7782	46,2500	46,4505	47,9809	49,4890	50,7445	50,7445	53,3800	53,3047	53,2295	53,1294	53,0293	53,0293	53,0293	<b>50,4024</b>
Volvo	46,0805	47,1681	47,1681	47,3115	48,9368	48,6869	49,4643	49,4643	49,4643	52,5437	65,1751	76,5017	71,2820	71,2820	71,8565	68,8167	<b>56,6240</b>
VW	45,9711	46,4985	46,4985	46,4985	47,9965	50,1771	49,9794	49,9794	53,0065	55,4069	56,9801	56,9801	56,9801	59,2646	62,8062	62,5001	<b>52,9702</b>
<b>Total</b>	<b>45,3329</b>	<b>46,0189</b>	<b>46,5287</b>	<b>46,8640</b>	<b>47,8775</b>	<b>49,3573</b>	<b>50,3233</b>	<b>51,6058</b>	<b>52,4360</b>	<b>53,9682</b>	<b>54,7286</b>	<b>56,5109</b>	<b>57,8468</b>	<b>59,5656</b>	<b>60,5763</b>	<b>61,9332</b>	<b>52,5962</b>

Table 2: Average power (in kW per 1 litre displacement)

This isolation cannot be found in regard to power development, however the mentioned firms dominating the consumption also show a strong performance in terms of power, with the exception of Mercedes, which are considerably closer to the mainstream. Volvo here is a remarkable case with an indistinguishable performance up until 2010, when a sudden rise occurs, surpassing the overall stable and high performing BMW. Jaguar showed a better initial performance, being on par with BMW but then experiencing a period of slump with virtually no development, only emerging the mainstream in a similar way to Volvo in 2012. Lastly, it can be concluded that overall both variables show a similar extent in development and an almost parallel progress. Overall, there can be no clear preference identified towards one variable.

This data from the two variables can be further combined to improve the visualisation of the findings. In calculating the percentage annual change in values for both variables per each manufacturer and from this building an overall average percentage annual change for both variables across the entire period and plotting these on a scatter diagram, the improvement of each manufacturer in both variables becomes both apparent and comparable. Besides the previously shown data that focusses on absolute values, this approach does also show the relative rate of improvement, thus further revealing the performance of the manufacturers.

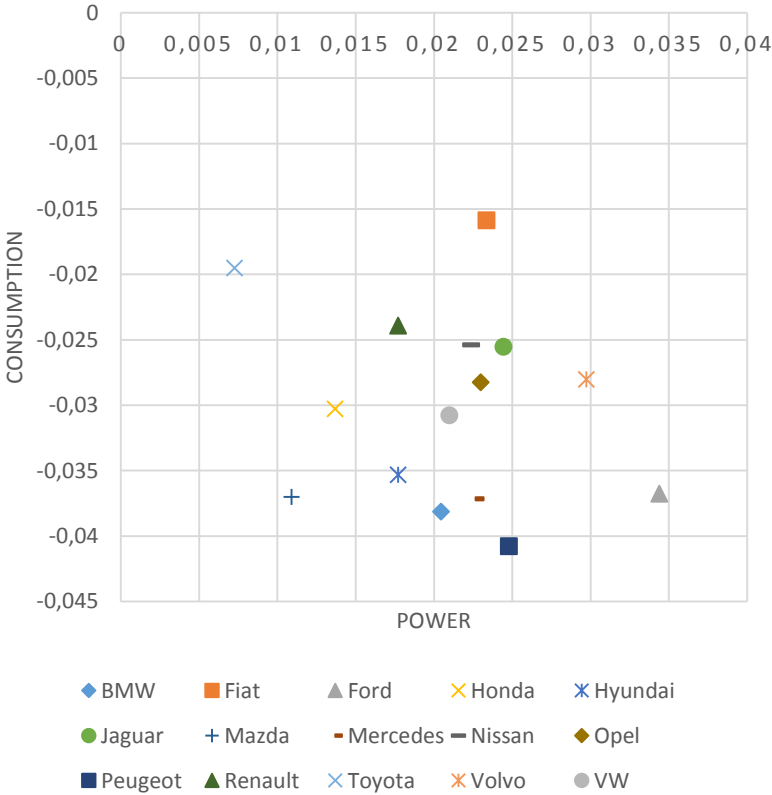


Figure 3: Overall annual percentage change in both consumption and power

This for example reveals a strong performance in relative improvement from Peugeot, which otherwise does not become as apparent from the figures with absolute values. Furthermore, this direct comparison of values reveals the tendency each manufacturer shows in the rate of improvement to either variable. Here, a majority of manufacturers shows a tendency to stronger improvement in terms of fuel consumption than in power.

From this information and keeping in mind that these manufacturers account for the vast majority of the car market, it is now possible to forge the data into a new graph in order to plot the trajectory, therefore visualising the direction of innovation. The corresponding two figures (Figure 4 & Figure 5) show both industry-wide development in both fuel consumption and power across all car classes and distinguishing between both petrol and diesel. Below both figures, the corresponding development across the entire period in percent is given.

This visualisation of the overall industry-wide development confirms what was already hinted in the previous figures on all individual manufacturers. Especially overall, there is a steady improvement in both variables, almost linear and remarkably equal in extent. The distinction between both types of fuel offers a certain improvement in level of detail of industry observation.

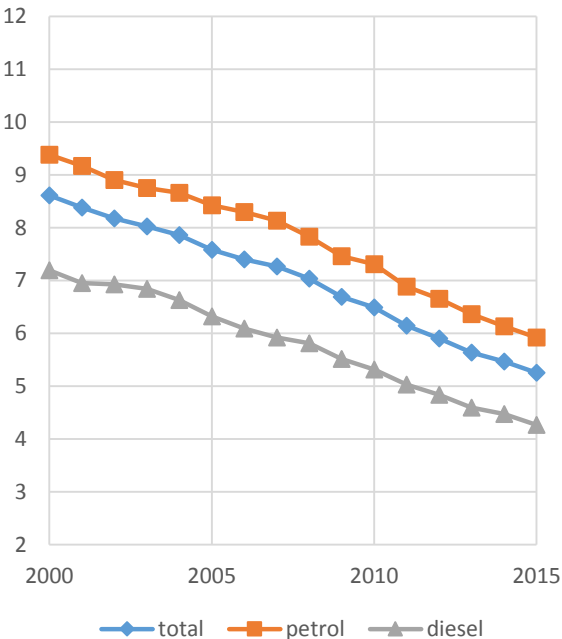


Figure 4: Consumption, all manufacturers, all classes

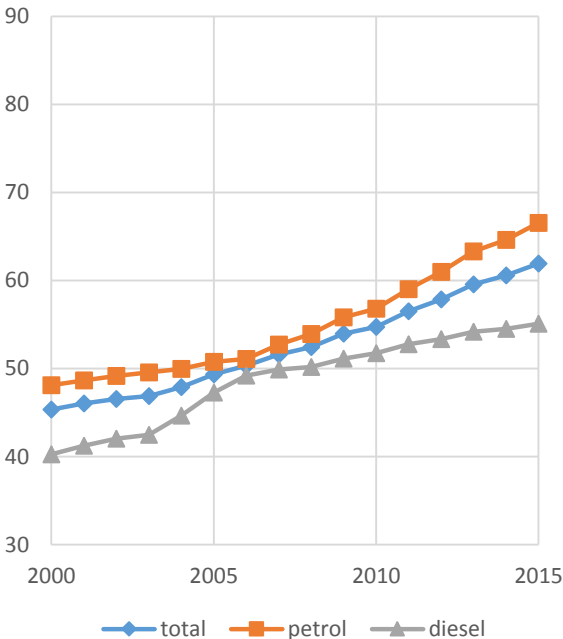


Figure 5: Power, all manufacturers, all classes

**-39%**      **-37%**      **-41%**      **37%**      **38%**      **37%** |

In terms of consumption, it becomes apparent that overall engines of both fuel types improved rather parallel, no clear preference can be identified. However, from the percentage numbers, a slight advantage in terms of consumption can be found for the diesel engine (+2 %), marginally narrowing the gap between both fuel types. In terms of power, there is a different result, showing an



initial concentration in progress in diesel engines, leading to almost a closure of the gap between the two fuel types around 2006 after a strong increase within only three years. Then, however, the rate of improvement could not be maintained in diesel engines and as petrol-powered engines improved their power at an increasing rate, diesel progress stabilised at a lower rate, further enlarging the gap between the two. Eventually, this leads to an almost identical percentage of improvement. The indication from this graph is that diesel engines, despite their initial upsurge in power performance, cannot keep pace with the incipient technology push in petrol engines accelerating power performance development mid-period.

Overall, this leads to a sound initial overview of the basic development of the industry and results in trajectories revealing the direction of technological change for both variables. As apparent, both trajectories in total are fairly linear and even when distinguishing between the two fuel types, a difference becomes only apparent in power performance, suggesting the approach of a technological ceiling for this fuel type. For a more detailed insight into the innovative performance of the different manufacturers, the trajectories are subdivided into the different car classes. The existence of a technical ceiling for diesel engines would thus become apparent, as would other characteristic features of the trajectories.

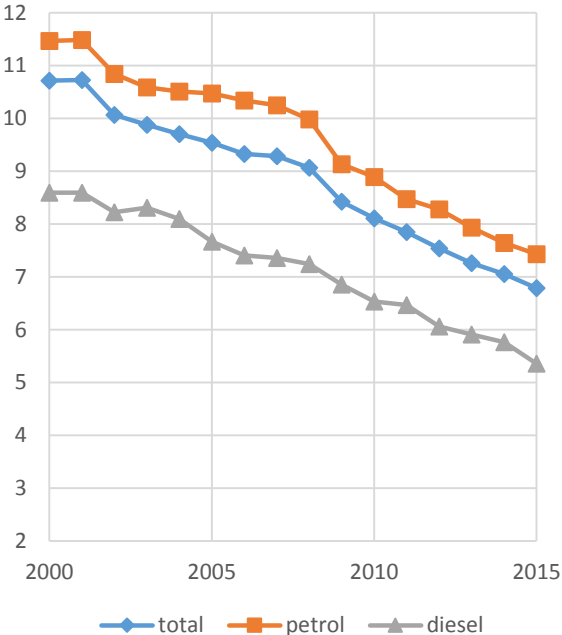


Figure 6: Consumption, all manufacturers, class B

-37%      -35%      -38%

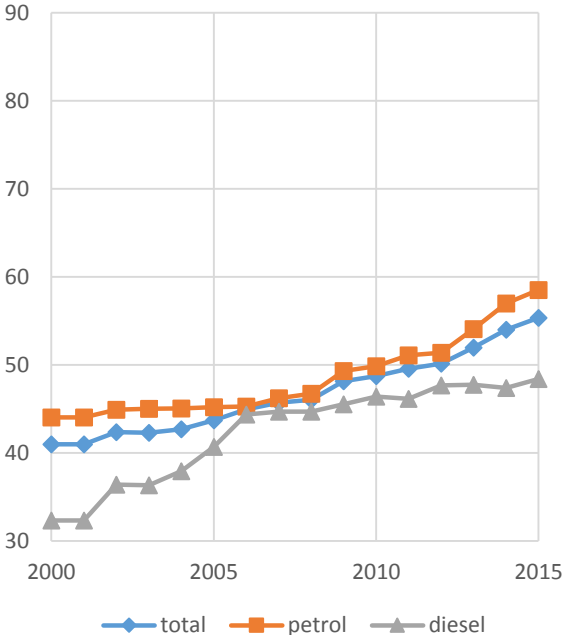


Figure 7: Power, all manufacturers, class B

35%      33%      50%

The smallest class of cars in this survey, class B, which corresponds to VW Polo / Ford Fiesta, instantly shows the value of the further subdivision of the overall results for all classes. As can be seen in the corresponding charts (Figure 6 & Figure 7), the results in this class are skewed from the overall

results. The consumption for both fuel types starts at a remarkably higher fuel consumption, emphasising the importance of repeatedly pointing out that both variables are converted into relative figures as explained in 3.2. Hence, these smaller cars do not show a *real* higher fuel consumption than the average, but a higher *relative* consumption.

Overall, the consumption starts at a far higher level for both fuel types, with the difference between both fuel types being more pronounced than across all classes. The progress along the period resembles the all-classes progress, featuring one significant leap of petrol progress between 2008 and 2009. Eventually, however, as the percentage numbers show, both fuel types improve almost equally well as overall, with diesel engines being 3 % stronger in improvement here instead of the 2 % overall. Furthermore, the imbalance between diesel and petrol engines in this class becomes apparent from the shift of the total curve towards the higher petrol curve. As diesel engines were not as widely spread as in other classes, at least at the beginning of the period, the diesel sample is subsequently smaller.

The development of power performance shows similarities to the consumption figures, again showing a lower overall level as compared to the overall figures. The progress itself of the curves however comply with the observations made in the overall figures, also showing an initial catch-up process of the diesel engine, resulting in almost equality between both fuel types, followed by an onset in petrol performance development that the diesel cannot pursue. As above. Instead the diesels' performance remains at a slower rate and even shows signs of stagnation towards the end of the period, whereas the petrol engines show another big leap towards the end of the period. Furthermore, the remarkable low start of diesel performance at the beginning of the period has to be pointed out, almost only reaching 75 % of the levels of the overall figures. This low start, followed by the early and steep leap explains the variations of percentage improvements in this class as compared to overall. While petrol motors show a weaker development in this class, (-5 %), diesel engines achieve an improvement of 50 %, surpassing overall figures by 13 %.

The following class can be considered the most popular and most important class. Class C cars include bestsellers such as the VW Golf or Peugeot 308 and this class is served by most manufacturers, be it those that rather focus on smaller and cheaper cars or those that normally offer bigger and expensive cars. Hence, it can be regarded as the class with most competition and therefore biggest pressure to innovate.

This importance and dominance is mirrored in the charts (Figure 8 & Figure 9), showing a close resemblance to the overall development in both progress but also values. As before, the consumption shows the more steady development, with the absence of larger leaps. Only initially, a

stronger leap can be identified in diesel engines, but over the whole period, both fuel types show a stable development with neither major leaps nor signs of stagnation. The percentage improvements are in total only 1 % better than overall, as the diesel engines improved by 43 % rather than 41 %.

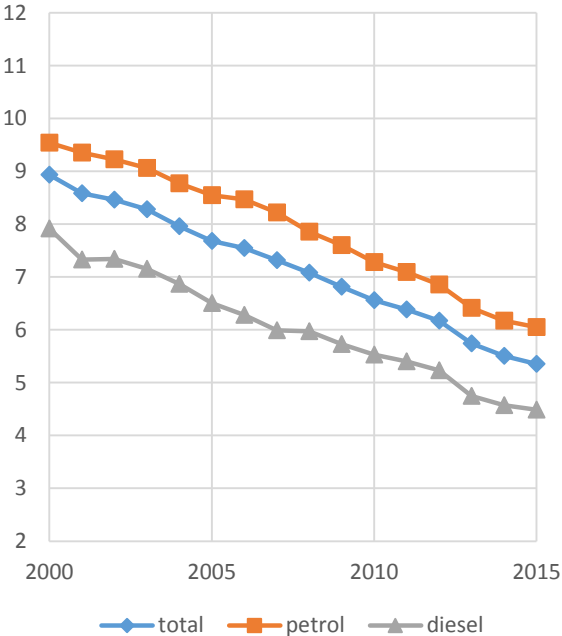


Figure 8: Consumption, all manufacturers, class C

**-40%**      **-37%**      **-43%**

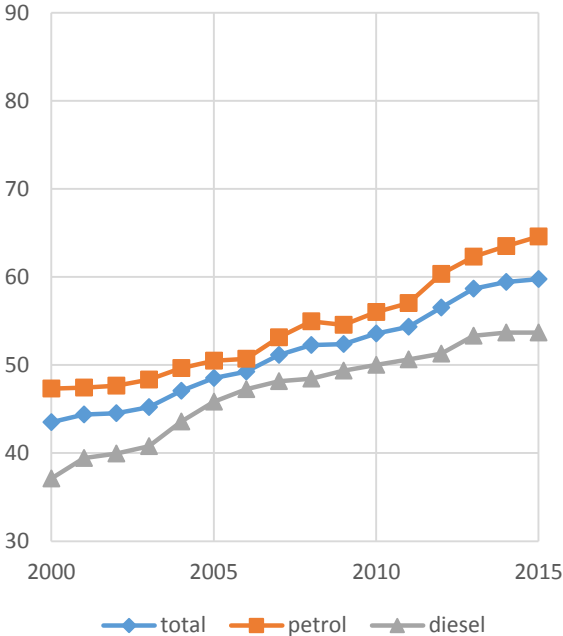


Figure 9: Power, all manufacturers, class C

**37%**      **37%**      **45%** |

In terms of power, again a similar pattern to the overall data can be seen. An initial surge in diesel performance, narrowing the gap, is followed by a rise in petrol performance, leading to an increasing distance between both fuel types. However, diesel development does not set in as abruptly as in class B or as late as overall, but instead shows a gradual progression, indicating an innovative process already at work at the beginning of the period. Furthermore, the approximation between both fuel types mid-period is not as pronounced as in the previous charts and the following upsurge in petrol technology is both stronger and irregular, with distinctive steps being identifiable. Stagnation in diesel technology can also be identified, however at a very late stage of the period and only after another significant step upwards. In total percentage figures, class C developed identical to all classes combined at 37 % improvement. However, as in class B, the development is skewed towards diesel engines, although not as distinct, with diesel engines improving by 45 % as compared to 37 % overall.

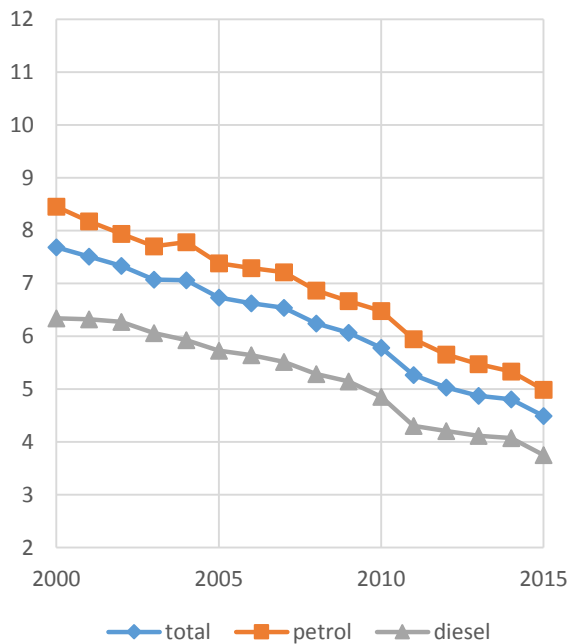


Figure 10: Consumption, all manufacturers, class D

-42%      -41%      -41%

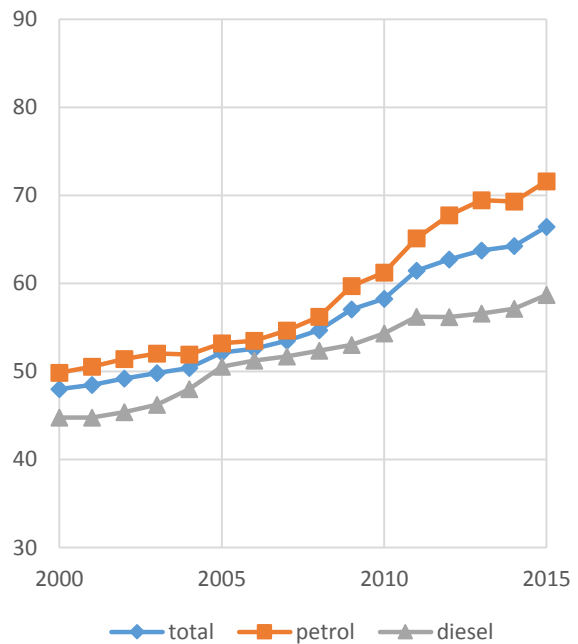


Figure 11: Power, all manufacturers, class D

38%      44%      31%

The following class, consisting of cars such as the 3 series by BMW or the Volvo S60 shows different results than the previous two classes. As becomes apparent from the related graphs (Figure 10 & Figure 11), the curve shapes show a stronger resemblance to those of the overall data. In contrast to the previous classes, the consumption data does not show the characteristic initial focus on diesel development. Instead petrol engines are advancing at a higher rate before being interrupted by a peculiar outlier in 2004, after which it took a couple of years to gain momentum again. The diesel engines, although progressing gradually for the first two thirds of the period, match this velocity only with the big step they make between 2010 and 2011, before again showing signs of slowing. However, as the last entry for 2015 proves, the stagnating tendencies of the neighbouring class C are not shown. The percentage change in consumption is in equilibrium, with both fuel types improving by 41 %.

Development in power shows a relatively late and subtle start in diesel engines, while petrol engines at the beginning of the period are showing a higher development rate than in the lower classes. As before, the comparably stronger development in diesel engines narrows the gap between both fuel types towards a minimum between 2005 and 2006, earlier than in class B and narrower than in class C, before development in petrol engines rises here too. Here, however, the development in petrol engines is far more pronounced than in the previous classes, also excelling the combined average classes, leading to a growing gap between both fuel types, despite diesel engines also showing a stronger development than the two lower classes and on average. Furthermore, diesel engines show

no sign of stagnation towards the end at a level significantly higher than the previous classes. Interestingly, when looking at the percentage improvement in power for this class, the total almost is the same as the previous class at 38 %, however instead of diesel engines, here petrol engines see the higher progress with 44% as compared to 31 % in diesel engines, therefore offering an inversed picture of the previous class.

Lastly, the biggest class in this survey, class E containing cars such as the Mercedes E class or the Jaguar XF shows the most interesting data variation as compared to the average figures. As becomes apparent from the graphs (Figure 12 & Figure 13), the total values resemble those of all classes combined, but the distinction between the two fuel types reveals differences in this class as compared to the previous smaller classes.

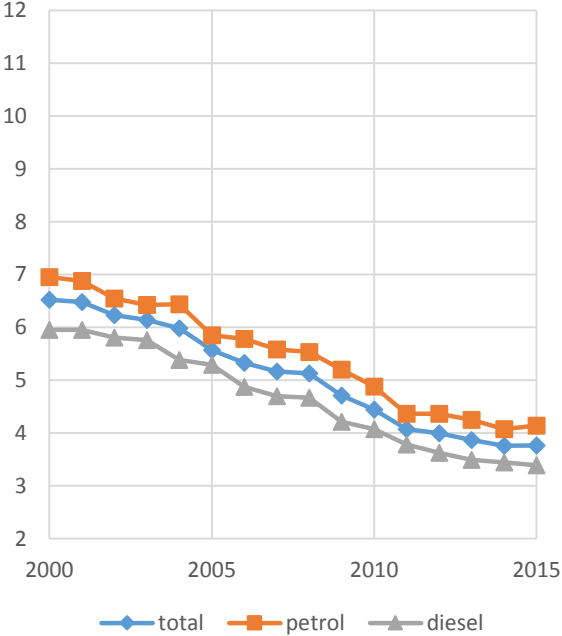


Figure 12: Consumption, all manufacturers, class E

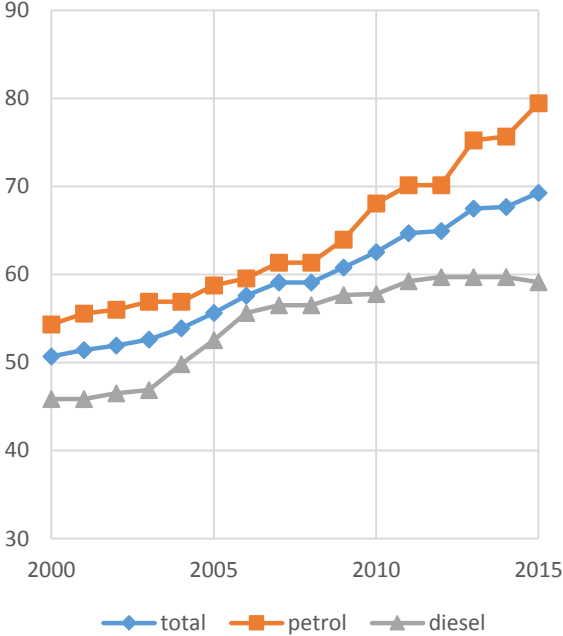


Figure 13: Power, all manufacturers, class E

**-42%**      **-40%**      **-43%**                      **37%**      **46%**      **29%** |

Most notably, in terms of fuel consumption, there is a strong proximity between petrol and diesel engines, with roughly one litre difference as compared to the approximately 3 litres at the beginning of the period in class B. Not only are both fuel types remarkably close to each other throughout the whole time period, but also show almost parallel development with only small occasional steps in individual years. Eventually, both fuel types show a tendency towards stagnation in the last years of the period at a noticeably low level of fuel consumption. In percentages, the class shows as much improvement as adjacent class D at 42 %.

As mentioned, for the development in power, the total figures resemble those of both the previous classes as those of the overall average. However, the two fuel types develop rather differently here as previously. Diesel engines show a rather slow development in power at the beginning, as in class D, however the emerging development gains more momentum as in the neighbouring smaller class up until 2006, while petrol engines in this period show only weak development. After three years of relative parallelism, yet maintaining a bigger gap between the two than in class D, the upsurge of diesel engines is mirrored by a corresponding upsurge in petrol engines in two steps until 2015 up to almost 80 kW per litre displacement, leaving the diesel engines far behind. Those, interestingly, were not able to keep the pace of the first half of the period and showed clear signs of stagnation and even decline at around 60 kW in 2015. It should be noted that this roughly equals the value at which diesel engines of the lower class D also showed signs of stagnation, supporting the notion of a technological frontier around this level. As before, the percentage figures reveal a concentration in power progression in petrol engines, even more pronounced than in class D, with 46 % increase in petrol engines, as opposed to only 29 % in diesel engines, the lowest growth of diesel power of all classes.

