Cristina De Stefano, M., Montes-Sancho, M. J., & Busch, T. (2016). A natural resource-based view of climate change: Innovation challenges in the automobile industry. *Journal of Cleaner Production*, 139, pp. 1436-1448.

DOI: 10.1016/j.jclepro.2016.08.023

A natural resource-based view of climate change: Innovation challenges in the automobile industry

Please cite as follows:

De Stefano, M. C., Montes-Sancho, M. J., & Busch, T. (2016). A natural resource-based view of climate change: Innovation challenges in the automobile industry. *Journal of Cleaner Production*, *139*, 1436-1448. https://doi.org/10.1016/j.jclepro.2016.08.023

Abstract

In recent years, uncertainty about climate change policies has deeply altered the competitive landscape of the automobile industry, and highlighted the key role that companies can play in reducing global CO_2 emissions through technological innovation. Given the complexity of the innovation process in this industry, mainly due to an interactive relationship with the market, this study adopts a socio-technical transition perspective in order to understand the type of technological innovations that automobile companies have developed for reducing CO_2 emissions from their products during a period of regulatory uncertainty. The Natural-Resource-Based View is used as a novel framework to categorize technological innovations into two important sets: product stewardship and clean technology. Product stewardship innovations are characterized by incremental changes in product components, with no substantial modifications of core product concepts. Clean technology innovations are characterized by significant alterations to existing product functionalities, infrastructures and consumer patterns, and imply major restructuring of both manufacturing processes and market acceptance. Under regulatory uncertainty, findings show that significant reductions of CO_2 emissions from vehicles have been due to clean technology innovations. The benefits from clean technologies persist over time. In addition, complementarities between product stewardship and clean technology innovations have occurred, with positive effects on further CO_2 emission reductions. These latter benefits, however, show only short-term effects, suggesting that continuous innovation in product stewardship is necessary in the next few years in this industry to survive in a carbon-constrained market.

Key words: Climate change, product innovation, CO_2 emissions, automobile industry.

1. Introduction

Climate change is one of the most pressing challenges facing society and requires the adoption of prompt and effective innovations in many sectors. This is especially true in those sectors which are heavily dependent on fossil fuel resources, such as chemical, paper or steel, whose processes generate the highest amounts of anthropogenic greenhouse gas (GHG) emissions — the main cause of climate change (Huisingh et al., 2015). Such sectors have been exposed to increasing institutional, customer and social pressures in recent years (Busch and Hoffmann, 2009; Reid and Toffel, 2009; Winn et al., 2011); pressures which have pushed companies towards the adoption of management and technological systems intended to reduce total emissions (Berrone et al., 2013; Howard-Grenville et al., 2014; Liou, 2015; Rietbergen et al., 2015).

After the Kyoto Protocol, however, the importance of changing production and consumption patterns has extended the focus to other industries whose products involve fossil fuel combustion, such as transport. This is the second-largest sector (after electricity) with the highest global CO_2 emissions (23%) (IEA, 2011). CO_2 is one of the most important GHGs, and cause of global concern (Busch and Hoffmann, 2007; Huisingh et al., 2015). Within the transport sector, the automobile industry contributes most to CO_2 production. Although emissions occur at nearly every stage of a vehicle's life cycle[1], and some efforts have been made to reduce process emissions (see, for instance, Ford's reduction emissions submitted to the PhilGARP Program)[2], the use of an automobile accounts for approximately 80% of the total primary energy consumption through its life cycle (Mildenberger and Khare, 2000). In Europe, passenger cars alone are responsible for around 12% of EU CO2 emissions (Pricewaterhouse, 2007). For this reason, the reduction of CO_2 emissions from vehicles has been the focal point of several policy actions in the last years (Rothenberg and Ettlie, 2011). These actions have contributed to making product innovation the target of companies' strategies to reduce CO_2 emissions and survive in the market (KPMG, 2010; McKinsey&Company, 2009; PricewaterhouseCoopers, 2007).

---

[1] Painting, coating and metal casting are the main manufacturing operations where air emissions occur. More than half of all releases and transfers of pollutants originate from the painting and coating operations. Besides that, the largest solid waste streams generated by an automobile assembly plant are wastewater treatment sludges, waste oil, plant trash, and scrap metal (Mildenberger and Khare, 2000).

[2] http://ophelia.sdsu.edu:8080/ford/10-21-2008/microsites/sustainability-report-2007-08/environment-case-philippines.html

In Europe, reduction in CO_2 emissions from new cars was first addressed by voluntary agreements (1998-2008) between automobile manufacturers and the European Commission (Croci, 2003). These agreements meant an initial afterthought of manufacturers' business models towards the adoption of innovations to reduce CO_2 emissions. In 2009, however, the European Commission introduced mandatory reductions in CO_2 emissions from passenger cars (EC 443/2009) after assessing that the reductions to that point were not enough to comply with the EU's planned reduction in GHG emissions.

The recent scandal of Volkswagen's manipulation of emissions tests, in September 2015, sheds light on the fact that automobile companies still have serious trouble reducing CO_2 emissions. Although some advances have been made to this end, the scandal seems to confirm the common knowledge about the aversion of the automobile industry to radical innovation. The last ICCT (ICCT, 2015) data, indeed, cast suspicions that companies may have dedicated part of their innovation capability to designing software to cheat on official emission tests, since the gap between test results and real-world performance has become a chasm, increasing from 8% in 2001 to 40% in 2014.

Recent studies, however, suggest that the innovation process in the automobile industry can be understood only by adopting a socio-technical transition perspective. In other words, innovation transition does not depend only on the willingness of companies to develop new technologies, but also on the coevolution of actions and interactions between car drivers, car manufacturers, policy makers and public opinion (Budde et al., 2012; Dijk and Yarime, 2010; Dijk et al., 2013; Penna and Geels, 2015; Rothenberg and Ettlie, 2011; Zapata and Nieuwenhuis, 2010). Thus, a more comprehensive analysis with a multi-dimensional perspective is needed to understand the innovation process of automobile companies. Previous contributions in this area, however, only provide qualitative analyses of the political and social context in which innovations are introduced, and descriptive assessments of how these innovations affect CO_2 emission reduction in such contexts (Penna and Geels, 2015). Further exploration is necessary.

The aim of this study is to contribute to this stream of research by increasing the understanding of corporate innovation strategies for reducing CO_2 emissions. In particular, this paper focuses on a period of high uncertainty, when carbon regulation was not yet in force (2000-2008), to examine the technological and social characteristics of a range of innovations that companies could adopt to reduce the carbon emissions of their products. This period of study also allows us to deal with data not directly related to the scandal mentioned above. In contrast to previous studies, this analysis of innovation moves away from an engineering perspective and it is contemplated under the Natural Resource Based View (NRBV) (Hart, 1995). This latter framework provides new insights into the innovations that companies can adopt to reduce carbon emissions, and arguments to discuss how companies can tackle climate change challenges without completely altering the status quo of their market. In addition, this work offers empirical evidence on how innovations affect product-related CO_2 emissions in the short and long term, assessing simultaneously innovation interactions in the two timescales. The main suggestion coming from the results is that the development of diverse innovations in a period of no carbon regulation can benefit companies by resulting in the lowest CO_2 emissions, even though the positive effects do not persist over time. Therefore, continuous innovation in product stewardship is required in this industry.

This study makes several contributions to the literature. First, it provides a practical application of the NRBV in the automobile industry, focusing on so far under investigated innovation strategies (product stewardship and clean technology) and their effects on product-related CO_2 emissions. Second, the adoption of this theoretical framework enriches the analysis of innovations designed to reduce CO_2 emissions leading from engineering studies, assessing the effect of innovation interactions on performance. Finally, this study analyzes how these innovations work over time to reduce CO_2 emissions.

The paper is structured as follows. First, the concept of climate change and technology innovation strategy is defined in Section 2. Second, the NRBV is introduced and hypotheses are developed according to this framework in Section 3. This is followed by the Method and Findings sections. The paper concludes with Discussion and Conclusion sections.

2. Climate change and technological innovation challenges

The issue of climate change is clouded by uncertainty about the type, magnitude and timing of its impact, as well as about the creation of a complex set of continuously changing public climate policies (Kolk and Pinkse, 2008). Such uncertainties fundamentally affect the strategic decision-making process of companies (Härtel and Pearman, 2010; Weinhofer and Busch, 2013). For this reason, management research has largely analyzed how companies face climate change uncertainties, in particular those generated by the continuously shifting institutional landscape, by analyzing various carbon strategies or practices (e.g., proactive/innovative, reactive/defensive, compensative) that firms adopt or can adopt to tackle climate change (Backman et al., 2015; Boiral, 2006; Cadez, 2016; Galbreath, 2011; Jeswani et al., 2008; Kolk and Pinkse, 2005; Lee, 2012; Lee and Klassen, 2015; Weinhofer and Hoffmann, 2010). In this field of analysis, other studies have even tested the impact of these practices on GHG reduction, not always reaching the same conclusion (Boiral et al., 2012; Doda et al., 2015).