Overall, these figures give an idea of the technological performance within the industry, hence revealing the technical innovation potential within this period. Not only do they reveal the general path the development has taken in the entire industry, but also offer insights on where technical progress was steered at in the different classes. Diesel engines saw their biggest innovative potential in terms of power growth in the smallest class of cars, doubling average power in only 15 years, whereas the same almost holds true for petrol engines in the largest class. Interestingly, this dispersion across the classes cannot be seen in the consumption figures. Here, innovation occurred much more linear, with both fuel types showing similar rates of improvement and also across all classes. Considering power to be the more emotional variable of the two, this might indicate a conscious concentration from the manufacturers on the fuel types in each class to fulfil customer needs, whereas the overall linear reduction in consumption hints for a larger scale reason equally effective across all classes and fuel types, such as a policy. After having revealed what general innovation in the automotive sector means, it is now possible to compare the individual performance of the manufacturers with this.

## 4.2 Technical Performance

In the following, the individual manufacturers will be examined. For this purpose, general charts according to the previous charts across all classes are shown. For further enhancement, class-specific graphs are also shown, comparing the manufacturer's performance in this class with the overall average of all manufacturers. For the purpose of maintaining clarity and simplicity within this work, these class-specific graphs are shown in the appendix and referred to accordingly.

### 4.2.1 BMW

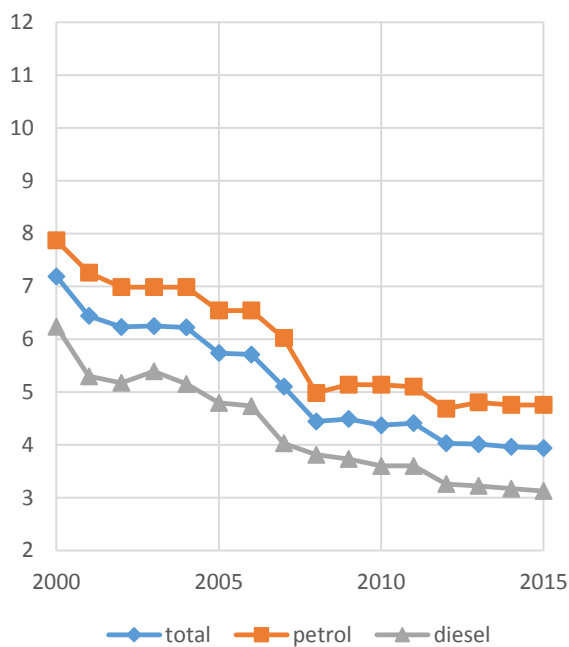


Figure 14: Consumption, BMW, all classes

**-45%**      **-40%**      **-50%**

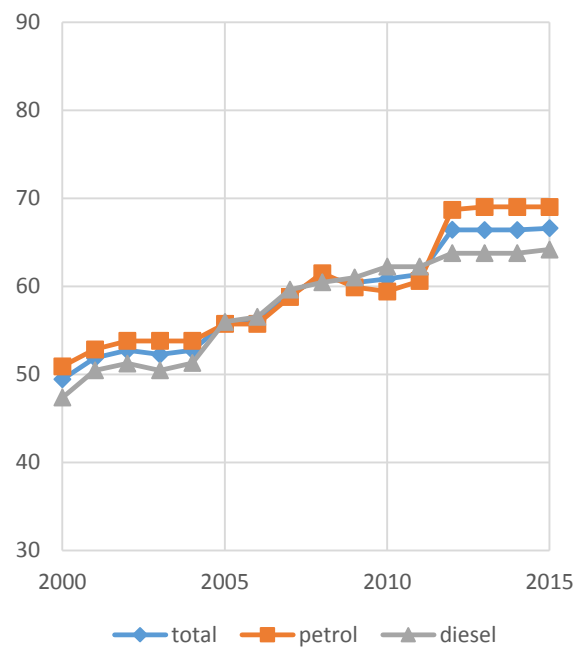


Figure 15: Power, BMW, all classes

**35%**      **36%**      **36%** |

As already mentioned when looking at the overall performance in 4.1, BMW shows a strong performance as compared to the manufacturer average. In terms of consumption, they are already 1.5 litres ahead of the average at the beginning of the period, indicating a strong innovative potential that already has been successfully used before the time period. Throughout the period, BMW succeeds to accomplish significant improvements in terms of fuel consumption at a rather early stage. Towards the end however, these gains show signs of stagnation, especially visible in two distinctive plateaus forming for petrol engines from 2008 onwards, showing no progress since 2012, yet at a remarkably low level. This is also mirrored in the percentage figures of improvement, showing above average improvement in all fuel types (-45% as compared to -39% in total) and a

strong focus of improvement for diesel engines, where they achieve cutting consumption to 50 %, nearly 10 % more than the average.

Power is characterised by a remarkable proximity of both fuel types across the period and even showing equality mid-period, before a steep development in petrol engines leads to a bigger gap between both types. Percentage-wise, the development does not exceed the overall development, however despite the four years of stagnation in both fuel types, the nominal values stay above the average.

In terms of classes, BMW is only present in the three biggest classes (Figure 48 – Figure 53). Here, throughout all classes, a performance above average is shown. Interestingly, the performance nominally does not vary strongly across the classes, showing similar figures and development in consumption and power across all classes. This does indicate a broad use of researched technology, as they manage to improve their variously sized engines across their classes towards a similar level of technology. At the average figures, in contrast, especially the smaller engines show worse technical figures than the bigger engines. Hence, the comparative advantage of BMW is more pronounced in the smaller classes and is only marginal in the biggest class E, where the competitors achieve a similar level in both categories. Even in the smaller classes, the late phases of stagnation cancel out the initial strong performances, leading to an overall percentage advantage of roughly 10 % in the smallest class and virtually no advantage in class D. This could either indicate a general technical ceiling that BMW reached beforehand and others later approached too, or BMW losing its innovative potential, thus experiencing a *personal technical ceiling*. While BMW is still maintaining a slight advantage, both could hold true and so far do not impose an imminent threat, but as soon as the other manufacturers manage to further improve their values, thus disproving the existence of a general technical frontier and revealing the problems to lie within the company.

#### 4.2.2 Fiat

Fiat is a manufacturer more focussed on the smaller cars and revealing larger gaps in its highest class D. In an attempt of consolidation, the range of products has been reduced throughout the whole period of assessment, focussing on successful models at the lower end of the size scope. The current restart with modernised bigger models from 2016 onwards was not captured in this work, thus leading to results characterised by the shrinking and omitting the regrowth that is yet to come.

The results for Fiat (Figure 16 & Figure 17) show a stark contrast to the overall figures and especially those of BMW before. Development seems more erratic and inconsistent, as both variables show a



phase of negative development at the end of the period for both fuel types. Although especially concerning power, the data shows remarkable steps in both types between 2005 and 2007, when a new generation of innovative turbo engines was introduced, the curves are also characterised by pronounced phases of stagnation.

The development in consumption seems less drastic, but more linear, with only one major step corresponding the petrol development between 2006 and 2007 linked to the aforementioned turbo engines. Nevertheless, stagnation towards the end of the period, not to mention the final rise, occurs at roughly one litre above the average at all fuel types.

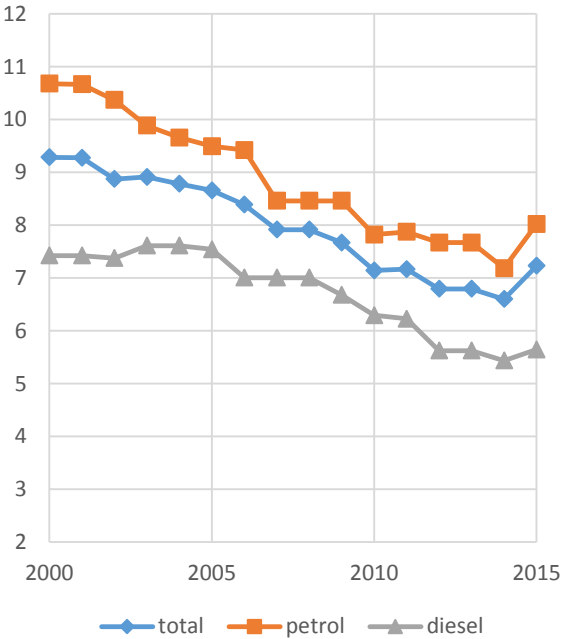


Figure 16: Consumption, Fiat, all classes

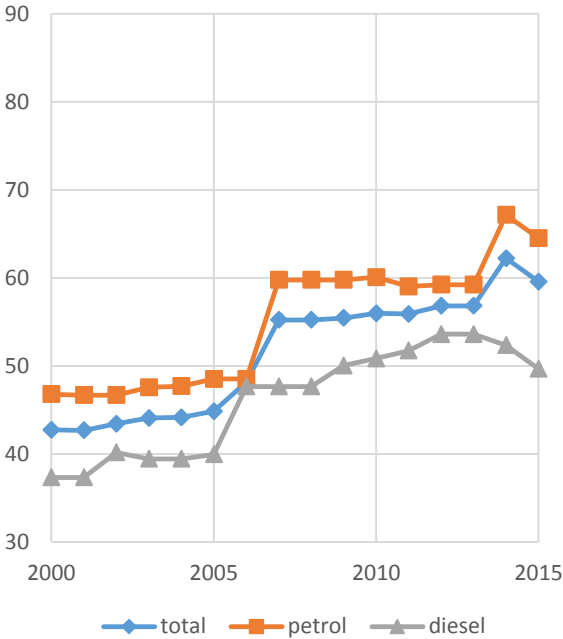


Figure 17: Power, Fiat, all classes

-22%      -25%      -24%      39%      38%      33% |

When looking at the class-specific data (Figure 54 – Figure 59), the picture improves slightly. In its main classes B and C, Fiat shows a robust performance. Consumption in these classes is characterised by a development according to the average, resulting in a strong overlap of both curves and Fiat’s curve oscillating around the average curve. Here, the explanation for the rise in values for Fiat’s overall graph becomes apparent. As bigger models and their engines were cancelled, the weight of the comparably worse smaller engines increased, leading to a rise on overall figures, which is not mirrored in the class-specific performance.

In terms of power, the smallest class is characterised by a distinct catch-up throughout the entire period, starting below average and ending above, resulting in a remarkable percentage increase in power of 80 %. The bigger class C is characterised by an overall better performance as compared to

the average across the whole period and by the protruding step caused by the introduction of said innovative engine generation. Overall and percentage-wise, the performance can be considered comparable to the average. The last figures for class D possibly explain the reasons for the restructuring of the range of models in favour of the smaller models. In terms of consumption, Fiat's models have never been better than the average and even in terms of power, there was only a short phase of competitiveness after the introduction of the new motors, which however did not lead to the initialisation of momentum to keep pace with the overall development pace. As already mentioned, the average engines of the higher classes are technically on a higher level than the smaller, so it was only consequent of Fiat to retreat from this segment given the available technology.

4.2.3 Ford

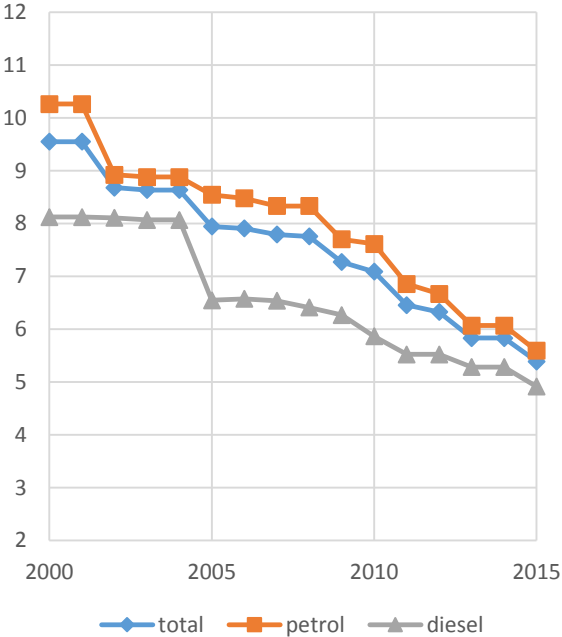


Figure 18: Consumption, Ford, all classes

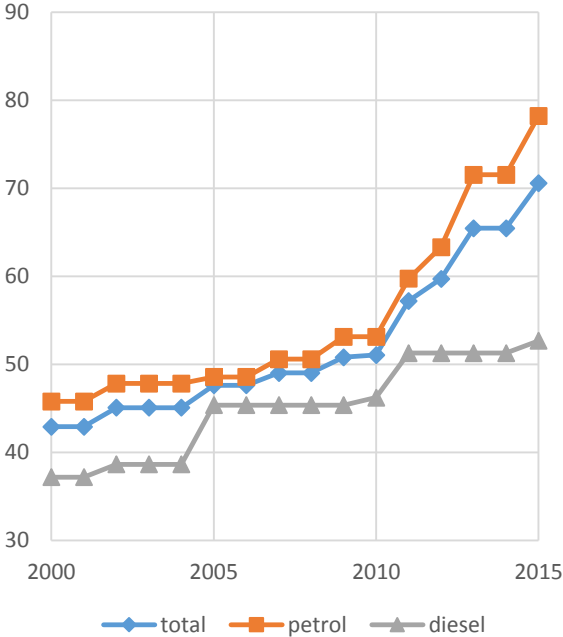


Figure 19: Power, Ford, all classes

-44%      -46%      -39%      64%      71%      42%

Ford is a rather versatile manufacturer that is strong in both the lower and the bigger size classes, although not present in the biggest class E. As becomes apparent from the graphs (Figure 18 & Figure 19), their development is characterised by a strong performance in both categories. Despite starting with total consumption values of approximately one litre above the average, they manage to achieve average values at the end of the period. Not excelling average values is due to the comparably poor performance in diesel engine development, which is characterised by a big step between 2004 and

2005, but otherwise rather mediocre development. Both combined lead to a percentage improvement almost reaching average values (-39 % as compared to -41 %). Petrol engines however, show a 9 % higher improvement rate than average, indicating a strong focus on petrol engines.

This focus can even clearer be identified when looking at power development. Whereas diesel engines show only two distinctive steps of improvement and otherwise rather stagnating progress, petrol engine development is characterised by extraordinary progress from 2010 onwards that does not show any sign of stagnating or even slowing tendencies. Furthermore, the clear focus on petrol engines can be clearly identified by the shift of the total curve closely towards the petrol curve.

Overall, Ford achieves a total power improvement of 64 %, as compared to 37 % by all manufacturers and even 71 % in petrol engines as opposed to only 38 %, nearly doubling the average.

Class-wise, the focus of Ford on improvement in terms of power becomes apparent. The consumption development across the classes mirror previously experienced patterns. The development of the smallest class is characterised by a successful development from initial above-average values towards below-average figures, while the middle class C shows a development oscillating around the average curve, with initial and final values equalling average values. The biggest class is characterised by consumption development above average throughout the entire period, despite the technological advances.

In terms of power however, the strong potential from Ford becomes clearly apparent. Across every class, they manage to achieve a remarkable result due to the significant upsurges from 2010 onwards, when they introduced their advanced turbocharged engines. Interestingly, this increase in power does withstand the increasing competitive pressure with increase in size classes, leading to a 64 % increase in class B and even 69 % increase in class D, therefore remaining competitive across all classes. Furthermore, their results challenge the notion of a general technological frontier derived from BMW's late stagnation.

#### 4.2.4 Honda

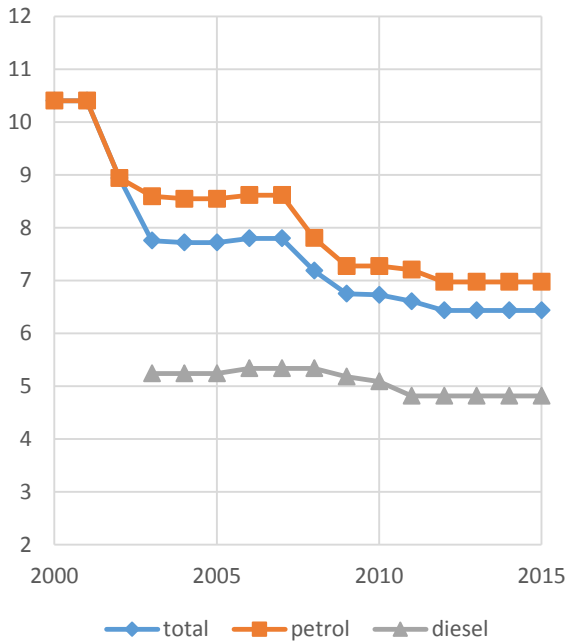


Figure 20: Consumption, Honda, all classes

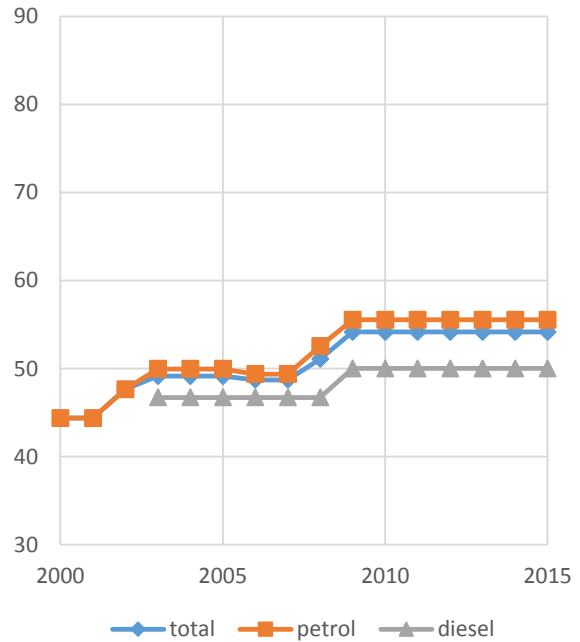


Figure 21: Power, Honda, all classes

-38%      -33%      -8%      22%      25%      7%

Honda is a manufacturer more focussed on the smaller classes, similar to Ford, but lacking their aggressive technology push and being rather inconspicuous. Their overall values (Figure 20 & Figure 21) mirror this illustratively. The consumption figures are dominated by development in petrol engines, which itself mainly consists of two separate phases of improvement until the middle of the period and otherwise stagnating. This is only surpassed by the development in diesel engines, which only shows a slight improvement mid period and a solid phase of late stagnation at a comparably high level. This is also shown in the percentage figures, where the two steps in petrol development still accumulate 33 %, but diesel improvement only amounts to a meagre 8 % drop in consumption.

A similar picture can be found when assessing the power values for Honda. Again, it is characterised by two steps of improvement in petrol engines, corresponding to the steps in consumption progress, with the lately introduced diesel engines picking up the second step. Otherwise, there is virtually complete standstill in engine development, resulting in extraordinarily meagre improvement percentages of as low as 7 % for diesel engines.

When assessing the class values (Figure 66 – Figure 71), an interesting picture can be identified. Despite the low amount of innovative activity, Honda seems rather healthy in both classes B and D. The distinctive steps of innovation at least in terms of consumption ensure a competitiveness with the other manufacturers, as the big steps of improvement result in a couple of years grace period

before being reached by the average. In class B, this works for both consumption and power, showing a pattern of innovation whenever necessity occurs in form of the average values catching up. Surprisingly, this does also nearly work in class D, where the consumption manages to maintain average values overall and only power shows a lack of ability to keep pace with industry-wide development, stagnating at a lower level. Class C in turn shows differing data. Here, Honda at no time manages to achieve average consumption figures, despite its significant steps and data shows that another immense step would be needed to close the increasing gap that built towards the end of the period, as Honda's consumption stagnated. Power-wise, however, they manage to avoid falling back behind much, although improving in total by only 15 %. Here, they are living off their power advantage they possessed at the beginning of the period to level out the weak performance.

4.2.5 Hyundai

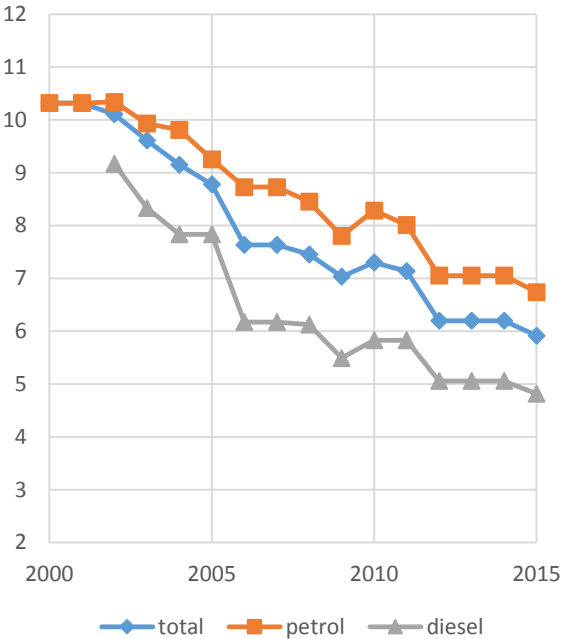


Figure 22: Consumption, Hyundai, all classes

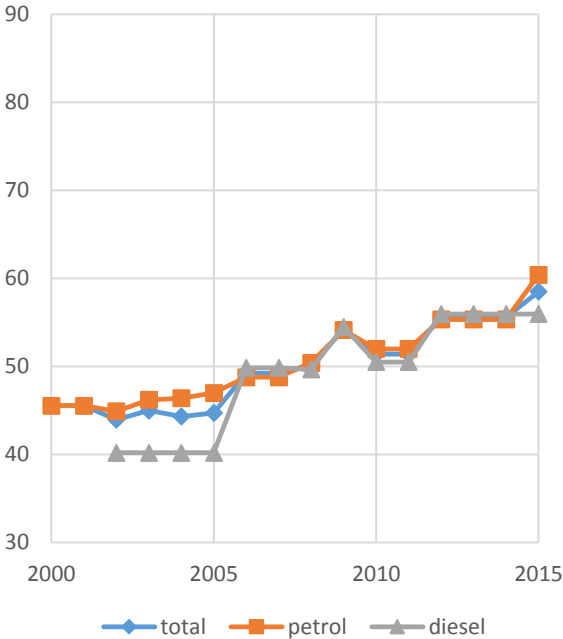


Figure 23: Power, Hyundai, all classes

**-43%**      **-35%**      **-47%**      **28%**      **33%**      **39%** |

Hyundai is one of the firms that probably underwent one of the biggest changes in image throughout the examined period. Starting as a rather conservative and favourable niche brand, they managed to transform their brand into a modern and recognised one on the car market. This conservative heritage however can still be identified from their data (Figure 22 & Figure 23), as the clear focus of innovative activity lies on the reduction of consumption instead of improving power. Early on, the relatively thirsty diesel engines saw a vast improvement in consumption, revealing a strong initial

focus on this type of fuel that possesses a strong importance on the assessed European market and hence was considered vital for the survival and subsequent establishment. The short phase of rise in consumption can again be traced to the temporary absence of bigger models in these years, resulting in a rise of average values in this period.

Power development shows is rather weak and only characterised by an initial upsurge in diesel power in order to achieve competitiveness. While diesel engines subsequently show values according to the average, petrol engines lack behind in power development, only showing a tendency towards the end of an insistent push of innovation.

Class-wise (Figure 72 – Figure 77), the initial tendency towards conventionality is confirmed by the data. Across all classes, a development at the pace of the average industry is shown in both consumption and power. In the bigger classes, there are signs of a strong and targeted innovative effort in order to achieve competitiveness and improving values towards average standard, but besides these initial sparks, there are neither signs of weaknesses nor signs of innovative strength, let alone technology leadership. Innovation here seems to be a measure to remain in the midfield, but not to stand out. Simultaneously, the absence of remarkable weaknesses across all classes hints a well-balanced innovative system that is used in a very precise way and to a clear extent – and has been so far successful in doing so.

#### 4.2.6 Jaguar

Jaguar is a clear and distinct premium brand. Their range of products is limited to the biggest two classes, with even the bigger one only being covered since one year before the assessment period. Its heritage clearly lies in big luxury vehicles and the advance into the lower car classes was both an experiment and a necessity. An experiment, because so far, the brand has only offered highly luxurious cars in classes not even covered in this work and the reaction of the customer was uncertain for the most part of the period covered here and a necessity, as in order to stay economically viable in the increasingly tough automotive market, sales figures had to increase. This was enabled by the affiliation with Ford, providing the basic elements to undertake this revolutionary expansion of business activities. Simultaneously, the affiliation with Ford leads to another phenomenon, making Jaguar one of the two special cases besides Volvo in this work. Both have been sold by Ford in the second half of the observed period. This can be seen descriptively by the figures for Jaguar (Figure 24 & Figure 25), showing both the technical reluctance up until the sale and the subsequent sudden onset of innovation due to availability of funds.

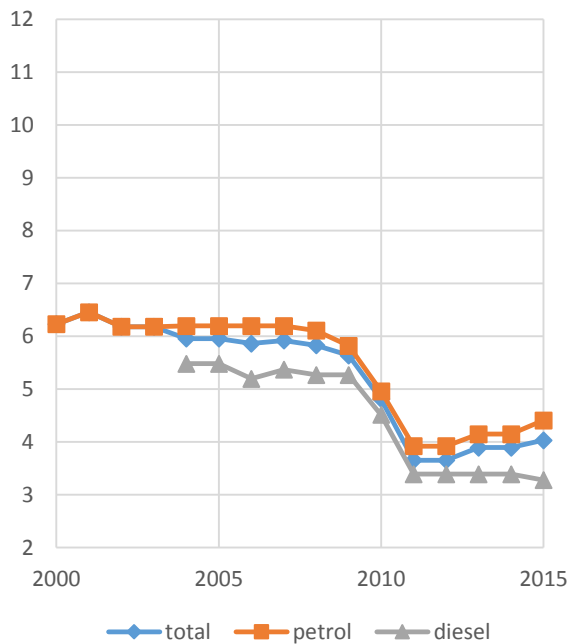


Figure 24: Consumption, Jaguar, all classes

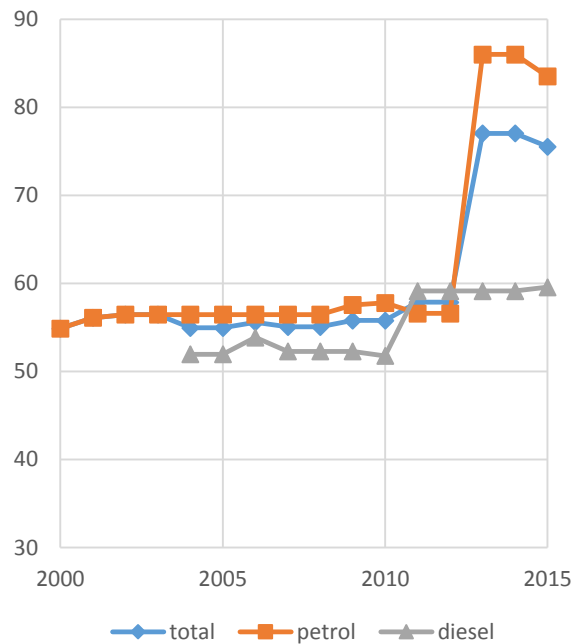


Figure 25: Power, Jaguar, all classes

-35%      -29%      -40%

38%      52%      15%

An interesting feature is the closeness of both fuel types, both in terms of innovative preference, but also performance. This only unravels with the big innovative steps towards the end, where diesel engines do not improve their power at all. The overall averages are again skewed by the temporary absence of a class D car until introduction of the Jaguar XE in 2015, but nevertheless, the surge can also be identified in the class figure.

These class figures (Figure 78 – Figure 81) reveal, that Jaguar throughout the entire time period performed remarkably well without much innovative activity due to advantages at the beginning of the period. Hence, as becomes apparent in consumption figures of class D, virtually without any progression, Jaguar remained below average up until 2008, which is also the case for the power development in this class. The only positive development occurring was in form of the introduction of the new XE model with the new owner Tata, instantly rendering Jaguar above average again, especially in terms of power, achieving a remarkably high value.

The similar pattern can be seen in the bigger class E, where also only slight development occurred in both variables, leading to Jaguar living off its initial advantage. In terms of consumption, this advantage however is not as pronounced, leading to a closer progression along the average than in terms of power. Nevertheless, in both cases, Jaguar's reserves enable above-average figures up until 2005, when remaining innovative efforts under the ownership of Ford were focussed on keeping pace with industry-wide development of consumption, while power stagnated. Interesting here,

despite Jaguar being a niche manufacturer providing with only a small sample to this work, is the fact of being able to observe the effect of changing ownership in terms of innovative activity. As soon as the new owner took over and provided both a perspective and funds, Jaguar was almost instantly able to develop highly innovative products that even surpass the established German competitors at the premium end of the range. These astonishing innovative results are remarkable for such a small company.

4.2.7 Mazda

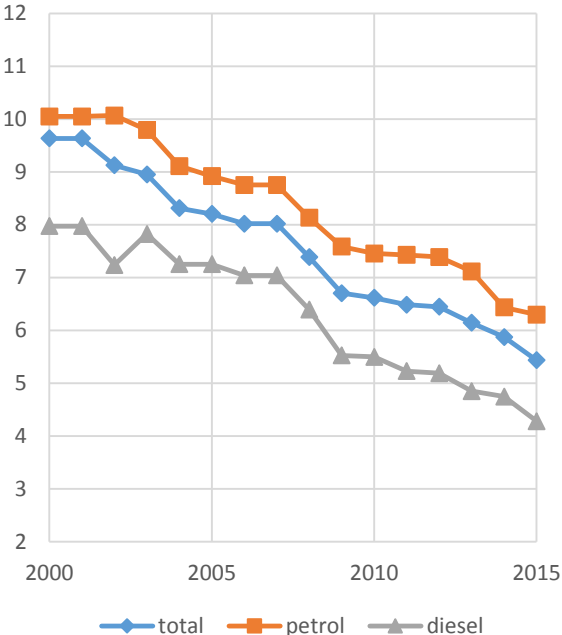


Figure 26: Consumption, Mazda, all classes

**-44%**      **-37%**      **-46%**

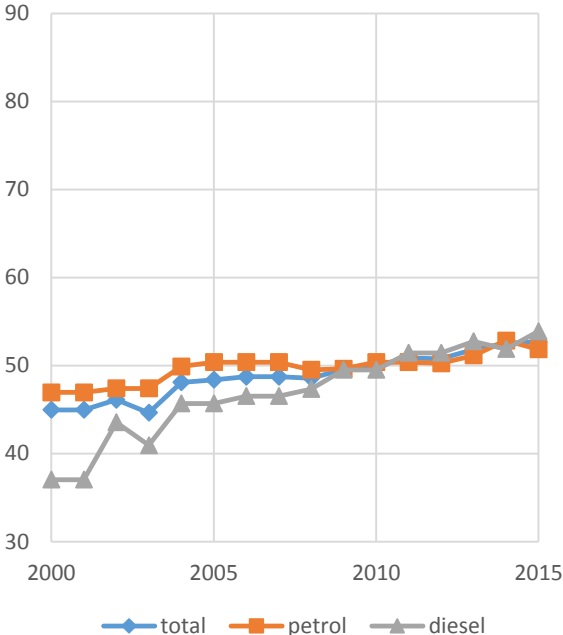


Figure 27: Power, Mazda, all classes

**17%**      **10%**      **45%**

Similar to Honda, Mazda is a Japanese manufacturer long established on the European market, focussing on smaller cars. Again, this is a typical manufacturer operating in the midfield and from its overall figures (Figure 26 & Figure 27), it becomes apparent that innovative activity was mainly channelled into lowering consumption instead of increasing power. In total, Mazda achieved a lowering by 44 % in consumption, but only a 17 % increase in power, with the exception of a bigger rise in diesel power towards the beginning of the period to reach a comparative level. The stagnation in power sets in at a level that the other manufacturers reached on average in 2009. In terms of consumption however, Mazda achieves to maintain a relatively competitive level in both fuel types, but again shows no signs of extraordinary technology.



Class-wise (Figure 82 – Figure 87), these findings are confirmed. Interestingly, Mazda’s initial position in terms of consumption is the better the bigger the class, with the consumption values in class B being almost 2.5 litres above the anyway high average. Nevertheless, in all classes, technical progress can be identified in attempting to maintain average levels throughout the entire period and also succeeding doing so. It is another prime example of a manufacturer pursuing a rather purposeful innovation strategy just so far as to maintain competitiveness and being satisfied in the midfield. Strongest innovative efforts can be seen in the smallest class in the initial attempt to lower consumption to industry-levels.

In terms of power, a similar pattern can be seen, being aggravated by the fact that Mazda’s subtle innovation strategy seems to preferably focus on lowering consumption. Therefore, there is now improvement in power in class B over the entire fifteen years, instead only slight rises in the second half can level out initial deterioration in power values. The other classes show at least a positive development in terms of power, but again are also characterised by strong periods of stagnation and a growing gap between industry average and manufacturer’s values.

4.2.8 Mercedes-Benz

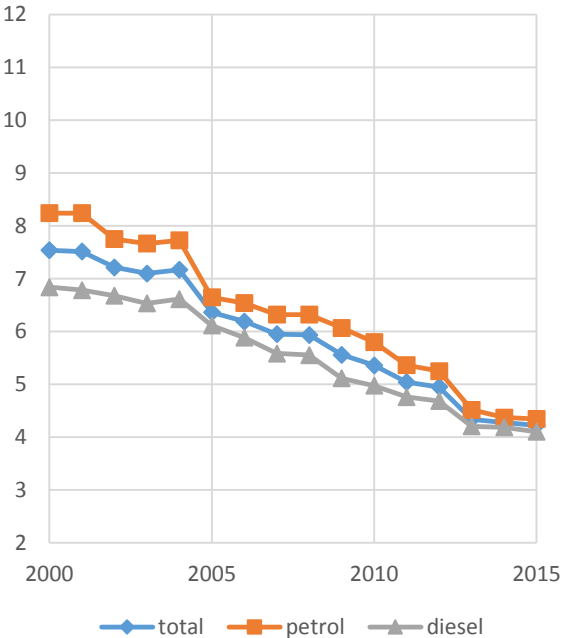


Figure 28: Consumption, Mercedes, all classes

-44%      -47%      -40%

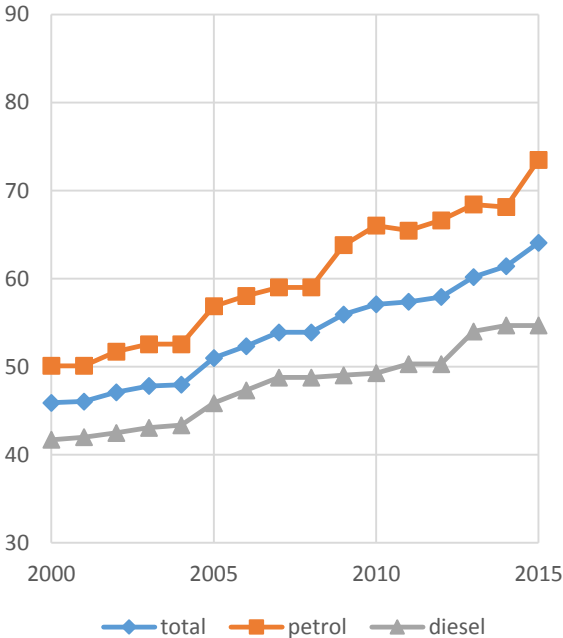


Figure 29: Power, Mercedes, all classes

40%      47%      31%

Mercedes-Benz, as a premium brand oriented at the bigger car classes shows a distinctive difference in its data (Figure 28 – Figure 29) as compared to both the industry-wide average, but also one of its traditional competitors, BMW. As with BMW, a strong correlation between both fuel types can be observed, however, as opposed to BMW and the industry average, not in terms of power, but rather in consumption. This is insofar remarkable as diesel engines' popularity is largely explained by the advantages in terms of fuel consumption. The explanation lies in the combination of a slightly worse value in diesel consumption and a slightly better value for petrol engines, as compared to BMW. Furthermore, innovative activity, with the exception of a bigger step between 2004 and 2005, seems rather linear and well-balanced between diesel and petrol engines.

Power development similarly shows a parallel progression between the fuel types, indicating however an advantage in petrol engine development, as the gap between both types is increasing with time and eventually shows an upward surge tendency for petrol and a stagnation tendency for diesel.

Class-wise (Figure 88 - Figure 93), surprising results are revealed. The smallest class, not a class traditionally associated with Mercedes, shows the manufacturer's biggest problems with innovation in terms of consumption only maintaining average levels by two distinctive steps of progress, while otherwise stagnating. In power, there is almost no development up until 2012, far below the industry average that only can be set off by a remarkable step upwards, however still not reaching average levels. This is astonishing for a brand with an image such as Mercedes. In class D, Mercedes shows the best performance, although limited to steady and gradual innovation, clearly focussed though on improvement in consumption and only recently power. Class e performance can be considered disappointing for a brand with such a focus. Both consumption and power almost entirely remain below industry average, power even further falling behind towards the end. A distinctive innovative input as can be seen at Ford or Jaguar lacks completely, which is surprising due to the financial background of the manufacturer.

#### 4.2.9 Nissan

Nissan is the third of the rather conservative Japanese brands besides Toyota on the European market. As with the others, it has established its niche, but is lacking a clear and distinctive profile that would protrude from the industry average. As with Fiat, the sample of Nissan is characterised by a small size and gaps in the higher of the two classes where it is present. Nissan is not as focussed as other manufacturers on offering a complete range of products on the European market, but instead

concentrates on a smaller number of successful models, which is unfortunately mirrored in this sample.

As becomes apparent from the figures (Figure 30 & Figure 31), the data is dominated by the small sample size and the gaps in it, leading to rather distorted overall graphs. Nevertheless, they indicate both a rather weak start and irregular innovation activity, primarily dominated by a huge step

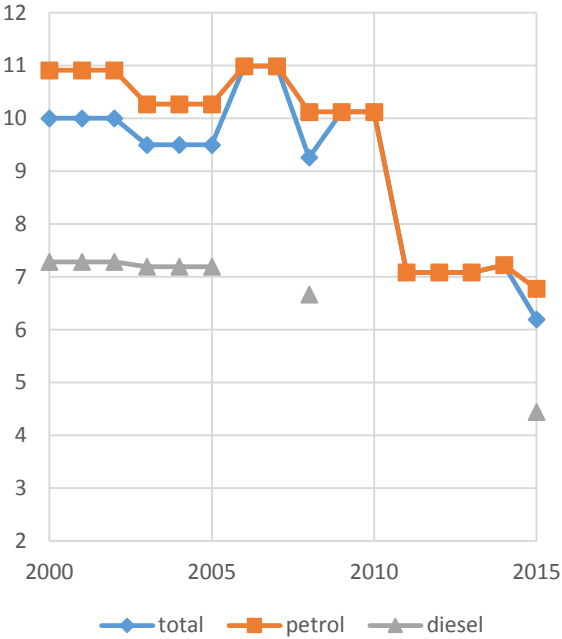


Figure 30: Consumption, Nissan, all classes

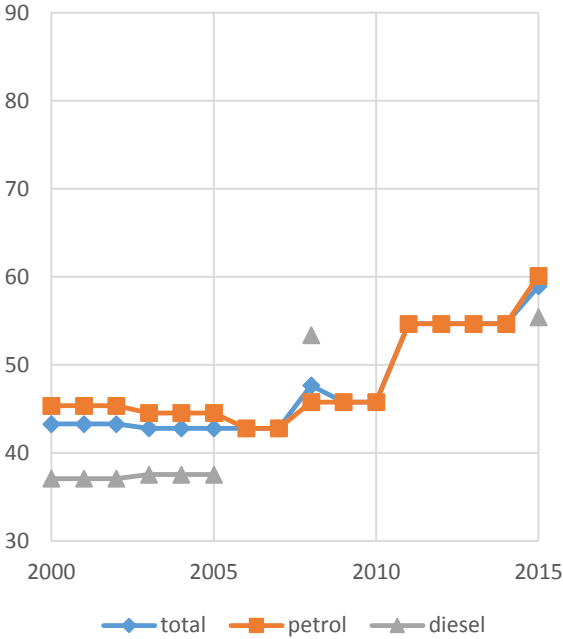


Figure 31: Power, Nissan, all classes

**-38%**      **-38%**      **-39%**      **36%**      **33%**      **49%** |

between 2010 and 2011 resulting in a significant improvement in petrol consumption, but also petrol power. Interestingly, the diesel engine performance is not as far behind initially and despite the immense gaps, the introduction of modernised diesel engines shows competitive values, despite activity clearly being focussed on petrol engines.

Class-wise (Figure 94 – Figure 97), only class B offers viable information as the gaps in class C are too big to reveal much more than the ability to introduce competitive engines in 2015, after largely stagnating in the beginning and showing erratic engine values in between, if any at all. In class B, however, it becomes apparent that Nissan largely stayed behind in fuel consumption and eventually in power, as there is almost no sign of any innovative activity up until 2010, where a single big step was achieved in both variables, catching up to industry levels, but nothing else. It might be that neither the market nor the offered and examined products are prioritised by Nissan far enough to

trigger further innovative activity. In any case, these results surprise considering a globally active, established and big car manufacturer such as Nissan.

4.2.10 Opel

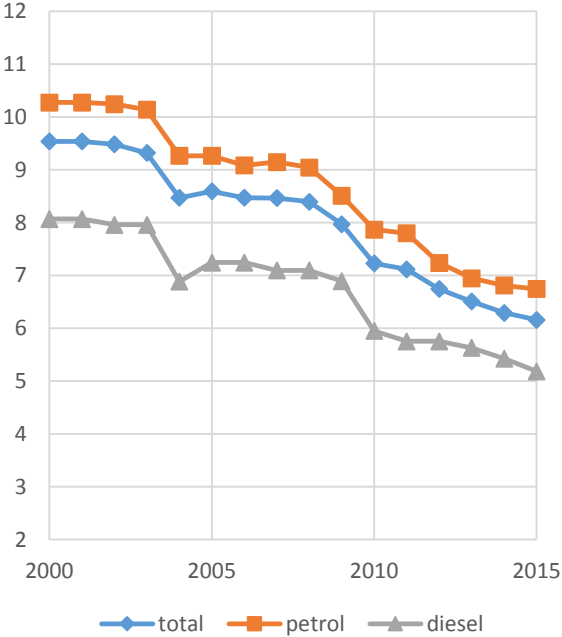


Figure 32: Consumption, Opel, all classes

-35%      -34%      -36%

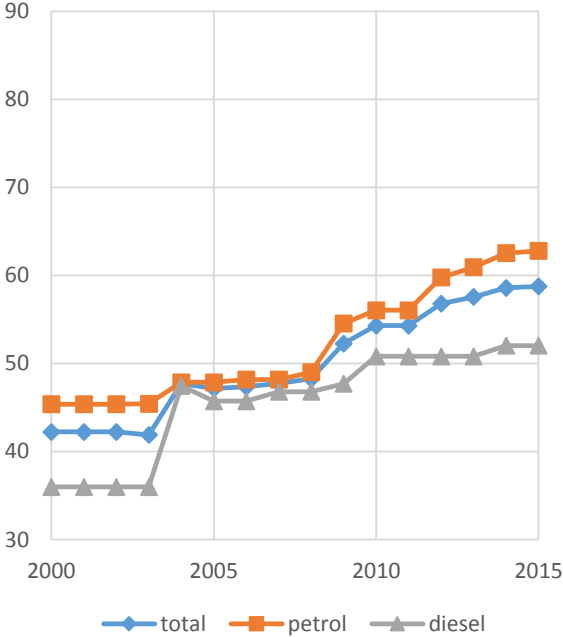


Figure 33: Power, Opel, all classes

39%      38%      45%

Opel, together with its British twin brand Vauxhall that will always be considered included in this work, is a car manufacturer rather focussing on the smaller end of the model spectrum and belonging to General Motors. In comparison to the average development, the graphs (Figure 32 & Figure 33) show certain anomalies. In terms of consumption, it becomes apparent that Opel is constantly lacking behind by roughly a litre both at the start and the beginning of the period and in both fuel types. Innovative activity seems to be rather focussed on the power development, where a stronger development can be noticed. However, even this does not enable Opel to overall achieve average values here, let alone such upsurges in power as Ford, one of Opel’s main direct contestants, attained.

In the class-wise data (Figure 98 – Figure 103), this general impression is largely confirmed. The below-average performance in terms of consumption can be found across all classes, with all three showing a similar pattern of innovation with the introduction of new model generations and stagnating phases in between. Power-wise, the rather poor performance in class B stands out,

showing almost no variation from 2004 onwards. In class C, however, a stronger effort to keep pace with average figures is made, with each new introduction narrowing the gap again, despite never reaching it

Then, there is the surprising performance in class D, where Opel not only manages to keep pace with the average development in power, but from mid period onwards even manages to build and expand a lead. It might not be an improvement as strong as Ford’s, but it still shows the innovative potential within the brand.

4.2.11 Peugeot

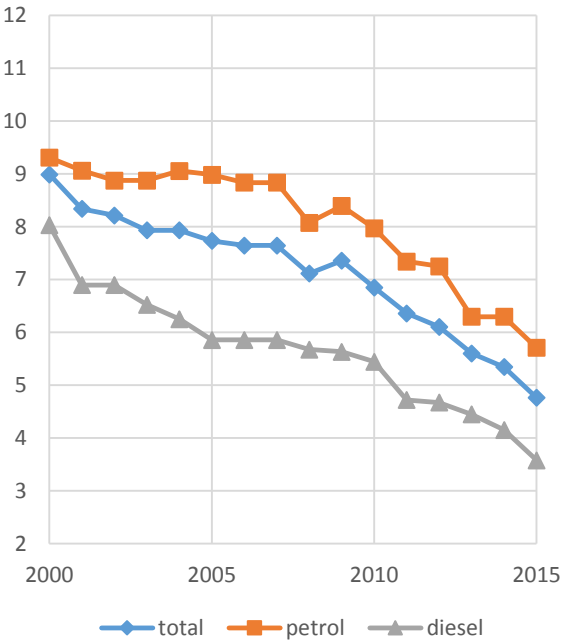


Figure 34: Consumption, Peugeot, all classes

-47%      -39%      -55%

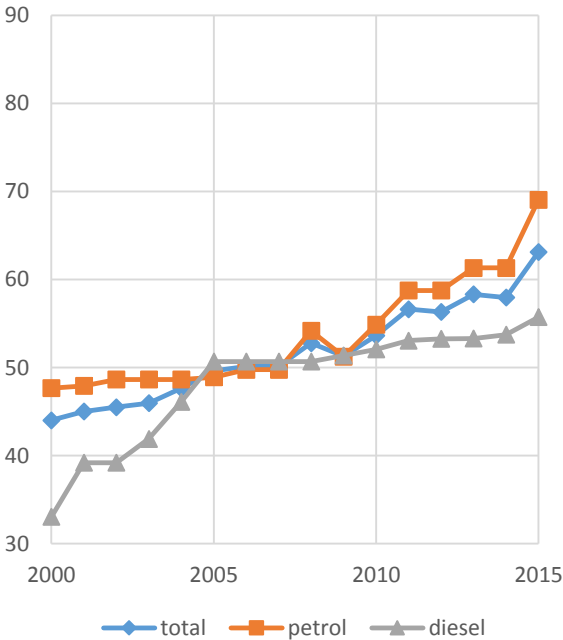


Figure 35: Power, Peugeot, all classes

43%      45%      69%

Peugeot is similarly set as Opel or Ford, with a strong range of products in smaller and middle size classes and a pronounced reputation for diesel engines that is also mirrored in its data (Figure 34 & Figure 35). Across all classes, the consumption values of diesel engines are always better than average and improve stronger than petrol values, indicating a focusing. Power-wise, the values are characterised by as strong initial improvement in power values for diesel engines, even surpassing petrol engines, while then phasing out and in turn petrol engines being target to strong improving activities. Overall, Peugeot shows a strong innovative activity across both fuel types, especially in terms of power.

This is also mirrored in the class-wise data (Figure 104 – Figure 109), where at least in terms of consumption, Peugeot eventually manages to perform above-average, despite certain negative peaks in both the smallest and the largest class mid-period. In terms of power, the performance is more linear and always close to the average figures and in all classes showing a positive tendency eventually. Peugeot might not be the most innovative manufacturer in this survey across all classes, but it manages to achieve sound innovative progress across a large span.

4.2.12 Renault

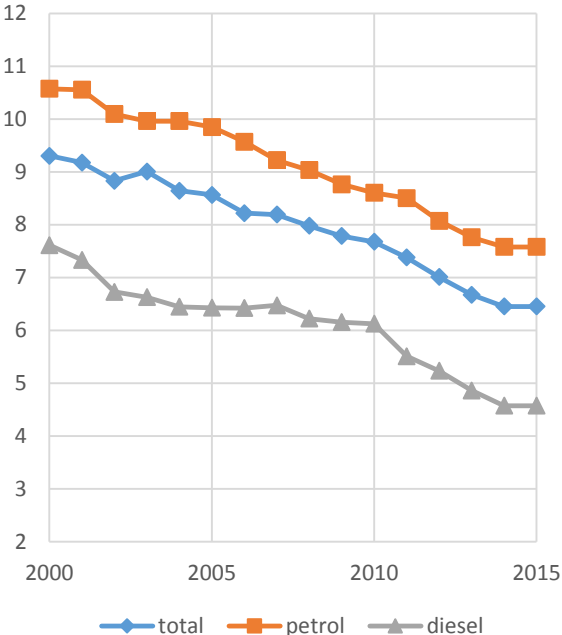


Figure 36: Consumption, Renault, all classes

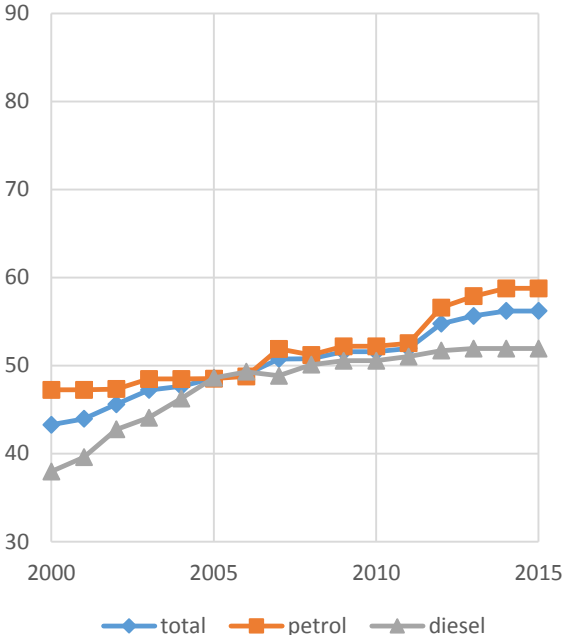


Figure 37: Power, Renault, all classes

**-31%**      **-28%**      **-40%**      **30%**      **24%**      **37%** |

Renault is the natural competitor of Peugeot, with a very similar range of products. This similarity can also be seen from the comparison of the graphs (Figure 36 & Figure 37), showing a strong resemblance between the two. However, the graphs also show that Renault cannot achieve the level of innovative progress in neither consumption nor power development. Especially towards the end, Renault shows tendencies towards stagnation, while Peugeot shows signs of further development.

This is also seen in the class-wise data (Figure 110 – Figure 115). In terms of consumption, the strongest performance is seen in class B, where Renault only manages to hold the average levels. In the other two classes, despite gradual innovation, average levels cannot be held and a gap is building

up with the time. The most innovative activity here in the end of the period can be seen in class C, while class D shows signs of stagnation.

In terms of power, the strongest performance can also be seen in class B, where a strong mid-period push in combination with slight and more gradual improvements overall ensure being above average for the second half of the period. This gradual improvement is absent in class C, which is characterised by two distinctive steps, which however cannot outreach overall average progress consistently and only reach these levels. This is not accomplished in class D, where the second half of the period is dominated by a prolonged phase of stagnation and a subsequently increasing gap.

4.2.13 Toyota

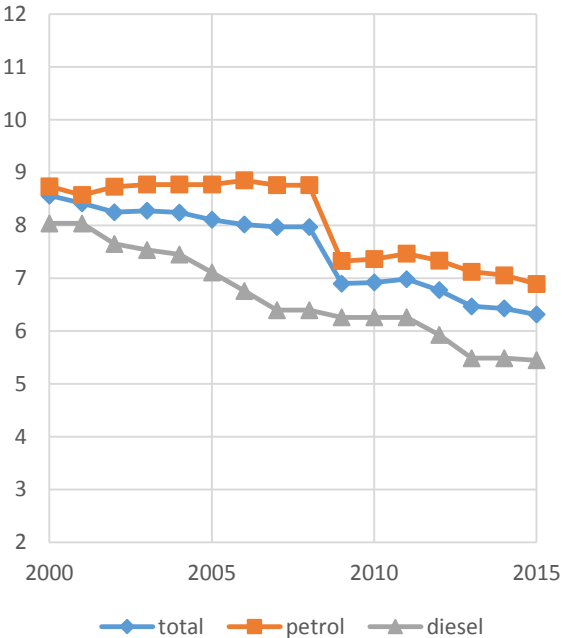


Figure 38: Consumption, Toyota, all classes

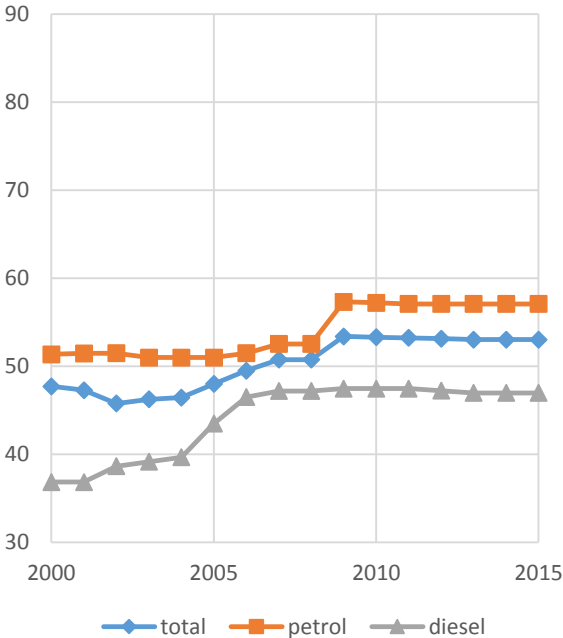


Figure 39: Power, Toyota, all classes

-26%      -21%      -32%      |      11%      11%      27%

Toyota is the strongest of the Japanese brands, worldwide and on the European market and infamously known for its eco-friendly hybrid cars, where they play a pioneering role. A certain affinity to eco-friendliness can also be identified from the graphs (Figure 38 & Figure 39), where Toyota shows remarkable low initial values in terms of consumption – at least for their petrol engines. The proficiency in diesel engines, despite constant effort for improvement, is not strong enough to reach average diesel consumption levels in 2015, while petrol development seems stalled up until 2008, when a big step separates another portion of stagnation until 2015.

Interestingly enough, this is also mirrored in terms of power development. An initial surge to improve diesel engines does not reach overall average levels and transfers into a long phase of stagnation, while petrol engines, with the exception of one distinct step, remain stagnant throughout the entire period.

From the class-wise data (Figure 116 – Figure 121), this is also confirmed. While the subtle innovative activity is enough to maintain above-average performance in both categories in class B for most of the time, it results in below-average performance in the bigger classes. In both cases, towards the end a complete absence of activity can be noted, which for a manufacturer with a reputation such as Toyota comes extremely surprising.

4.2.14 Volvo

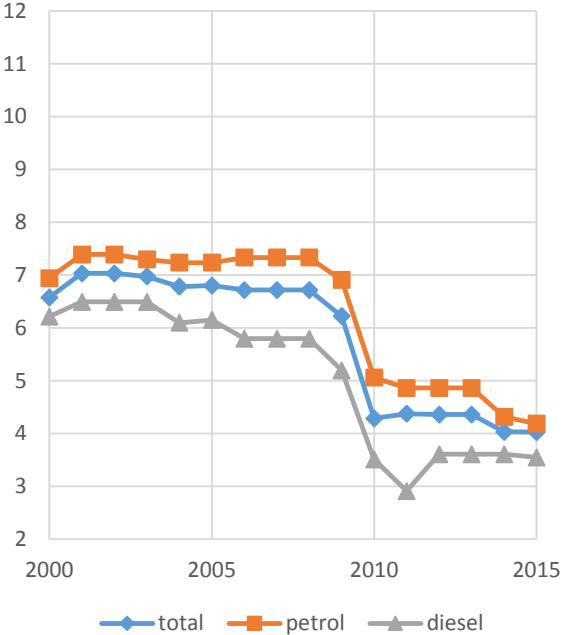


Figure 40: Consumption, Volvo, all classes

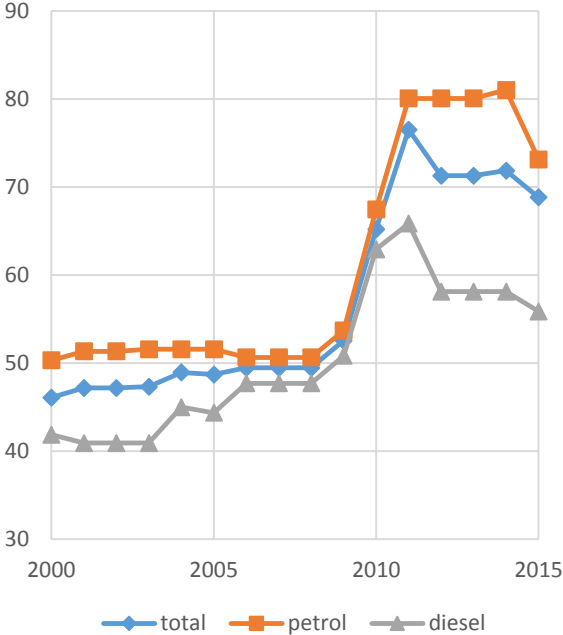


Figure 41: Power, Volvo all classes

-39%      -40%      -43%      |      49%      45%      33%

As already mentioned, Volvo is the second special case in this work next to Jaguar. Just as the latter, Volvo has been part of the Ford Group and then found new owners following the sale by Ford. In Volvo’s case, this is Geely from China, which, in a similar way to Tata with Jaguar, mostly limits itself in providing funds and leaving the operational business to the Swedes. The range of products is also characterised by a premium claim and dominated by larger cars. Ford’s legacy can be descriptively be seen from the graphs (Figure 40 & Figure 41). The existence under the ownership of Ford is largely



dominated by the complete absence of innovation with the only progress noticeable in diesel engine improvement. This however rapidly changes around 2010, when suddenly an extreme upsurge sets in for both petrol and diesel engines in consumption and power. While diesel engines see an incredible improvement in consumption figures, petrol engines see a rise to power levels far above the average. This is further confirmed by the class-wise data (Figure 122 – Figure 125), where consumption development keeps up with industry-wide values, but especially in class E, the upsurge in power is exceptional. Given the previous rather disappointing performance by Toyota, Volvo’s performance is a nice surprise. As with Jaguar, a brand that has been deemed dead with the purchase by unestablished car manufacturers from Asia, manages to show such remarkable performance in such a short period of time, while others, far more established, fail to achieve these levels.

4.2.15 Volkswagen

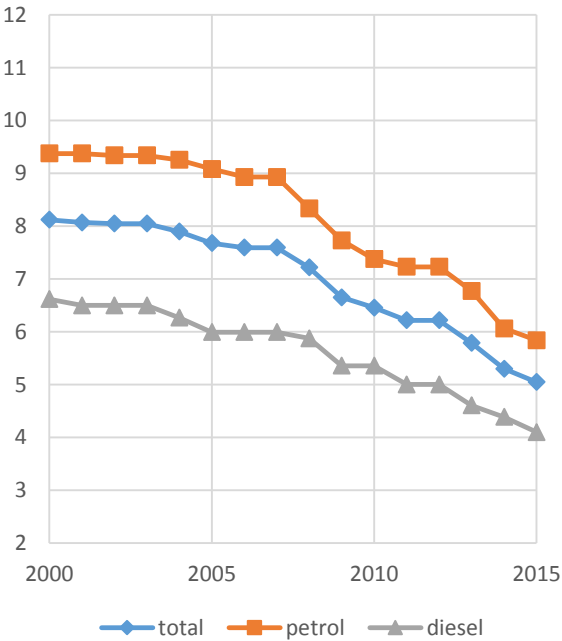


Figure 42: Consumption, Volkswagen, all classes

**-38%**      **-38%**      **-38%**

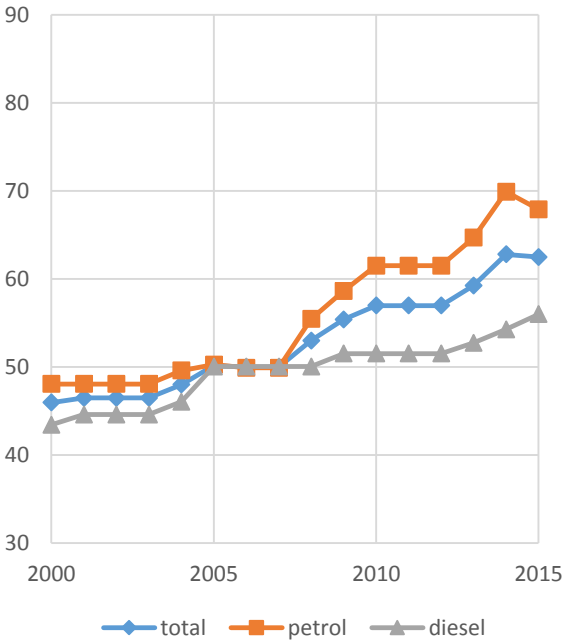


Figure 43: Power, Volkswagen, all classes

**36%**      **41%**      **29%** |

Volkswagen is the synonym of a European car mass producer. It lacks presence in the highest class of this survey, but other than that is ubiquitous. The corresponding figures (Figure 42 & Figure 43) describe a company with a steady development and improvement, at least in terms of consumption. Both fuel types are subject to almost parallel and ongoing improvement, being mirrored by the identical percentage gain figures, also roughly corresponding to the average figures. In terms of power, development occurred more erratic and isolated. After an upsurge in diesel engines and a subsequent

phase of equality between the two, a strong phase of petrol improvement ensues, leading to a growing gap. Diesel engine development only accelerates again towards the end of the period, when petrol figures stop rising.

The initial impression of activity according to industry average is further confirmed by the class-wise data (Figure 126 – Figure 131), revealing a brand that targets innovation towards maintaining average levels. It becomes apparent from all classes, how development cascades occur as soon as values drop below average, maintaining a rather unobtrusive and conservative profile. Whether this shows the actual limitation of innovative capabilities of a firm as embracing the car as Volkswagen is open to dispute. Otherwise, it can also be that innovation is only used to maintain a previously set level with which the firm is satisfied, without pushing to its technical limitations.

### 4.3 External Factors

#### 4.3.1 Emission standards

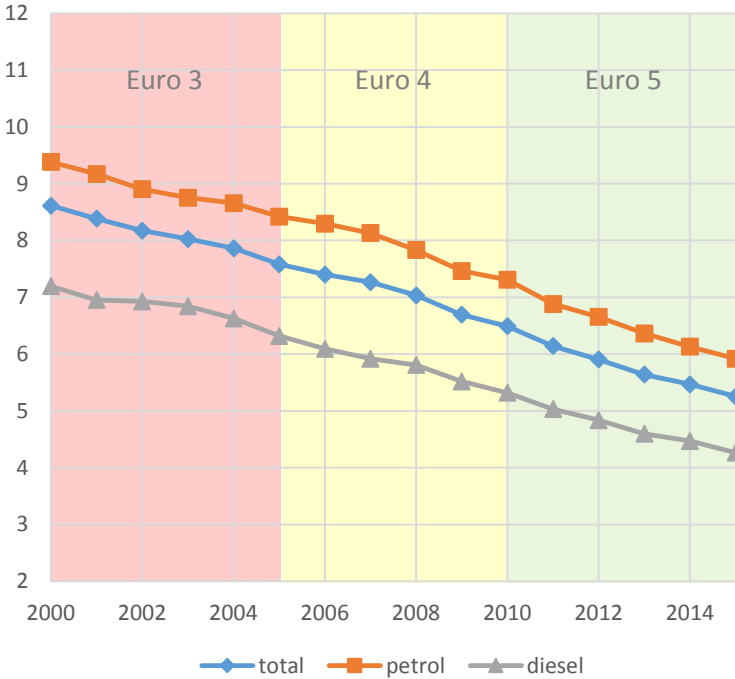


Figure 44: European Emission Standards and average fuel consumption

EU and EEA member states are subject to a very dense net of emission standards being introduced in a pattern of five years. In the period covered in this work, the regulations Euro 3 until Euro 5 are relevant. Euro 3 and Euro 4 have been resolved in 1998 and Euro 5 in 2007.

The emission standard system in Europe is built around individual stages (Euro 1 etc.) that are both well established and densely clocked. This, in combination with the fact that the stages are resolved with several years lead time explains, why there are no obvious reactions in average fuel consumption (Figure 44). Furthermore, these emission standards set limits on the emission of several pollutants that may only partially be tackled by reducing consumption and instead via sophisticated exhaust gas treatment. Then however, when comparing the introduction of the standards with the development of consumption of individual manufacturers (see 4.2), there is a tendency with certain manufacturers such as BMW, Honda, Peugeot or VW that show no or little progress in especially petrol consumption during the Euro 3 phase, but a strong progress in phases of Euro 4 and particularly during announcement and effect of Euro 5.

The key problem however, preventing to draw a reliable connection between fuel consumption and emission standards, remains the fact that the emission standards focus on pollutants that can be lowered by innovation in areas that are not captured in this work. An emission standard on carbon dioxide would be tied much closer to fuel consumption and would allow a better comparison.

Besides the European emission standards, there is also the mechanism implemented by the European Union to decrease carbon dioxide emission via upper limits for fleet consumption. This is insofar interesting, as it also falls in the period where certain drops in fuel consumption can be registered. Despite being in full effect from 2015 onwards and therefore virtually outside of the period covered here, firstly the date of publication has to be considered as the date since when car manufacturers knew what limits to expect when and being able to react accordingly. Furthermore, the mechanism is built with a phase-in, meaning a gradual onset up until 2015. This leads to the situation, where this fleet consumption mechanism, agreed upon in 2009 and gradually being introduced from 2012 onwards, shows chronologic parallels to Euro 5 emission standards and it is hard to factually determine the actual source of any fuel consumption progress to either of these mechanisms. In either case, due to the strong tie between carbon dioxide emission and fuel consumption, it appears that this distinct drop in fuel consumption for certain manufacturers might be connected to the fleet consumption limit, whereas the long-established emission standards result in a gradual overall pressure to decrease consumption. Without further data, however, this cannot reliably be stated.

#### 4.3.2 Fuel prices

As shown in previous work on innovation in the automotive sector shown in 2.1, fuel prices are shown to have an effect on parts of technical innovation in the automotive sector. In this work, there

is no distinction between different types of innovation such as different drive technologies, but rather a capture of innovative activity through improvement of technical data of the offered products. Nevertheless, the question prevails, whether a connection between the observed technical improvements and actual development in fuel prices in the observed area can be made.

When analysing the progress of fuel prices in Europe (Figure 45), it can firstly be noted that across the entire period, the average price for both fuel types increases from approximately € 0.70 in 2000 to approximately € 1.15 in 2015, a rise of approximately 64 %. Furthermore, when looking at the individual fuel types, an increase in petrol prices by approximately 56 % and even 90 % in diesel prices can be registered. On the other hand, these figures are put into perspective when considering real prices including inflation (Figure 46), showing the actual increase amounting to only 21 %. Nevertheless, the progression in fuel consumption shows a clear intention to lower consumption.

The progression in prices does not vary greatly between the fuel types in terms of swings, but it shows an interesting pattern. Besides the small-scale variations around a certain value, reminiscing a heartbeat curve, major movements can be detected. While the first half of the period was characterised by a gradually increasing rise in prices, the year 2009 saw a significant drop in prices, followed by a steep rise to even higher levels until 2012, culminating and merging into a slight fall towards the end of the period.

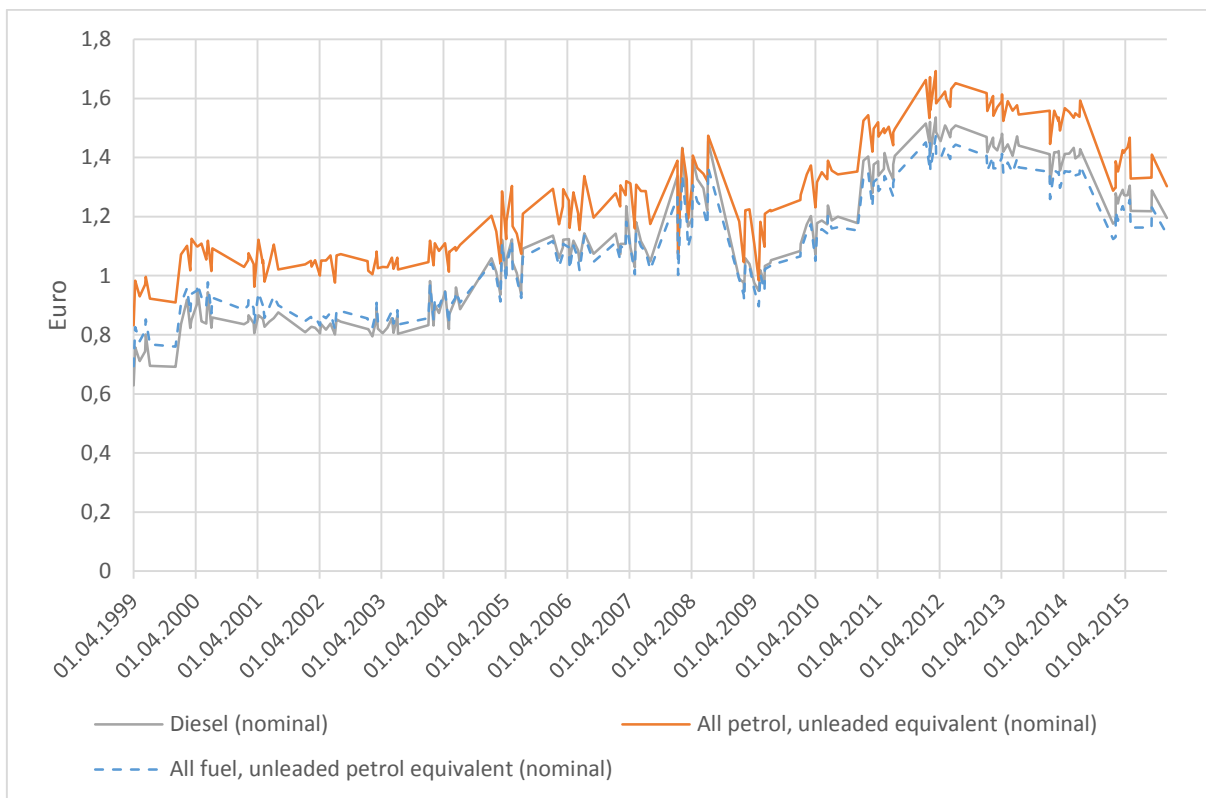


Figure 45: Fuel prices, according to types (nominal);  
 Source: European Environment Agency (2016), own illustration

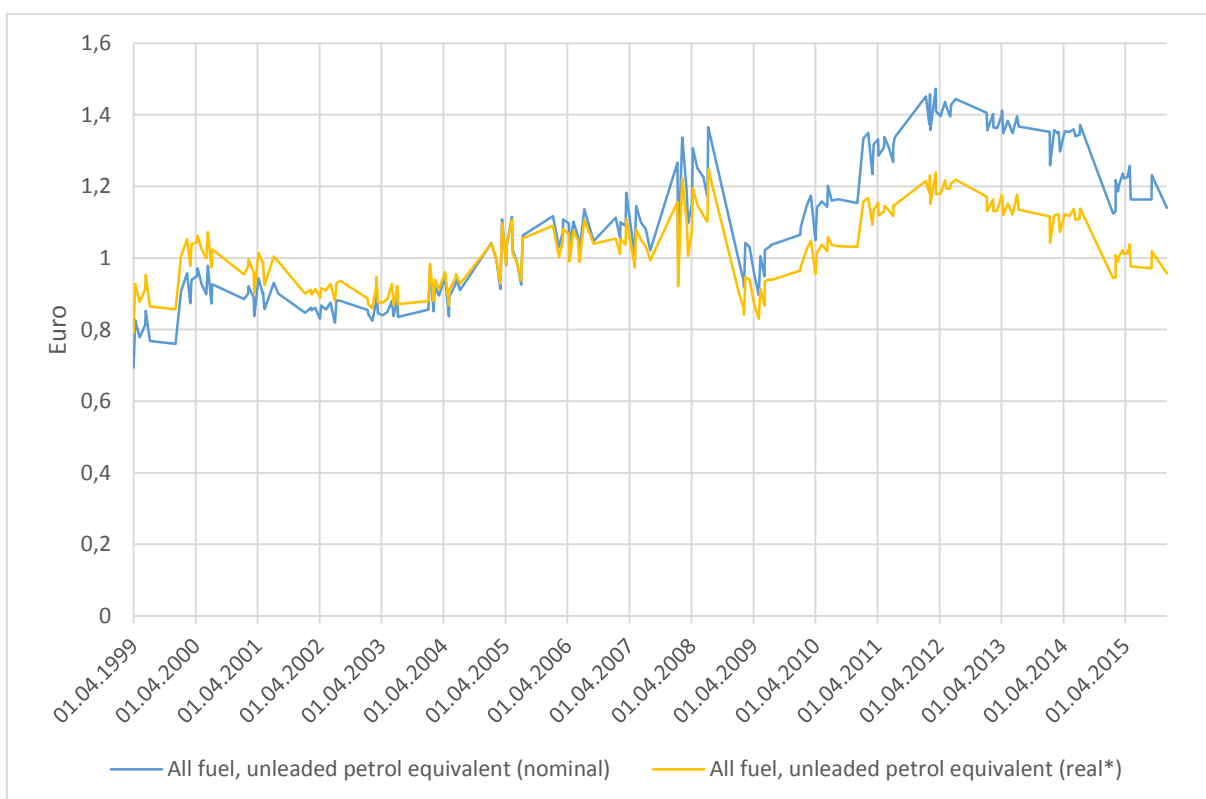


Figure 46: Fuel prices, real versus nominal, \* base year 2005;  
 Source: European Environment Agency (2016), own illustration

The innovative activity in the industry (Figure 4 – Figure 5) does not mirror this progression. Instead, the improvements in consumption occur in a linear way. The significant phases of disturbance from 2009 onwards in fuel prices show no effect on the progression in fuel consumption. Furthermore, the relatively high increase in diesel prices is not mirrored in the attempts to improve diesel consumption. Instead, both petrol and diesel engines show an almost identical rate of improvement, even across the classes. A strong and immediate impact of fuel prices on innovation processes in the automotive sector would have led to a prioritised target to lower diesel consumption.

Nevertheless, the impact of fuel prices cannot be neglected, yet on a larger time scale. The innovative activity of the manufacturers shows the importance of lowering fuel consumption. Both fuel consumption and power improved by a comparable rate, even across all classes. As fuel consumption is inevitably connected to fuel prices, this means that innovation in fuel consumption can be attributed to fuel prices in general. However, and this is connected to the findings of Zapata and Nieuwenhuis (2010) mentioned in 2.1, due to the delay in the automotive sector, fuel prices will not lead to short-term responses from the industry, but rather have an effect in the mid- to long-term, which corresponds to the data.

#### 4.4 Patenting Data

Another question in this work is whether a relation between innovative activity, here identified by technometric data, and patenting behaviour in the automotive sector can be found. The patenting activity in the relevant areas shows an immense degree of variation, as becomes apparent when looking at the figures (Figure 47).

While certain manufacturers file more than 2,000 patents per year, others file less than 500 patents in the same time. When looking closely at the data, an interesting pattern reveals itself. In general, the Japanese and Korean manufacturers show a remarkable degree of patenting activity, with Mazda being the only brand showing less than 1,000 patents per year in 2015. The biggest figures are shown by Toyota, with more than 6,000 patents in the relevant areas accounting for a quarter of the total patenting activity. In contrast, brands of European groups show a much lower number of activity, with less than 700 patents on average in 2015. The US-owned brands Ford and Opel however show a strong increase, with low number at the beginning of the period and Asian-level high numbers at the end.

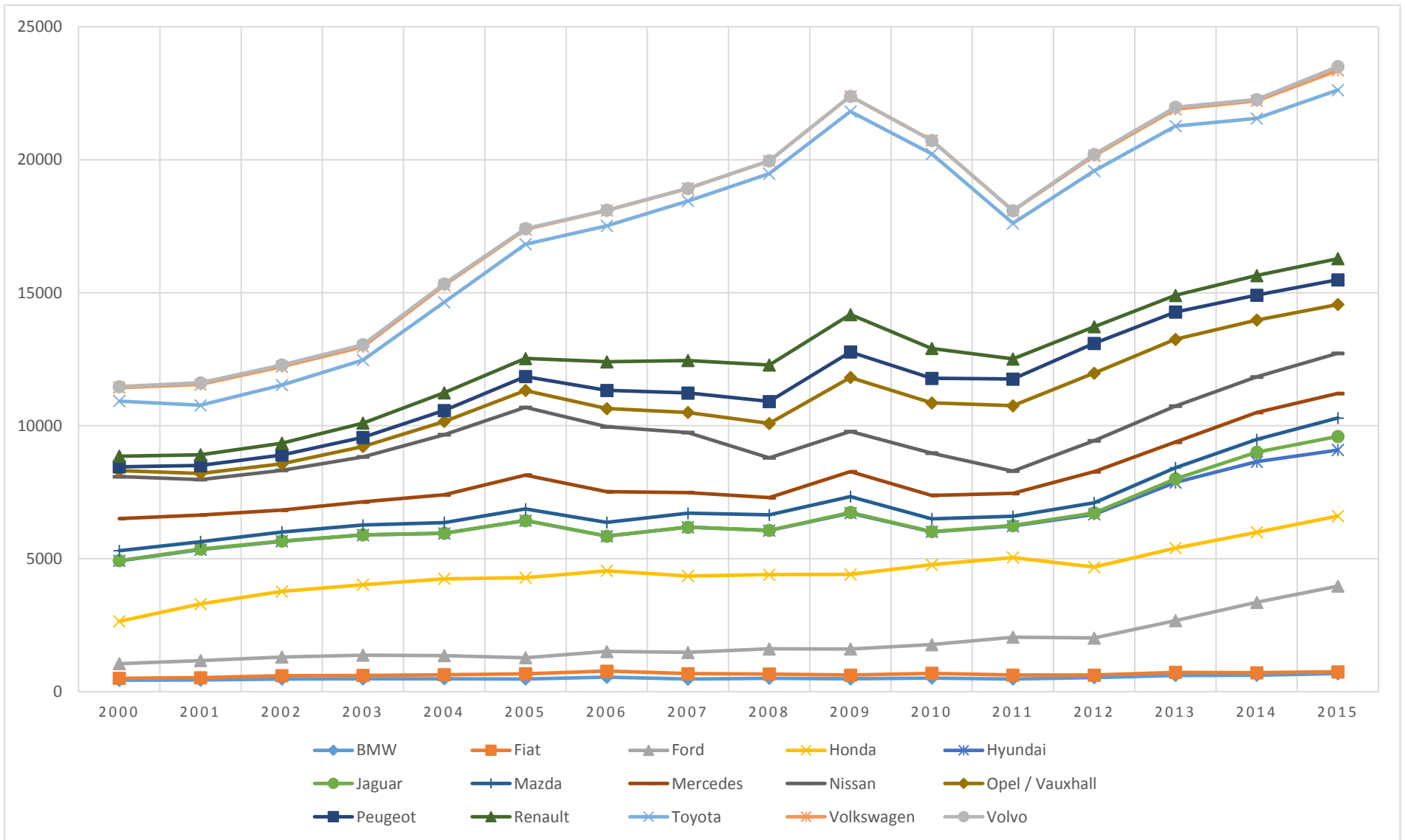


Figure 47: Overall patenting activity, all manufacturers, stacked

When comparing these figures with the observed performance in 4.2, it becomes apparent that there is no connection between the absolute numbers of patents and innovative performance revealed in this work. Instead, the Asian brands and especially Toyota showed a rather mediocre performance with little if any advances above average. According to the patenting figures, Toyota should be technology leader by far, especially, as the relevant areas of patenting in this work were limited to technology connected with the internal combustion engine and omitting Toyota's strong field hybrid propulsion.

Then again, a certain connection can be identified between patenting and technical performance, when looking at the development of patenting behaviour of the individual manufacturer. Firms with a positively developing performance in the technical data also show an increasing number of patents, such as Volvo, Ford, Jaguar or Peugeot. Consistently well-performing firms such as BMW or Volkswagen show a relatively stable patenting behaviour, while Fiat's patenting activity mirrors parts of its technical performance in its erraticism. In general, patenting increases in the industry and connections to actual technical performance or innovation can mainly be drawn by those that show a moderate patenting activity. In Asia, in contrast, patenting seems to be disconnected from actual innovation.



## 5 Discussion & Further Research

The results in this work offer several insights. Firstly, they reveal and characterise the innovation processes in the automotive sector by showing technical performance of all major manufacturers. This compilation of an industry innovation path, along the lines of Dosi's fundamental concept of technological trajectories, furthermore enables the assessment of the innovation performance of these manufacturers. These two steps reveal the character of the automotive industry. It is remarkable that industry-wide, the technical progress occurs in such a linear way and even across the classes shows such a balanced ratio between development in fuel consumption and power. On industry level, the curves even at class level show no indication of a major shock, drastically influencing the development. Instead, it gives the impression of a rather steady, i.e. mature industry that incrementally improves and is free of significant upheavals.

Nevertheless, when looking at manufacturer performance, certain surprising results are revealed. It is astonishing that bigger and financially robust manufacturers not necessarily show a strong performance in innovation leadership. Instead, for example Toyota, being a manufacturer normally perceived as very progressive, shows only average figures. This even more so considering the results from the assessment of patenting data that also shows a high activity by Toyota. On the other hand, manufacturers such as Volvo, having been on the verge of bankruptcy suddenly show technical performance that outshines the established premium competitors from Germany. Then again, this might also be linked to the fact that both Volvo and Jaguar had to restart completely, therefore being more venturesome. Volvo's concept of only offering relatively small but turbocharged four-cylinder engines even in the biggest car classes is a risk that the German competitors apparently do not want to take yet and, from a financial viewpoint, do not have to. Simultaneously however, this does reward the risk-tolerant brands Volvo and Jaguar, at least in this survey.

Besides these, many manufacturers seem to have settled for a pace allowing to follow the average without protruding from the masses. While external factors such as fuel prices definitely exert a general pressure on the industry to improve especially in fuel consumption, the industry shows no signs of short-term reactions to environmental influences. While this fundamentally mirrors the findings of Zapata and Nieuwenhuis (2010) concerning a strong delay in the spread of automotive innovation, it might need further confirmation in following studies tackling this question explicitly and in more detail.

Due to the extenuated and delayed responses by the automotive industry, revealing the actual effects of external factors would need a different approach. In order to reliably determine the effect

of the European emission standards, it is not enough to simply analyse the rather basic engine parameters that are covered in this work. Instead, this work could be enhanced by adding knowledge from engineering in order to achieve a broader set of technical data that also would allow for more in-depth examination. This detailed assessment of the development of several parameters of manufacturers' cars would enable a reliable evaluation of the effects that these emission standards had on the industry. Furthermore, the technical data distinguished between classes shows a difference between the average performance characteristics in these classes. In adding further engineering knowledge, a more profound understanding of engine physics could be used to develop a model that would cancel out the differing characteristics of differently-sized engines. The rather crude standardisation in this work seems to result in distortions that prevent reliable inter-class comparison.

Furthermore, this work concentrated on one market and on a limited number of models and engines. A following work could enhance the complexity in covering more markets, potentially all markets, and drastically increasing the covered sample of product range of each manufacturer. Adding statistical complexity, the gathered data could be analysed in a deeper way to enable more accurate results and revealing correlations reliably. This would require both the collection and processing of a wider set of data that goes far beyond the feasible scope of this work, but would definitely add to the accuracy of results.

As mentioned in the beginning, besides the provision of descriptive data on the innovative performance of the automotive sector, this work also wanted to improve the understanding of innovation in this sector, closing the possible gap that results from the usage of indicators such as patenting data in previous research. By taking a technometric approach, a more accurate insight on the actual outcomes of innovative processes could be given than with other indicators. Indeed, the comparison between the technical data and patenting data shows vast differences with Toyota for example showing exceptionally high numbers of patenting activity but only average improvement in technical outcome, while BMW shows a strong development in technical outcome while only showing a meagre patenting activity as compared to others. This discrepancy between the two approaches is noteworthy, especially for research concerning the influence of external factors on innovation as a measure of public control and guidance. With the adverse effects of the sector leading to the necessity for public intervention resulting from the actual outcomes of innovative processes within this industry rather than the innovative activity itself, it seems advisable to select an indicator being able to measure these outcomes. Here, the technometric approach appears to be a sound choice.

## 6 Conclusion

Concluding, this work offered a number of insights into the development of the automotive industry. Through the analysis of the technical development of the 15 most important manufacturers on the European car market, being one of the major markets in the relevant period 2000 – 2015, innovation – in the understanding of technical progress - in the sector could be plotted and identified. Fuel consumption and engine power have been selected as the two key technical variables with which to map the progress and hence innovative performance of the cars and subsequently the manufacturers. The character of the automotive industry as rather stable, calm and mature was revealed, showing a balanced progress in development both in the more rational factor fuel consumption and the rather emotional factor power. It has furthermore been revealed that even across the different car size classes, each comprising cars with different requirements profiles, showed a similar overall development and also a similar weighting between the two assessed technical factors. The relationship between diesel and petrol engines has been exposed, showing the distinct industry- and class-wide tendency of a focussing in power development in diesel engines in the first half of the examined period, whereas development then shifted to petrol engine power development in the second half.

The comparison of the individual manufacturers with each other and the industry-wide trajectory of innovation progress revealed the differing approaches of the manufacturers. It has been shown that major car manufacturers with a general technologically advanced reputation such as Toyota or Volkswagen show a rather conservative or even disappointing innovation performance in the assessed areas, while comparably small manufacturers such as Volvo that saw severe disruptions in ownership structure and economic conditions managed to show a surprisingly well performance after restarting. A consistently well-performing manufacturer showing above-average values across all classes and along the entire period has only been found in BMW.

The comparison of the innovation activity in the industry with the major two external factors affecting the car industry, fuel prices and emission standards, further emphasised the calm and rather delayed nature of the industry. Shorter-term changes such as the experienced drop in fuel prices between 2008 and 2009, or the later stagnation showed no corresponding response in the progression in fuel consumption development and even the disproportionate rise in diesel prices across the period in comparison to petrol prices was not met by an according shift towards a focus on development in diesel consumption. External factors were therefore found to be limited to a long-term influence on the direction of innovation activity.

Comparing the innovation activity with the correspondent patenting activity revealed certain surprises. Firstly, it was shown that the patenting activity is remarkably irregular in distribution across the manufacturers, with only Toyota accounting for 25 %. Here, a clear tendency has been revealed with Asian manufacturers contributing disproportionately towards the total number of patents, while European brands show a much more moderate level of patenting activity. The American-owned brands instead start low and increase towards Asian levels along the period. Therefore, a clear connection between the nominal amount of patenting activity and innovation performance could not be found, especially comparing Toyota's technical performance to its patenting activity. However, there have been hints in showing a relation between the change in patenting behaviour and technical performance, especially for brands at a non-Asian level of patenting. The discrepancy between patenting activity and technical improvement furthermore hints at the gap that this work aimed at closing. For research concerned with the external influence on innovative processes in the automotive sector, a focus on actual outcomes of innovative processes seems more sensible than concentrating on the innovative activities itself. Hence, in aiming at understanding innovative activities in the automotive sector, implementing a technometric approach being able to capture the actual outcome appears to be a rewarding choice

As mentioned, the primary goal of this work was the initial introduction of a new perspective on innovative processes in the automotive sector and the building of a new database using a technometric approach to do so, hence providing a descriptive set of results to understand the development of the sector in the last 15 years. Therefore, it is also meant as a basis for future work to build on in more detail. The findings in this work could further be enhanced in broadening the knowledge base behind. Through addition of dedicated engineering knowledge, experienced imbalances between the different engine sizes in attempting to harmonise their figures could be explained physically and hence overcome. The database, here concentrating on one of the major markets and only a selection of car classes and engines, could be broadened to a fully global approach, including all markets, all models and all engines to draw an absolutely accurate picture of the international automotive industry. Furthermore, the data to be collected could heavily be expanded in including more technical figures of the engine to be able to gain a more in-depth understanding of the occurred engine development to specify the directions the industry or certain manufacturers are following and being able to draw clear connections between the implementation of emission standards on certain pollutants and appropriate engine development. This broader set of data then would require added statistical complexity to accurately process and analyse the data to reveal accurate results.

The possibilities to add complexity are virtually endless, but a cornerstone has been set.

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## 8 Appendices

### 8.1 Technical Performance Figures

#### 8.1.1 BMW

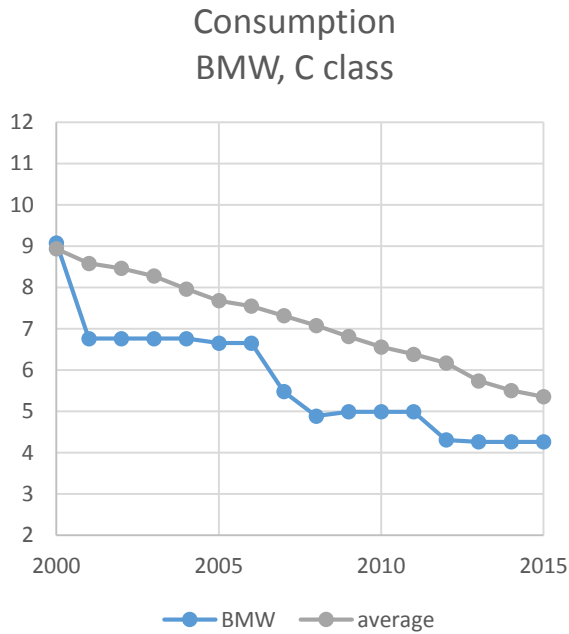


Figure 48: Consumption, BMW, class C

-53%

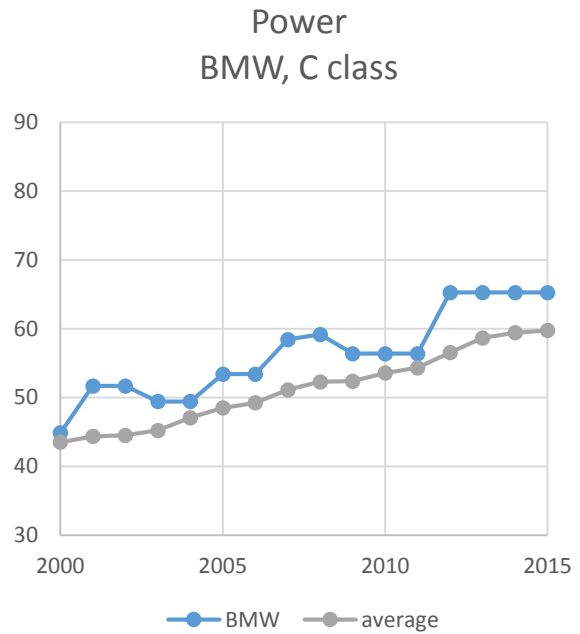


Figure 49: Power, BMW, class C

45%

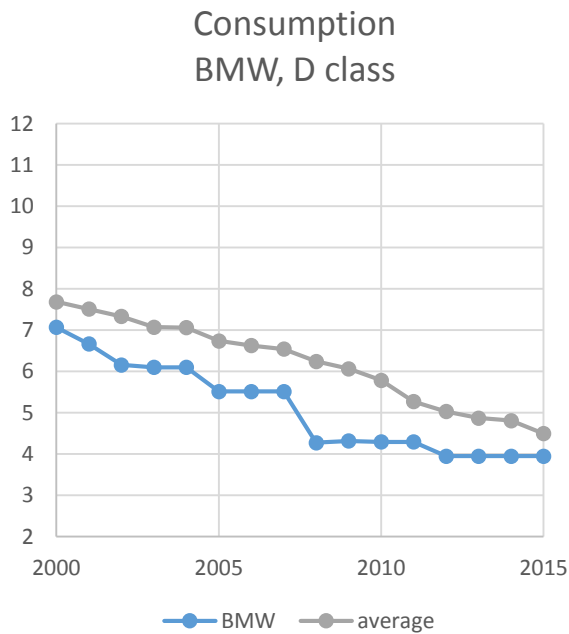


Figure 50: Consumption, BMW, class D

-44%

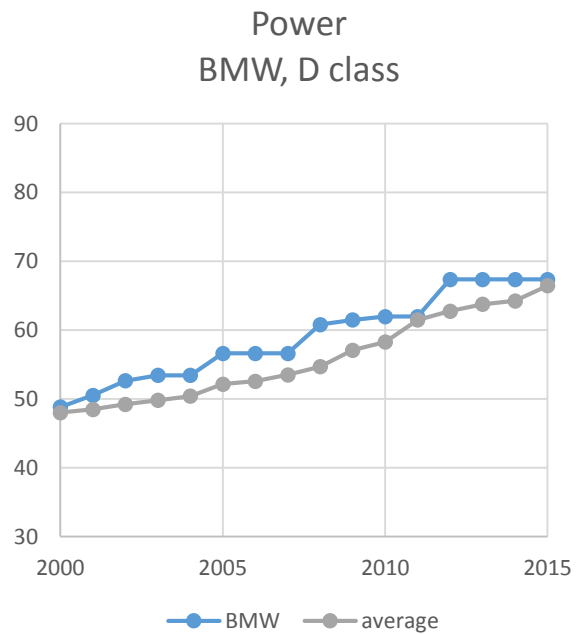


Figure 51: Power, BMW, class D

38%



Consumption  
BMW, E class

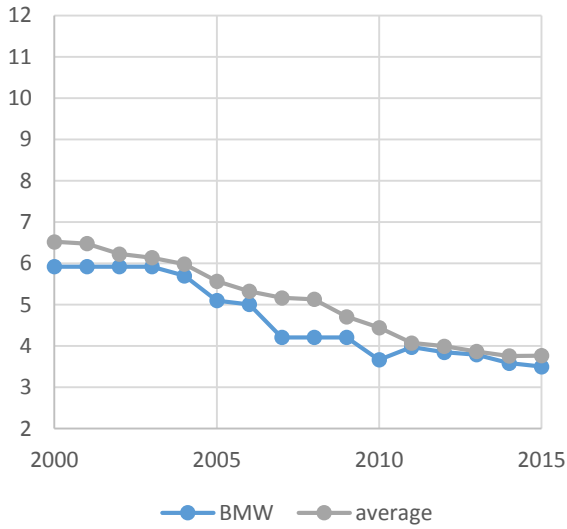


Figure 52: Consumption, BMW, class E

-41%

Power  
BMW, E class

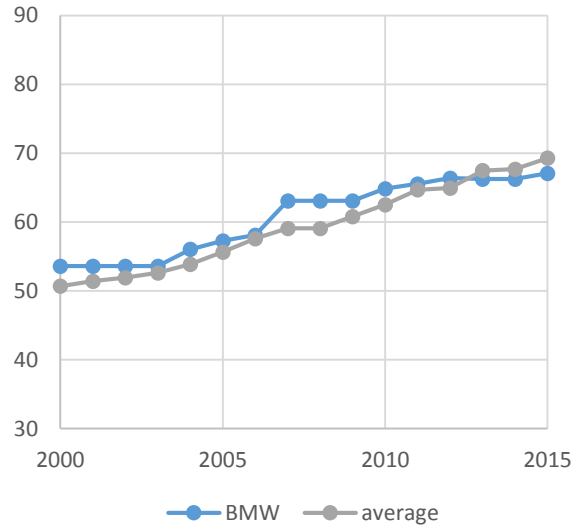


Figure 53: Power, BMW, class E

25%

8.1.2 Fiat

Consumption  
Fiat, B class

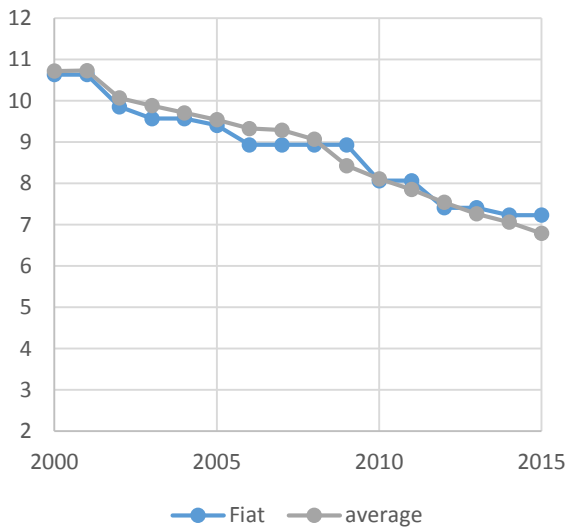


Figure 54: Consumption, Fiat, class B

-32%

Power  
Fiat, B class

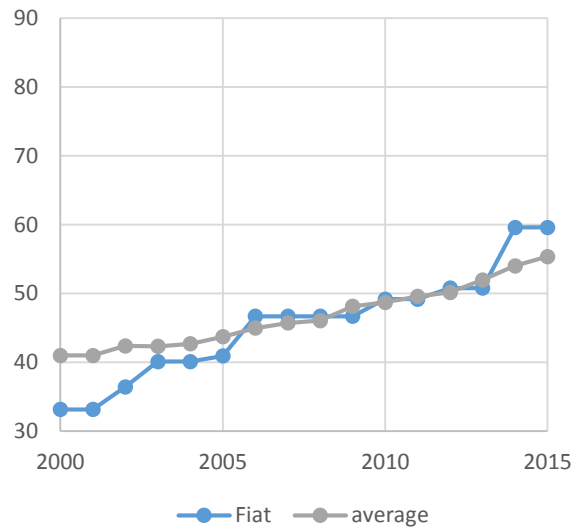


Figure 55: Power, Fiat, class B

80%

Consumption  
Fiat, C class

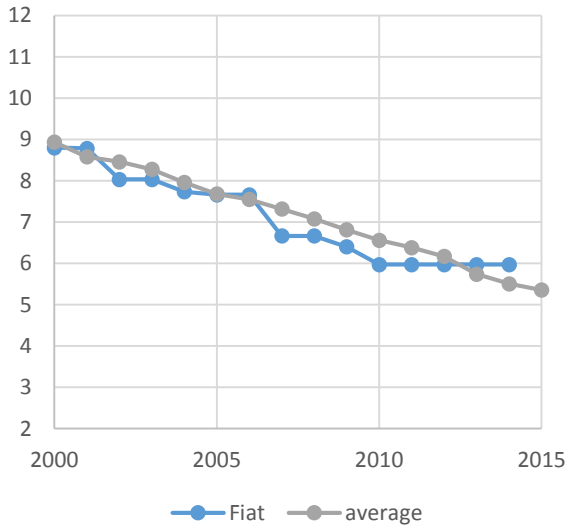


Figure 56: Consumption, Fiat, class C

-32%

Power  
Fiat, C class

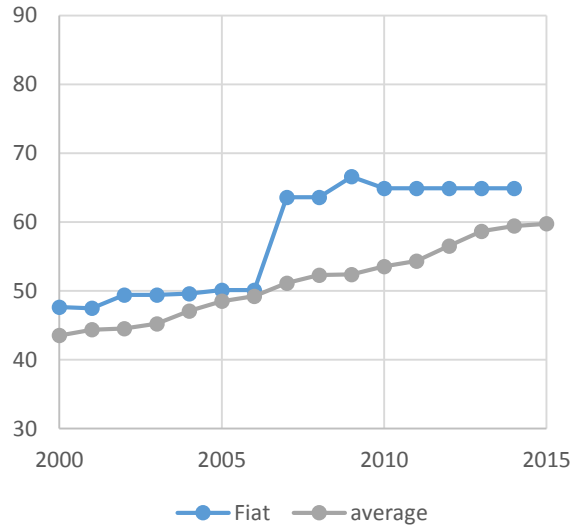


Figure 57: Power, Fiat, class C

36%

Consumption  
Fiat, D class

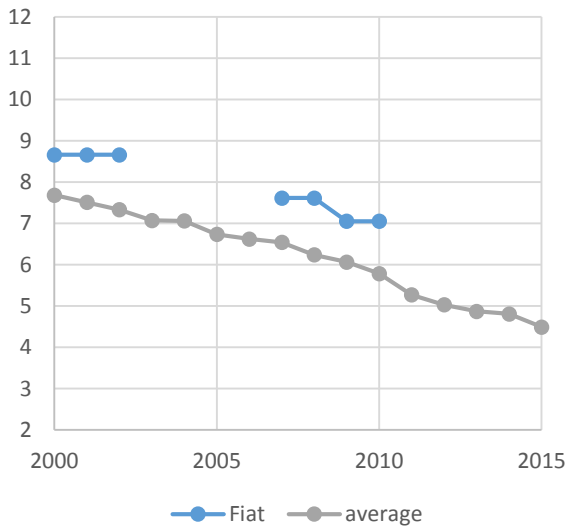


Figure 58: Consumption, Fiat, class D

-19%

Power  
Fiat, D class

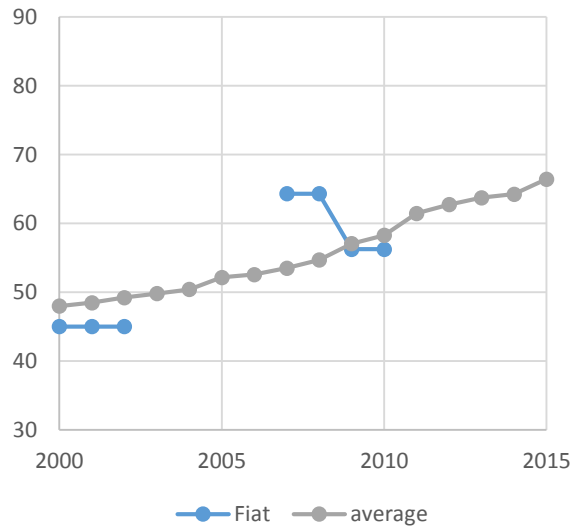


Figure 59: Power, Fiat, class D

25%

8.1.3 Ford

Consumption  
Ford, B class

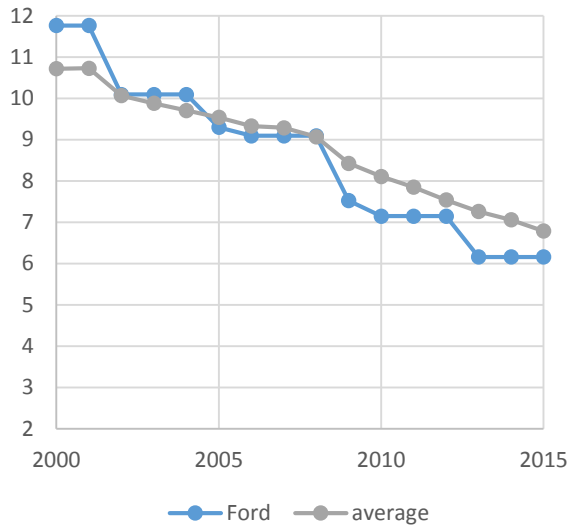


Figure 60: Consumption, Ford, class B

-48%

Power  
Ford, B class

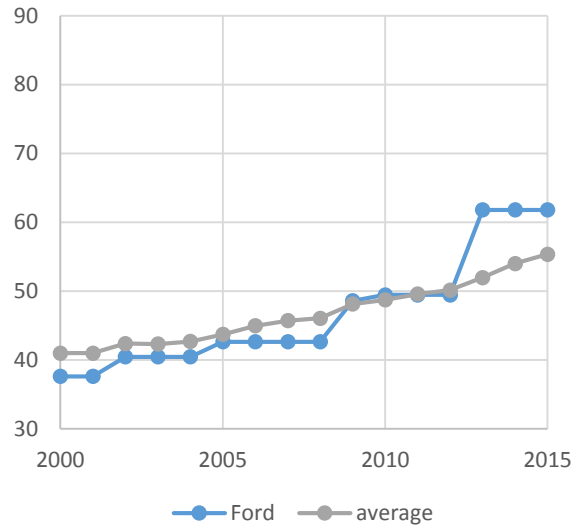


Figure 61: Power, Ford, class B

64%

Consumption  
Ford, C class

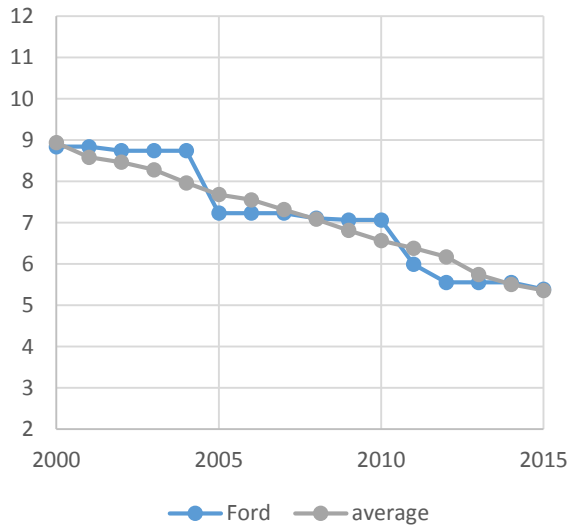


Figure 62: Consumption, Ford, class C

-39%

Power  
Ford, C class

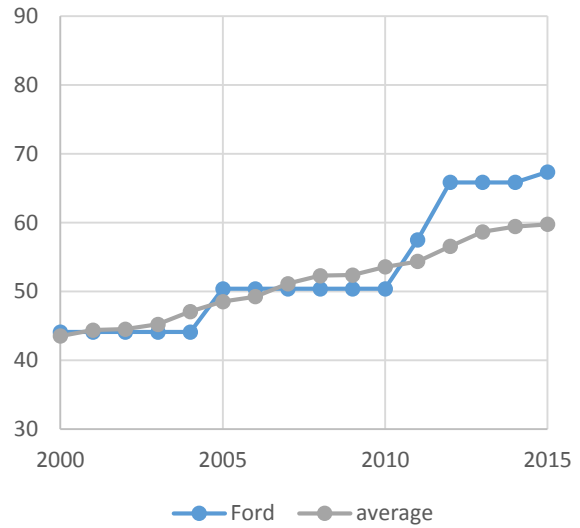


Figure 63: Power, Ford, class C

53%

Consumption  
Ford, D class

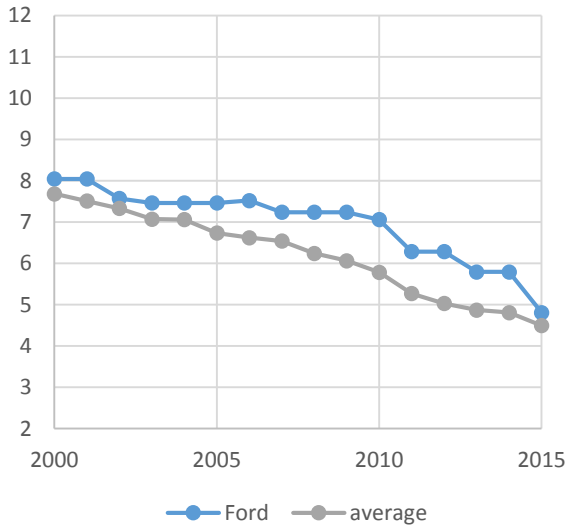


Figure 64: Consumption, Ford, class D

-40%

Power  
Ford, D class

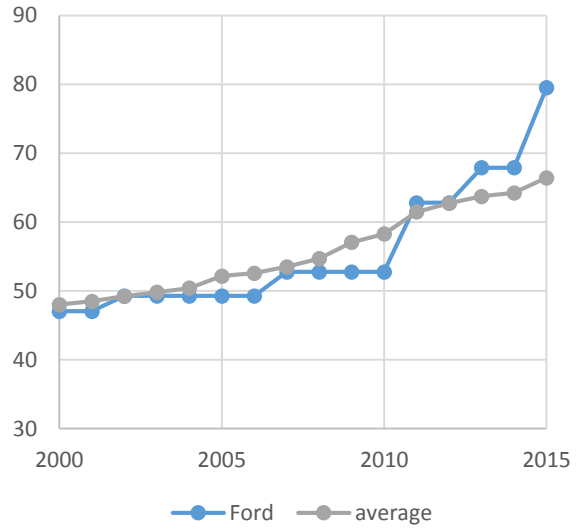


Figure 65: Power, Ford, class D

69%

#### 8.1.4 Honda

Consumption  
Honda, B class

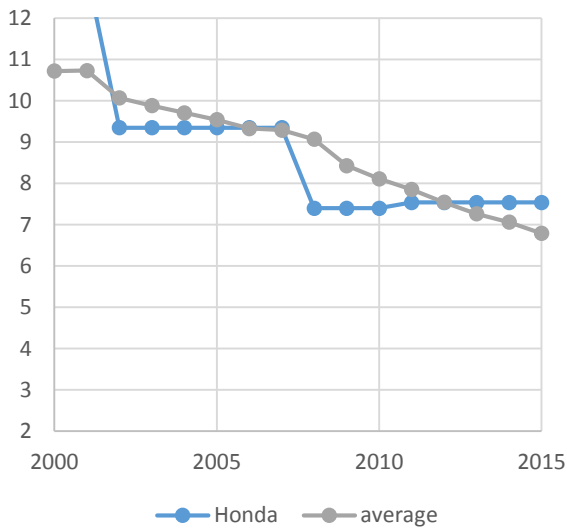


Figure 66: Consumption, Honda, class B

-43%

Power  
Honda, B class

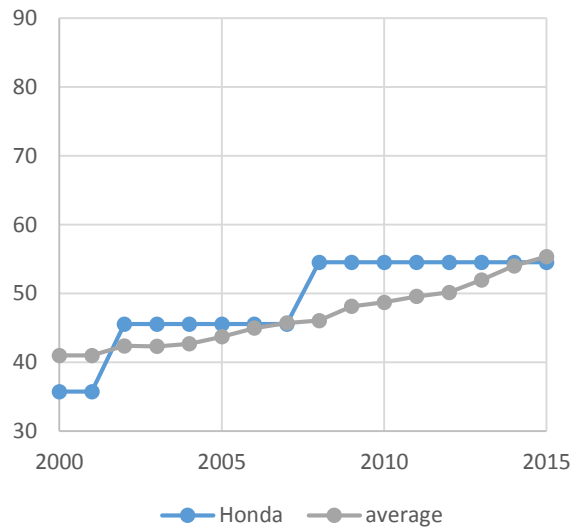


Figure 67: Power, Honda, class B

53%

Consumption  
Honda, C class

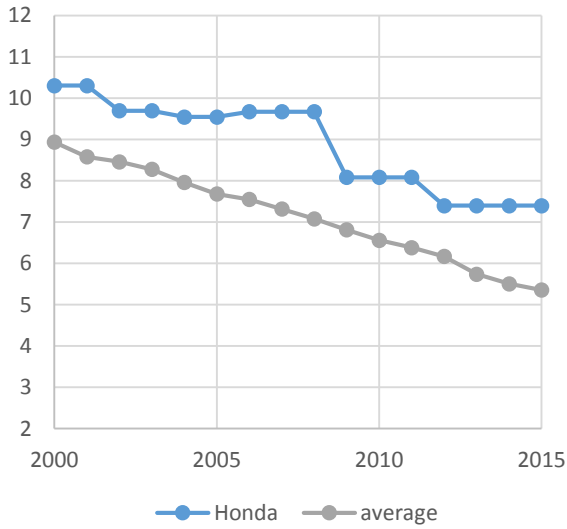


Figure 68: Consumption, Honda, class C

-28%

Power  
Honda, C class

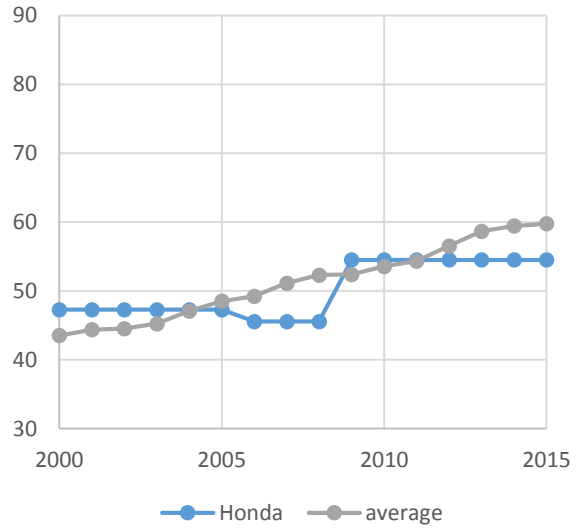


Figure 69: Power, Honda, class C

15%

Consumption  
Honda, D class

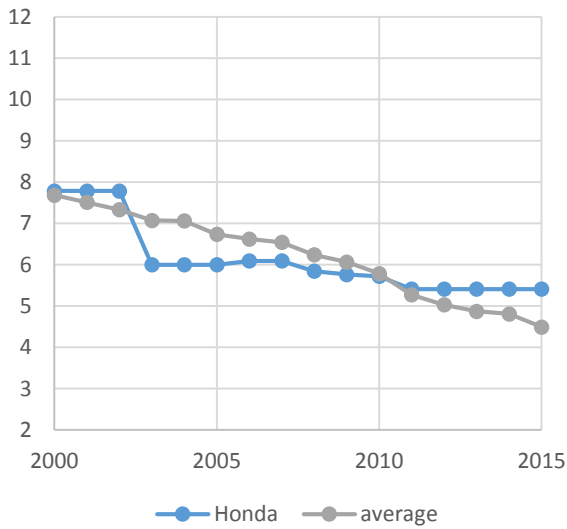


Figure 70: Consumption, Honda, class D

-31%

Power  
Honda, D class

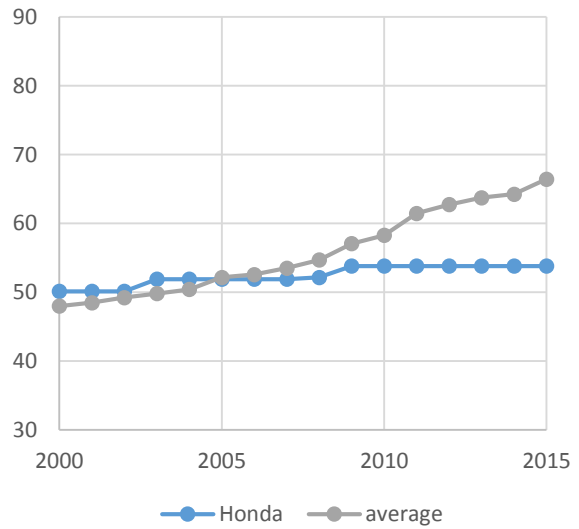


Figure 71: Power, Honda, class D

7%

8.1.5 Hyundai

Consumption  
Hyundai, B class

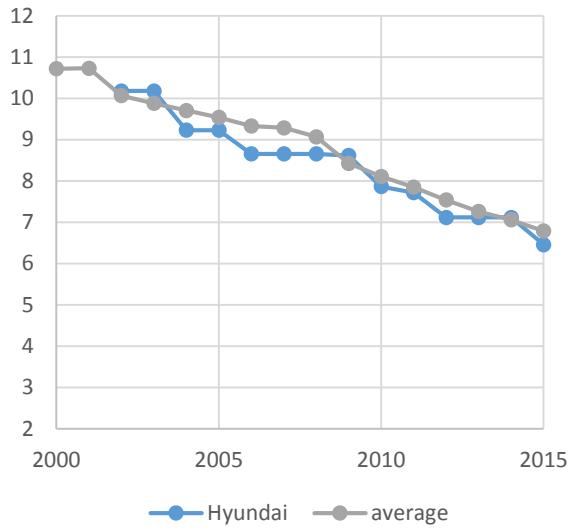


Figure 72: Consumption, Hyundai, class B

-37%

Power  
Hyundai, B class

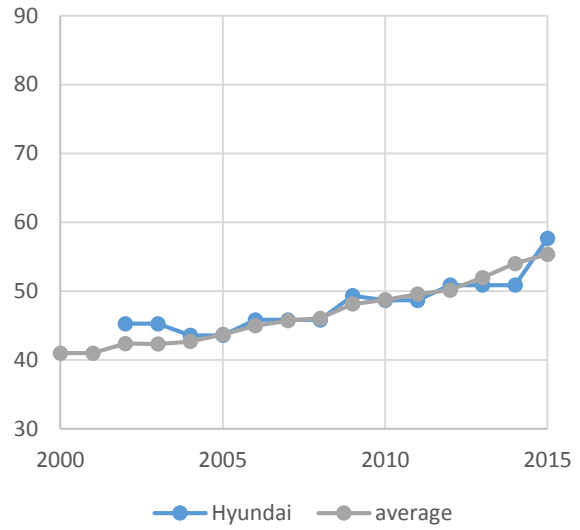


Figure 73: Power, Hyundai, class B

27%

Consumption  
Hyundai, C class

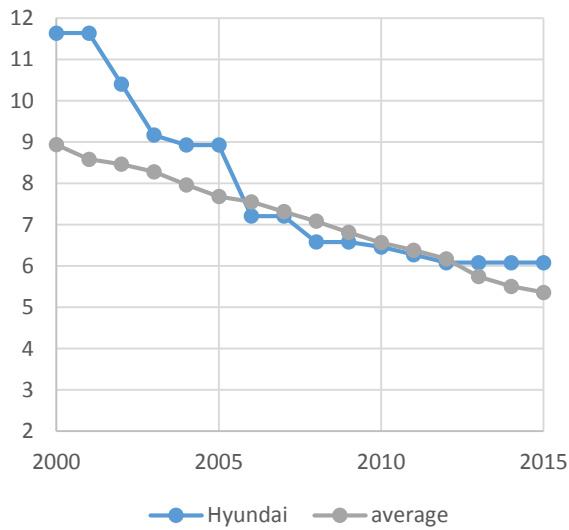


Figure 74: Consumption, Hyundai, class C

-48%

Power  
Hyundai, C class

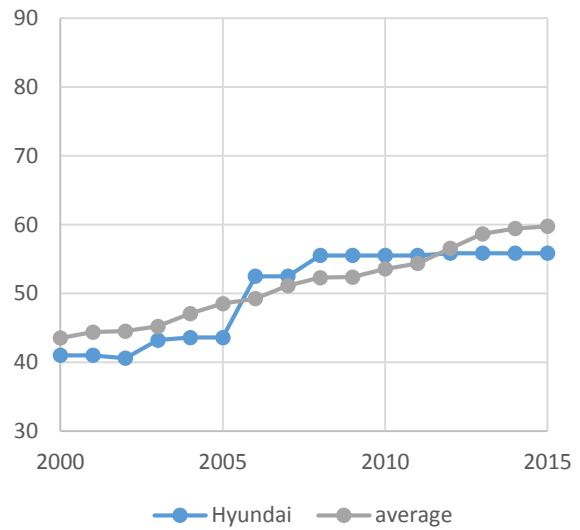


Figure 75: Power, Hyundai, class C

36%

Consumption  
Hyundai, D class

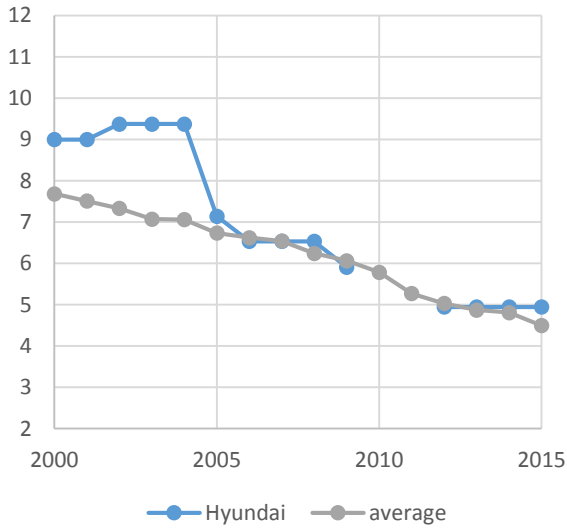


Figure 76: Consumption, Hyundai, class D

-45%

Power  
Hyundai, D class

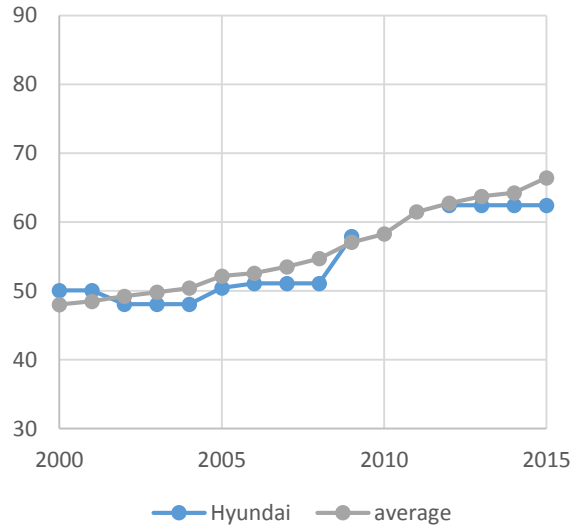


Figure 77: Power, Hyundai, class D

25%

### 8.1.6 Jaguar

Consumption  
Jaguar, D class

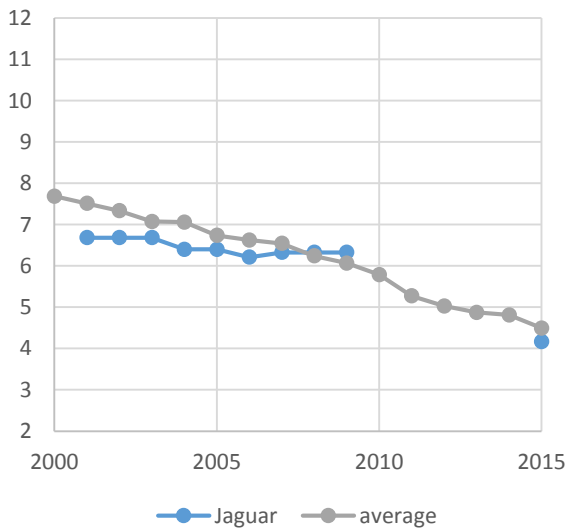


Figure 78: Consumption, Jaguar, class D

-38%

Power  
Jaguar, D class

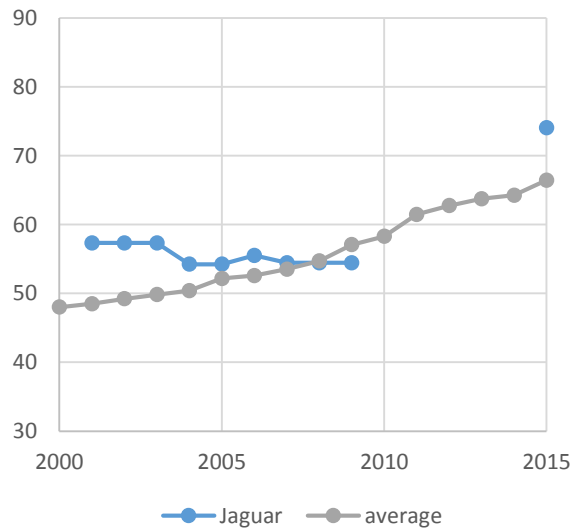


Figure 79: Power, Jaguar, class D

29%

Consumption  
Jaguar, E class

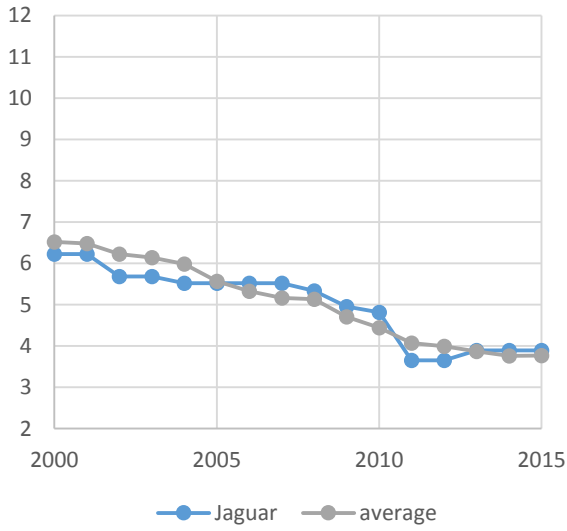


Figure 80: Consumption, Jaguar, class E

-37%

Power  
Jaguar, E class

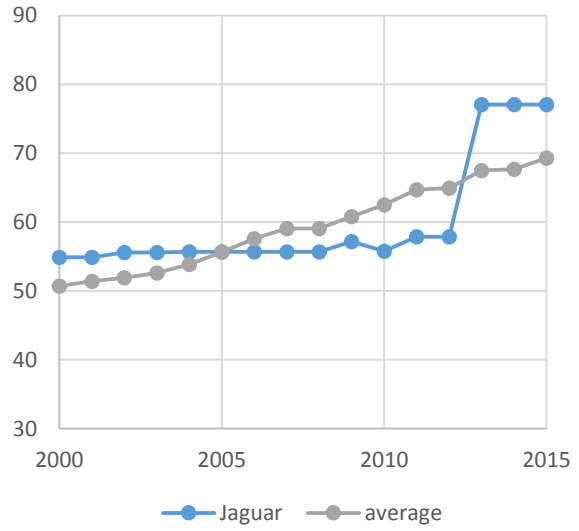


Figure 81: Power, Jaguar, class E

40%

8.1.7 Mazda

Consumption  
Mazda, B class

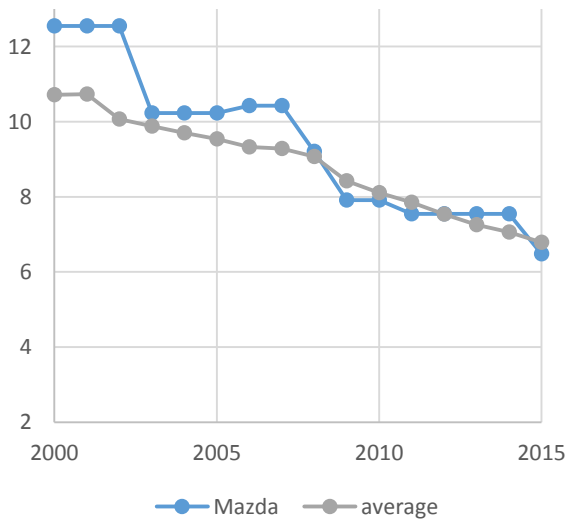


Figure 82: Consumption, Mazda, class B

-48%

Power  
Mazda, B class

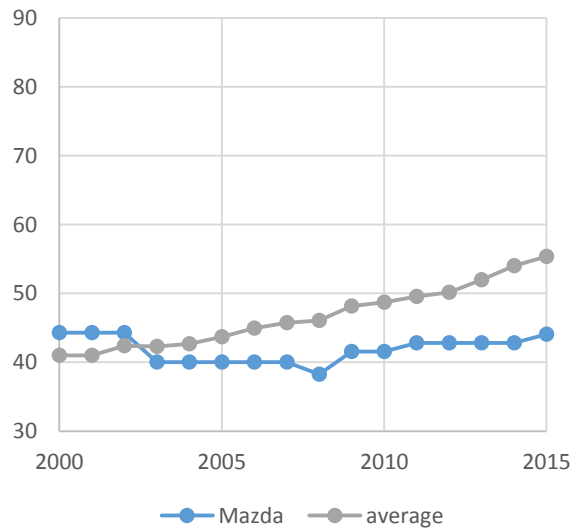


Figure 83: Power, Mazda, class B

0%



Consumption  
Mazda, C class

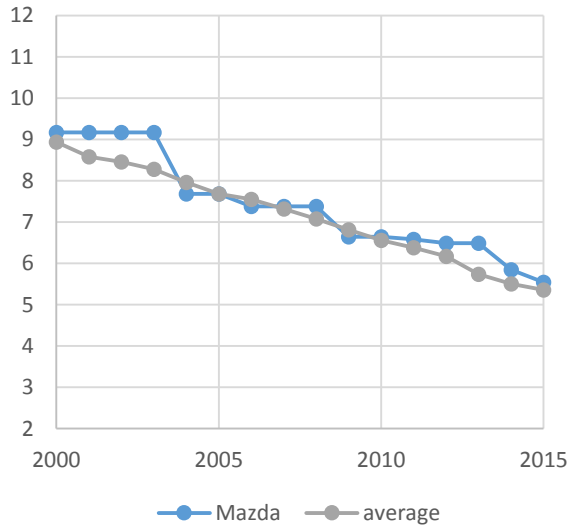


Figure 84: Consumption, Mazda, class C

-40%

Power  
Mazda, C class

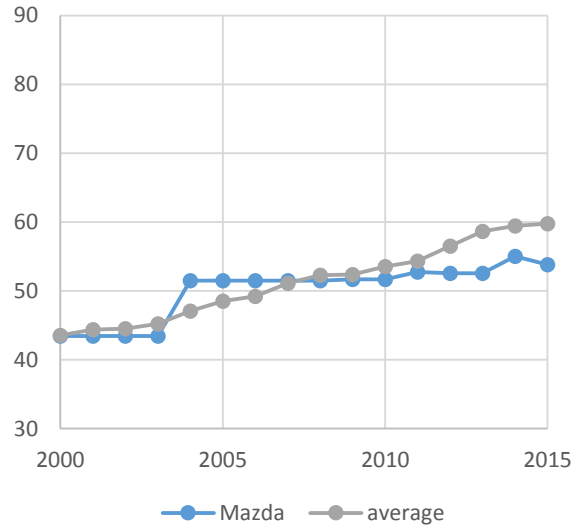


Figure 85: Power, Mazda, class C

24%

Consumption  
Mazda, D class

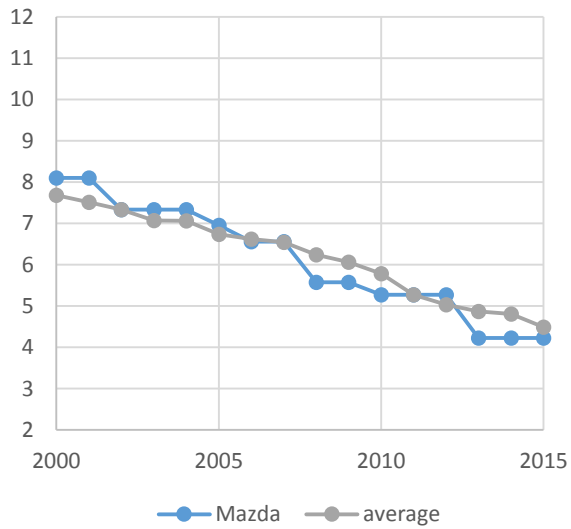


Figure 86: Consumption, Mazda, class D

-48%

Power  
Mazda, D class

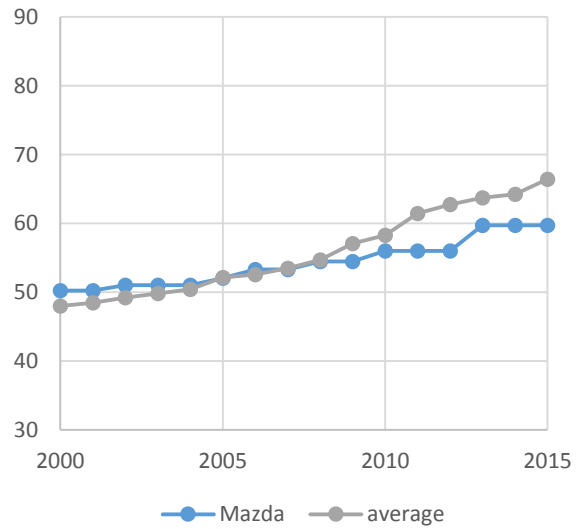


Figure 87: Power, Mazda, class D

19%

8.1.8 Mercedes

Consumption  
Mercedes, C class

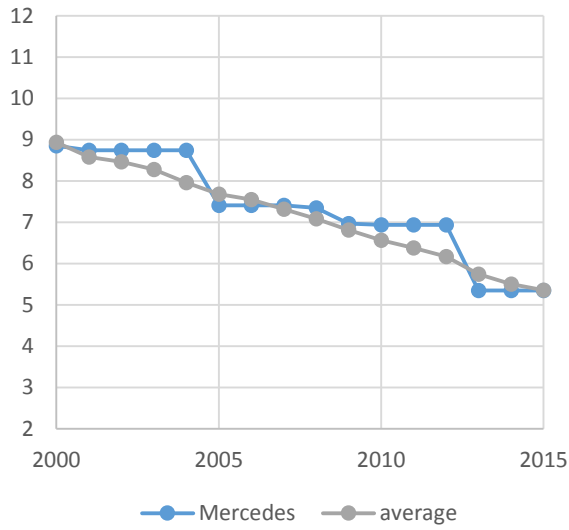


Figure 88: Consumption, Mercedes, class C

-40%

Power  
Mercedes, C class

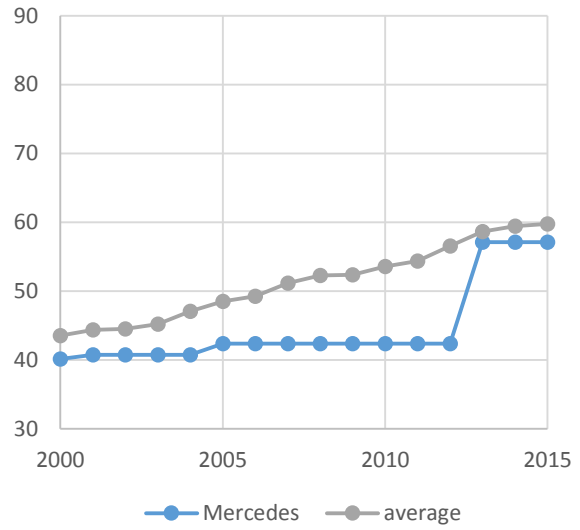


Figure 89: Power, Mercedes, class C

42%

Consumption  
Mercedes, D class

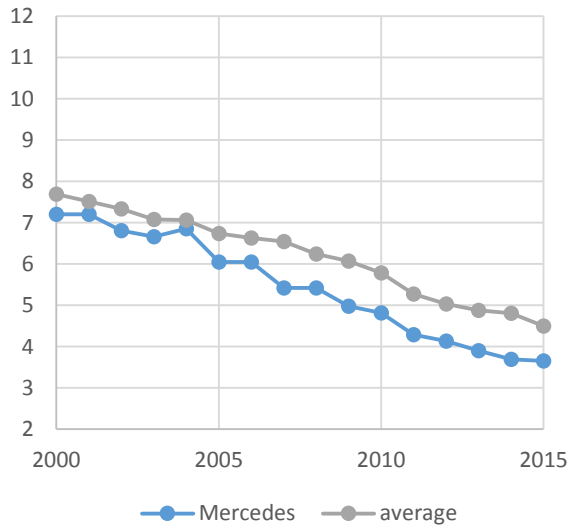


Figure 90: Consumption, Mercedes, class D

-49%

Power  
Mercedes, D class

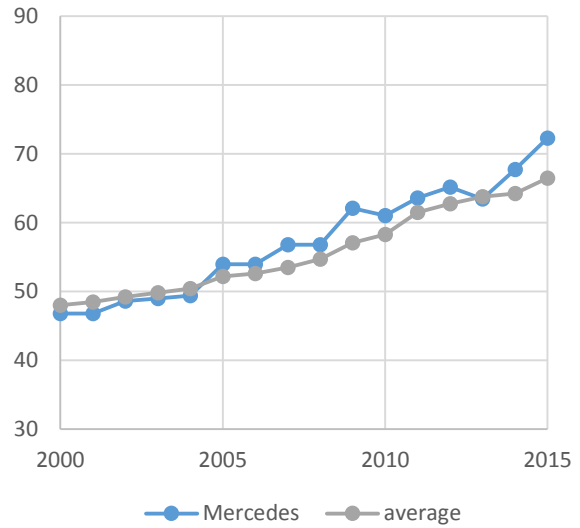


Figure 91: Power, Mercedes, class D

54%

Consumption  
Mercedes, E class

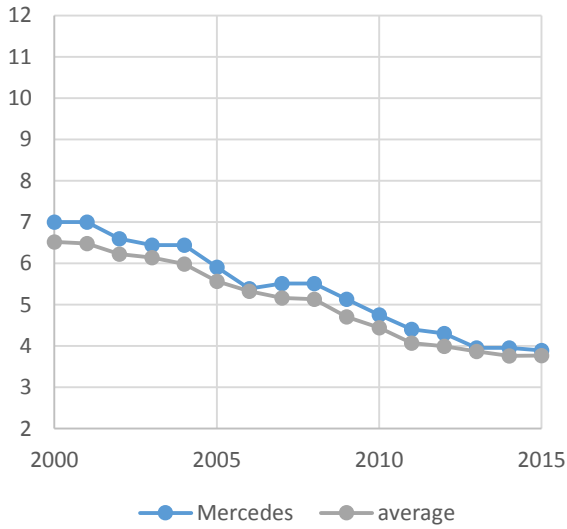


Figure 92: Consumption, Mercedes, class E

-44%

Power  
Mercedes, E class

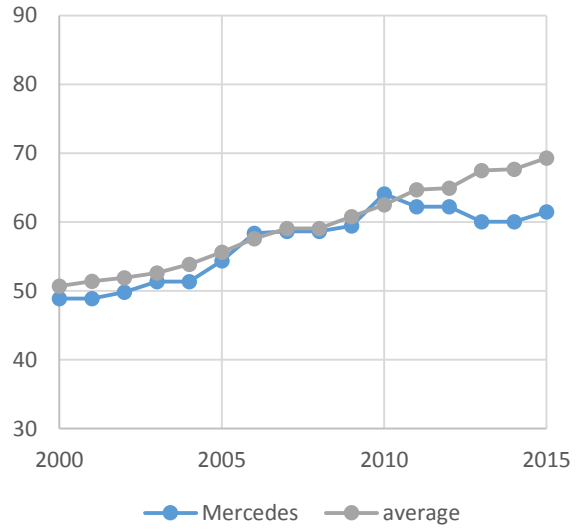


Figure 93: Power, Mercedes, class E

26%

### 8.1.9 Nissan

Consumption  
Nissan, B class

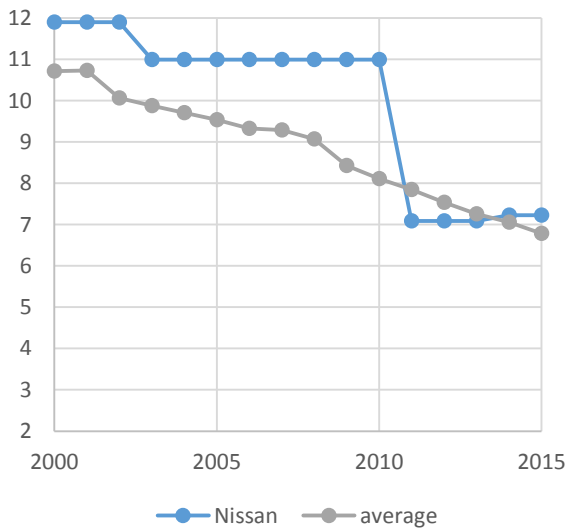


Figure 94: Consumption, Nissan, class B

-39%

Power  
Nissan, B class

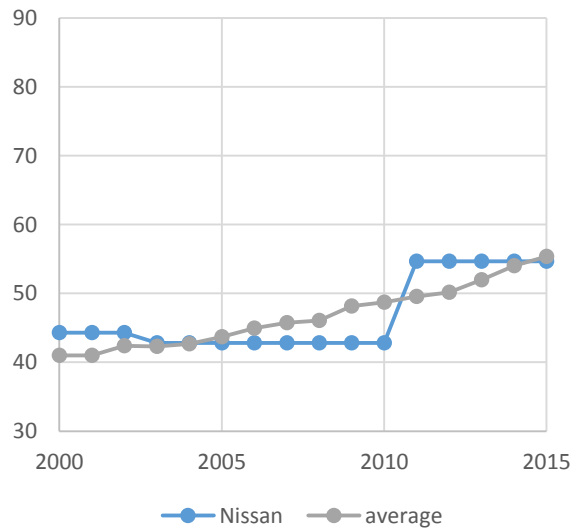


Figure 95: Power, Nissan, class B

23%

Consumption  
Nissan, C class

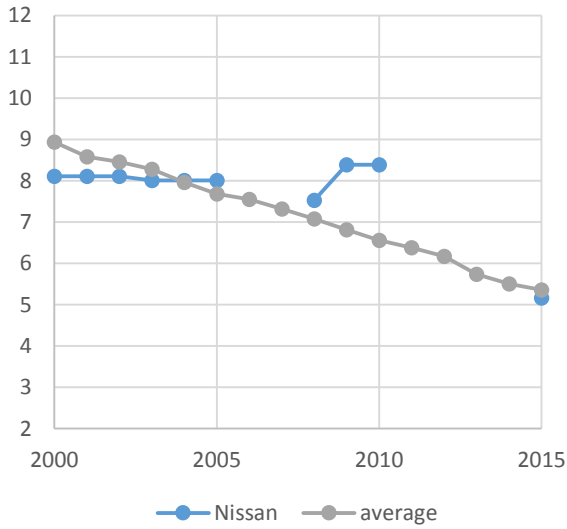


Figure 96: Consumption, Nissan, class C

-36%

Power  
Nissan, C class

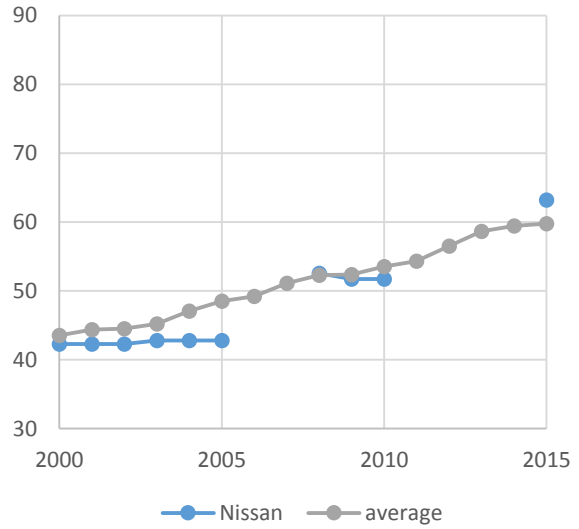


Figure 97: Power, Nissan, class C

50%

8.1.10 Opel

Consumption  
Opel, B class

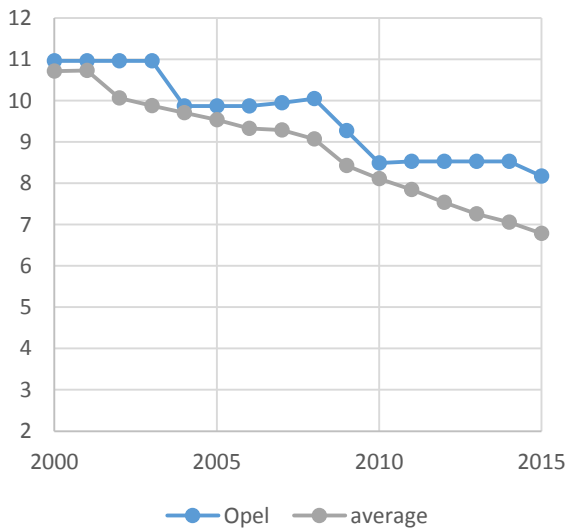


Figure 98: Consumption, Opel, class B

-25%

Power  
Opel, B class

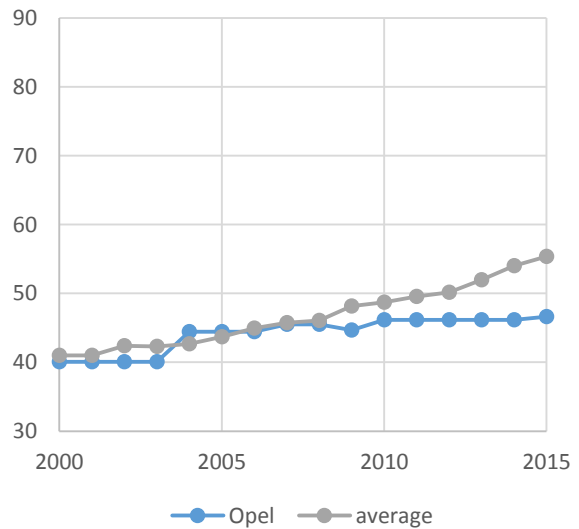


Figure 99: Power, Opel, class B

16%

Consumption  
Opel, C class

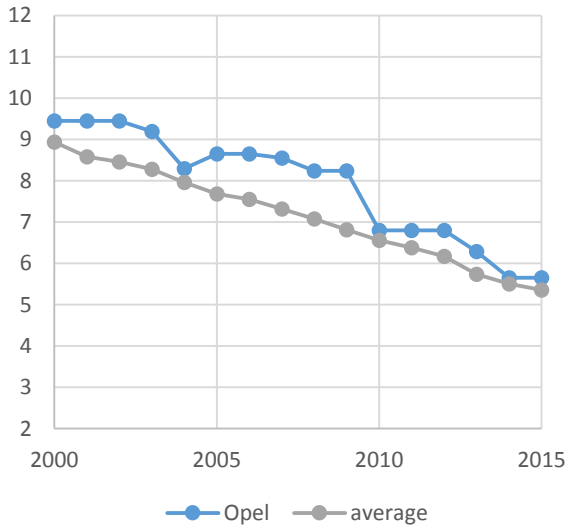


Figure 100: Consumption, Opel, class C

-40%

Power  
Opel, C class

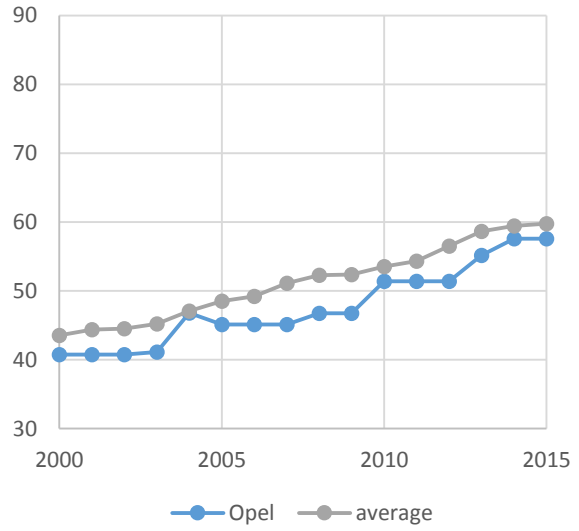


Figure 101: Power, Opel, class C

41%

Consumption  
Opel, D class

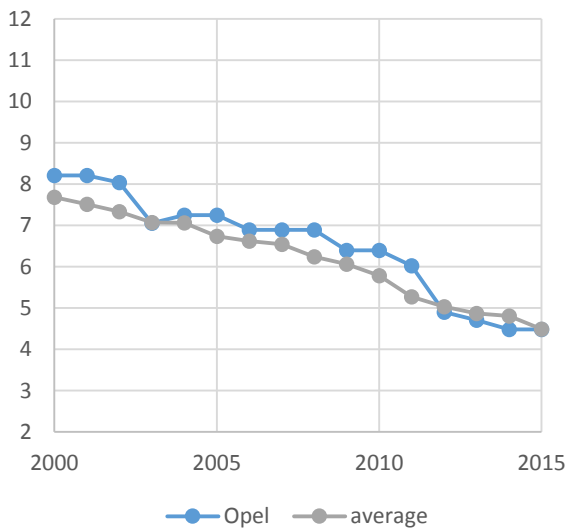


Figure 102: Consumption, Opel, class D

-45%

Power  
Opel, D class

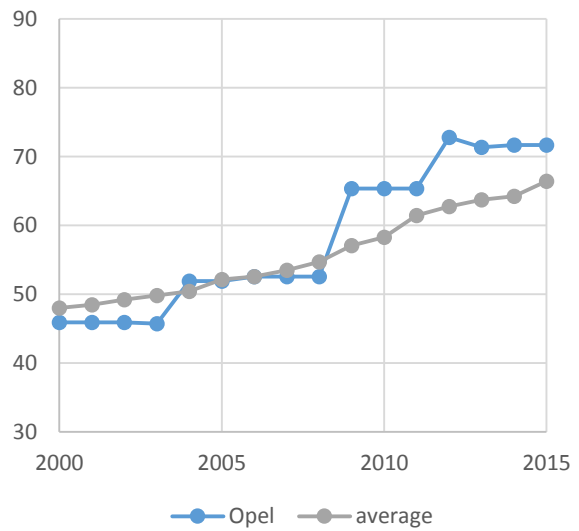


Figure 103: Power, Opel, class D

56%

8.1.11 Peugeot

Consumption  
Peugeot, B class

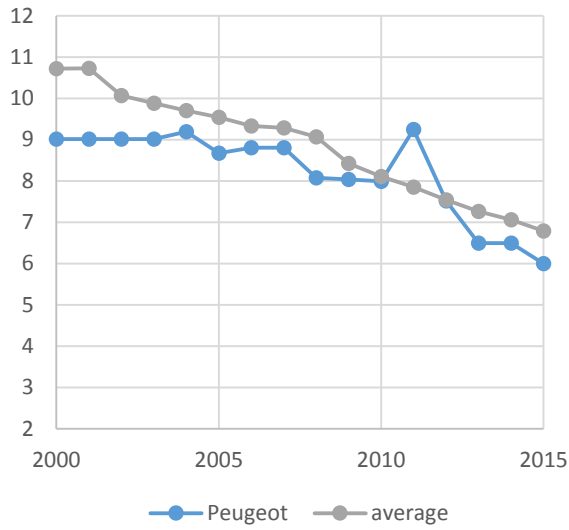


Figure 104: Consumption, Peugeot, class B

-33%

Power  
Peugeot, B class

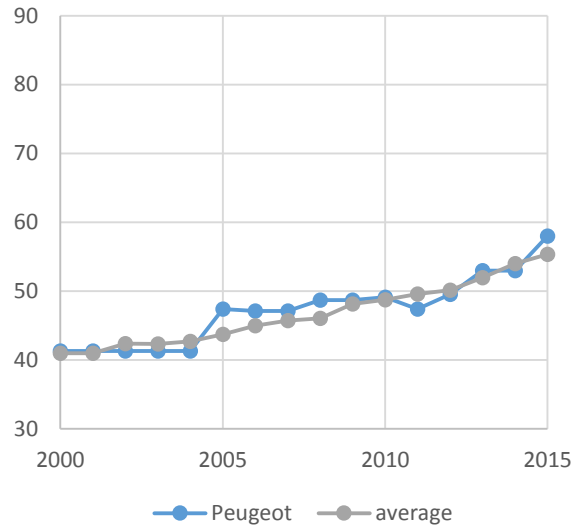


Figure 105: Power, Peugeot, class B

40%

Consumption  
Peugeot, C class

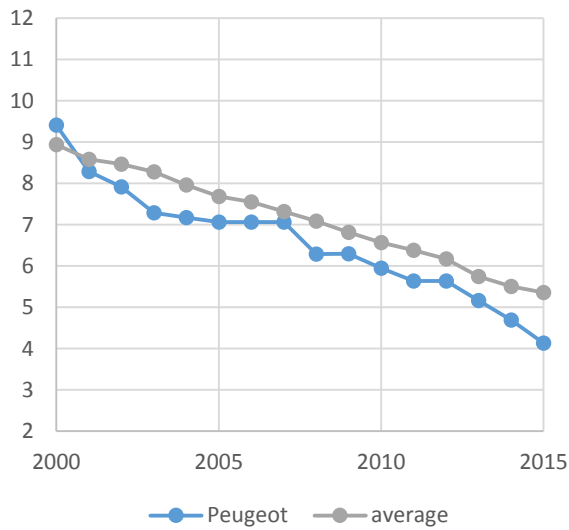


Figure 106: Consumption, Peugeot, class C

-56%

Power  
Peugeot, C class

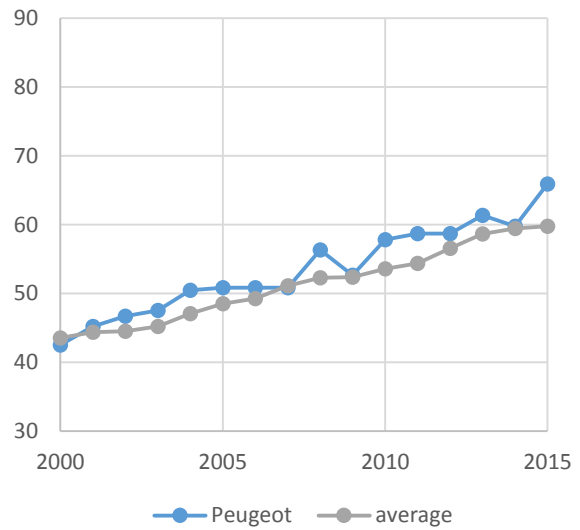


Figure 107: Power, Peugeot, class C

55%

Consumption  
Peugeot, D class

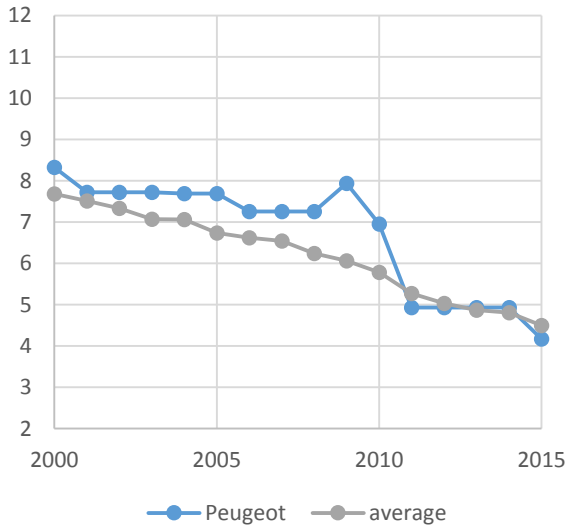


Figure 108: Consumption, Peugeot, class D

-50%

Power  
Peugeot, D class

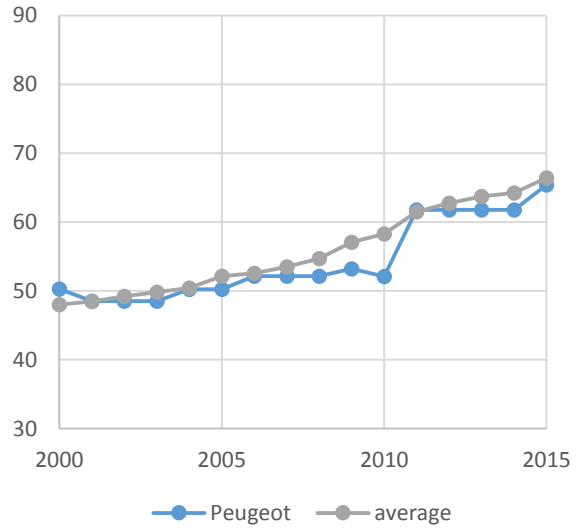


Figure 109: Power, Peugeot, class D

30%

8.1.12 Renault

Consumption  
Renault, B class

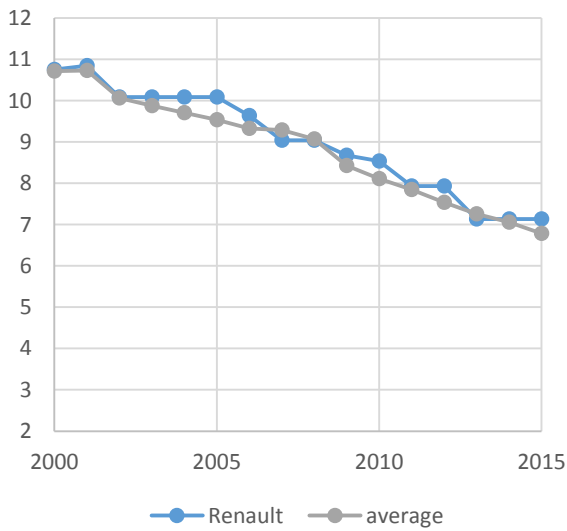


Figure 110: Consumption, Renault, class B

-34%

Power  
Renault, B class

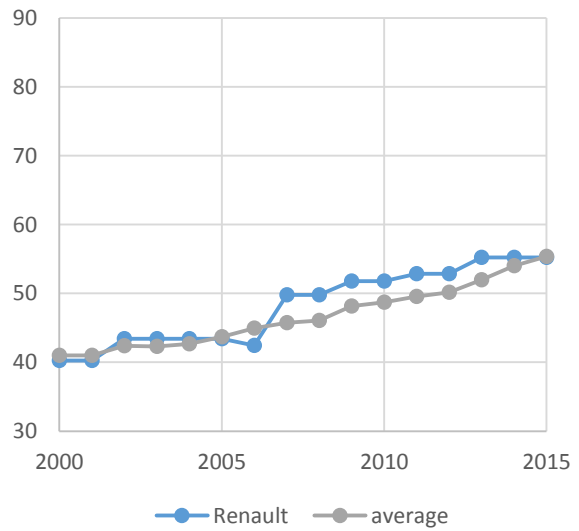


Figure 111: Power, Renault, class B

37%

Consumption  
Renault, C class

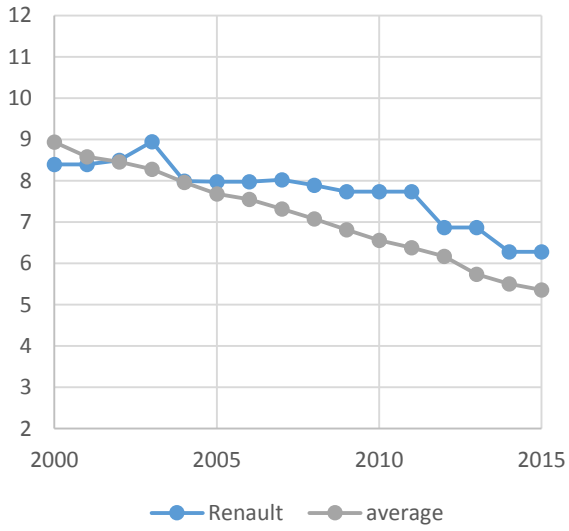


Figure 112: Consumption. Renault, class C

-25%

Power  
Renault, C class

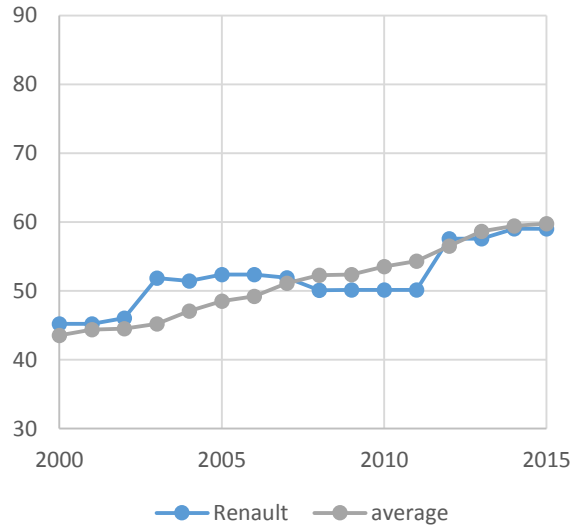


Figure 113: Power, Renault, class C

31%

Consumption  
Renault, D class

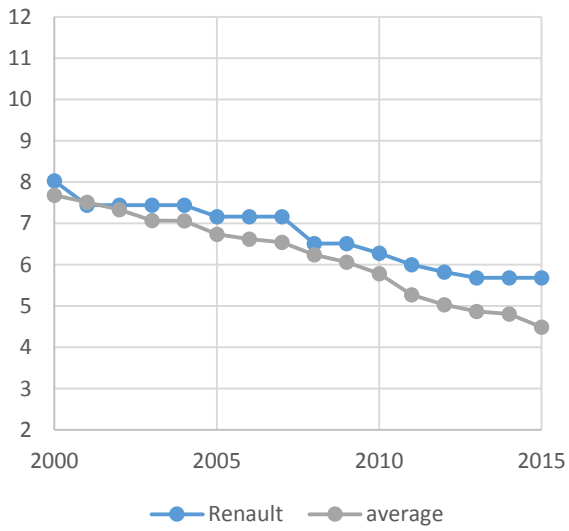


Figure 114: Consumption, Renault, class D

-29%

Power  
Renault, D class

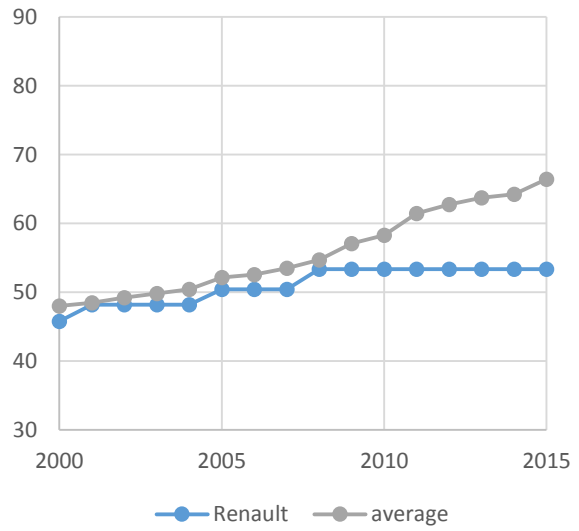


Figure 115: Power, Renault, class D

17%



### 8.1.13 Toyota

Consumption  
Toyota, B class

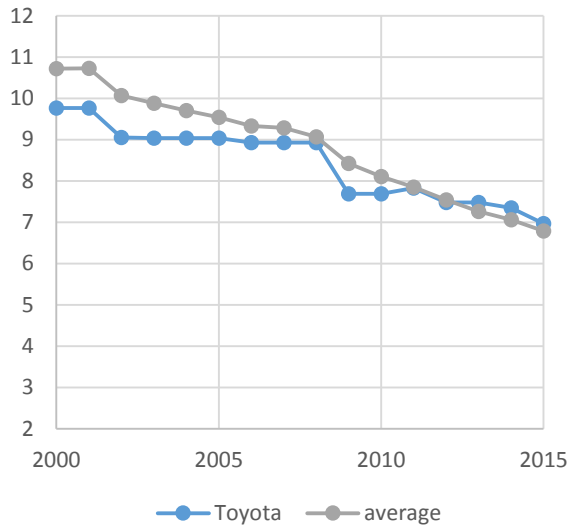


Figure 116: Consumption, Toyota, class B

-29%

Power  
Toyota, B class

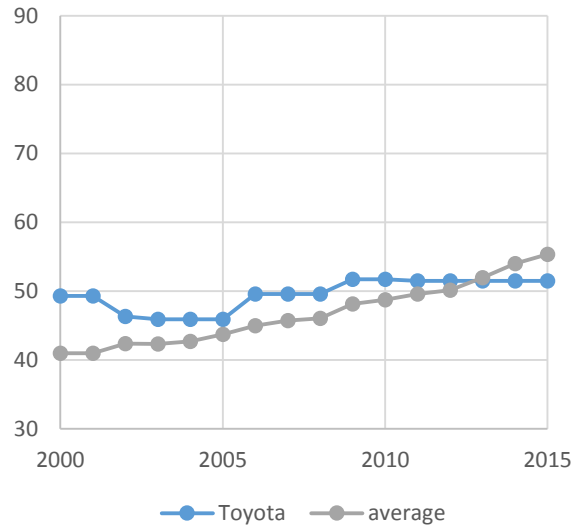


Figure 117: Power, Toyota, class B

4%

Consumption  
Toyota, C class

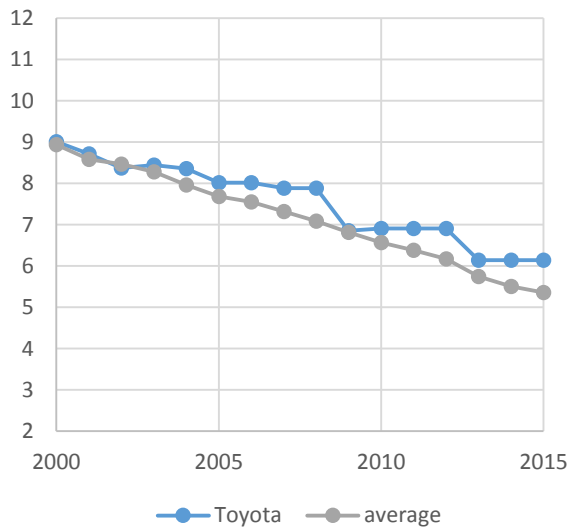


Figure 118: Consumption, Toyota, class C

-32%

Power  
Toyota, C class

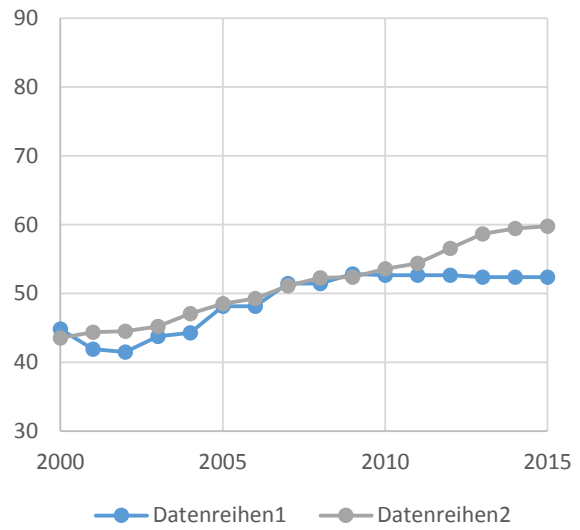


Figure 119: Power, Toyota, class C

17%

Consumption  
Toyota, D class

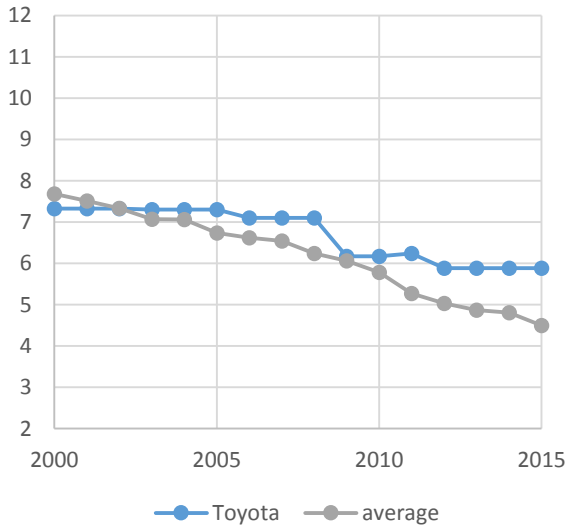


Figure 120: Consumption, Toyota, class D

-20%

Power  
Toyota, D class

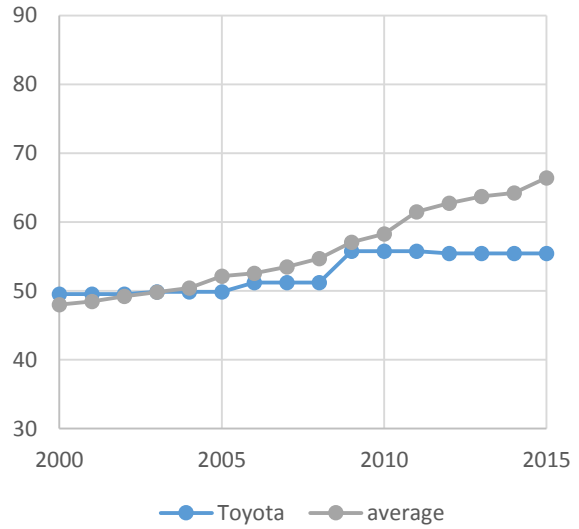


Figure 121: Power, Toyota, class D

12%

8.1.14 Volvo

Consumption  
Volvo, D class

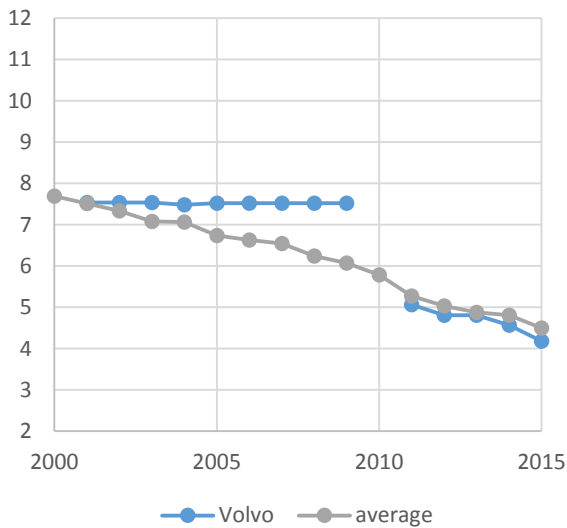


Figure 122: Consumption, Volvo, class D

-45%

Power  
Volvo, D class

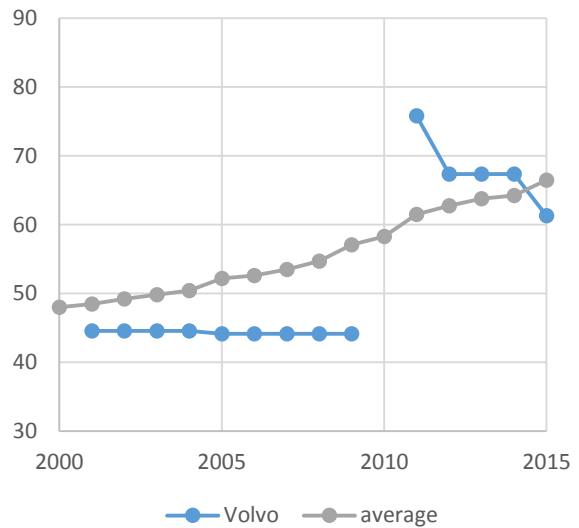


Figure 123: Power, Volvo, class D

38%

Consumption  
Volvo, E class

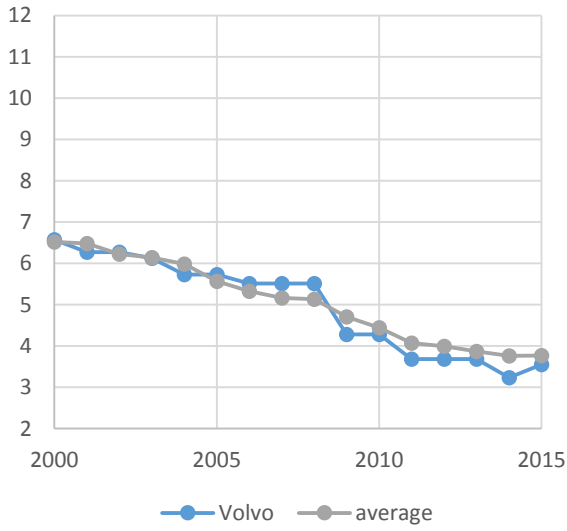


Figure 124: Consumption, Volvo, class E

-46%

Power  
Volvo, E class

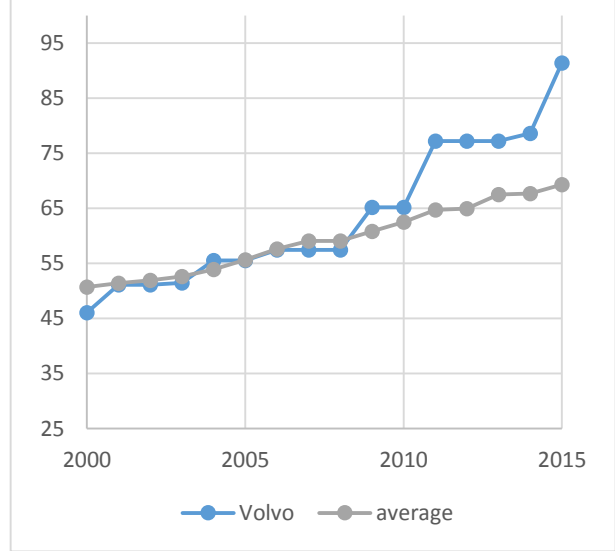


Figure 125: Power, Volvo, class E

98%

8.1.15 VW

Consumption  
Volkswagen, B class

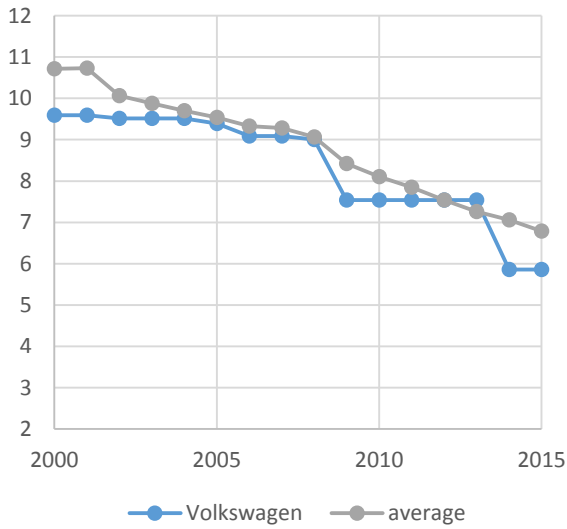


Figure 126: Consumption, Volkswagen, class B

-39%

Power  
Volkswagen, B class

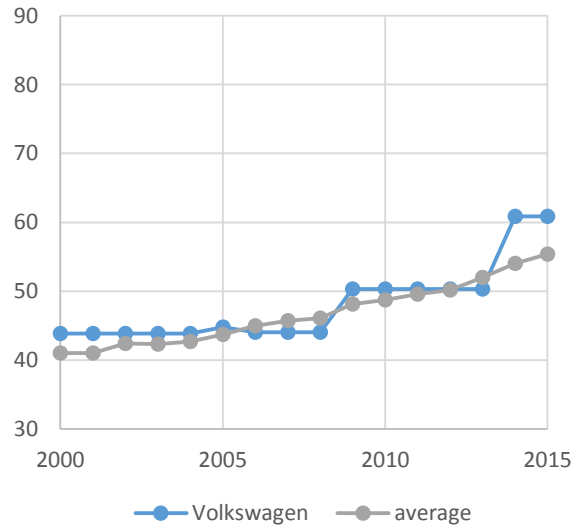


Figure 127: Power, Volkswagen, class B

39%

Consumption  
Volkswagen, C class

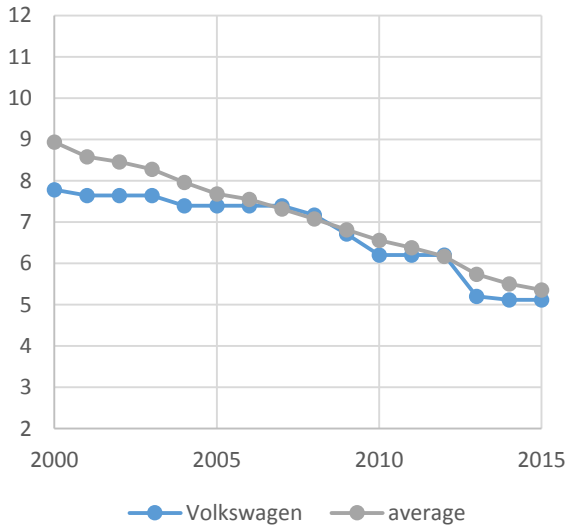


Figure 128: Consumption, Volkswagen, class C

-34%

Power  
Volkswagen, C class

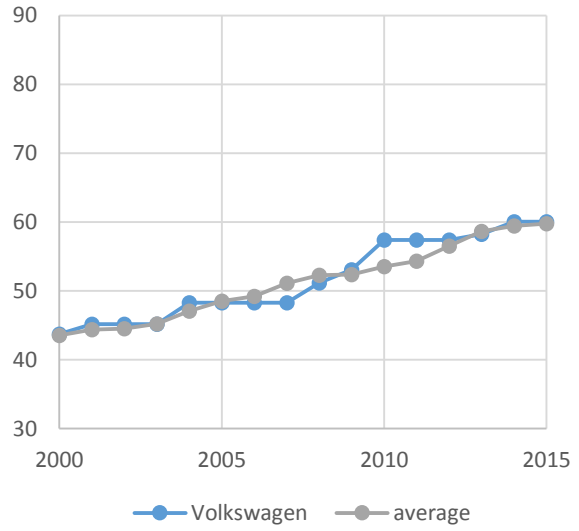


Figure 129: Power, Volkswagen, class C

37%

Consumption  
Volkswagen, D class

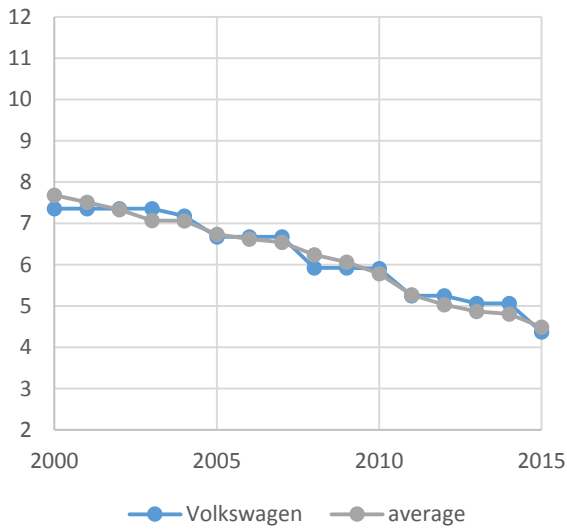


Figure 130: Consumption, Volkswagen, class D

-41%

Power  
Volkswagen, D class

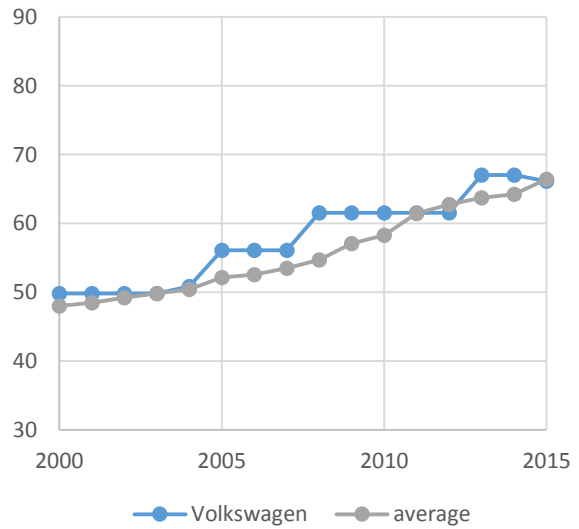


Figure 131: Power, Volkswagen, class D

33%