A parallel stream of research emphasizes the role of technological innovation within companies as one of the most important means of addressing global climate change (Benhelal et al., 2013; Lee, 2013; Penna and Geels, 2015; Pinkse and Kolk, 2010). Companies can have a clear influence on the specific trajectory of their technological change because, through research and development (R&D) and technological capabilities, they can invent technologies that help reduce emissions. Indeed, under climate change uncertainties, companies can be called upon to decide whether invest more in technology development or in technology deployment (Pinkse and Kolk, 2010), facing an innovator’s dilemma (Christensen, 1997). In general, a strategy formulation is treated as a rational process of matching corporate capabilities to market demands (Levy and Rothenberg, 2002). This means that firms need to have a clear picture of the future market in order to make technology innovation decisions (Hoffman, 2005). Climate change uncertainties tarnish such a picture, making the strategic rationales of different companies heterogeneous and based fundamentally on market expectations (Budde et al., 2012; Levy and Rothenberg, 2002).

In view of the fact that there is no “silver bullet” solution for climate change, the risk of “irreversible green mistakes” arising from the development of new technologies can be high for companies (Pinkse and Kolk, 2010; Rugman and Verbeke, 1998). Consequently, although firms need to move away from traditional processes and products to improve their carbon footprint, they are often resistant to doing so. The success of a technological innovation, indeed, depends strongly not only on long-term investments in R&D, but also on the capabilities of the companies which are bringing these technologies to the global mainstream market in the form of products and services (Pinkse and Kolk, 2010).

The dearth of new technologies that aim to reduce carbon emissions in any given industry can, therefore, depend on the characteristics of products. In some sectors (e.g., energy) technological innovation does not produce disruptive changes in the attributes of products (Rowlands *et al.*, 2003). In other industries, however, companies have to change products’ attributes and, consequently, the success of an innovation strategy will depend on the degree of acceptance of these changes by the market. A negative consumer response to green products could be a barrier, or could slow the introduction of technological innovations (Williander, 2007). In other words, markets are socially embedded and products are socially constructed; therefore, innovation is the result of an interactive form of learning between consumers and companies (Dijk and Yarime, 2010). Hence, in some industries, achieving the lowest CO_2 emissions through new technologies can be particularly complex if the technologies are not quickly accepted by the market (Lane and Potter, 2007).

Several studies argue this case with reference to the automobile industry. In this sector, climate change constitutes a major threat to the core technology because it requires changes to the internal combustion engine (ICE) (van den Hoed, 2007). These changes imply not only a deep restructuring of the industry's production and organizational processes, with major effects on economies and return on investment, but also a shift in consumers' preferences (Levy and Rothenberg, 2002; Magnusson and Berggren, 2001; Penna and Geels, 2015; Zapata and Nieuwenhuis, 2010). Furthermore, when companies consider technological innovations to reduce their carbon emissions, they can choose between several types of technologies with no guarantee of succeed in the market (Penna and Geels, 2015; Vergragt and Brown, 2007). This further increases the state of uncertainty for automobile companies in their innovation process. Overall, thus, the heart of the problem in the automobile industry is in implementing an innovation strategy that ensures that companies are profitable, and that cars are sufficiently fuel efficient and are in line with the prevailing consumer culture (Cousins et al., 2007).

3. A natural-resource-based view of innovation technology

The NRBV of a firm (Hart, 1995) offers a framework to analyze the different types of technological innovations that the company can adopt to tackle environmental constraints. This framework is proposed as an extension to the resource-based view (RBV) (Barney, 1991; Wernerfelt, 1984). While the RBV highlights the importance of valuable, rare, inimitable, and non-substitutable resources as preconditions for a firm's competitive advantage, it does not reflect the constraints imposed by the natural environment (Hart, 1995). Hence, the NRBV offers a connection between the natural environment and a firm's resources and capabilities. The NRBV and its extensions (Hart, 1997, 1995; Hart and Dowell, 2011) propose, fundamentally, three strategic capabilities for facing natural environmental constraints. These are pollution prevention, product stewardship, and clean technology. These capabilities form the foundation for technological innovations that enable firms to enhance environmental performance and, in turn, obtain a competitive advantage (King and Lenox, 2002; Porter and Van-der-Linde, 1995; Russo and Fouts, 1997).

Pollution prevention innovations aim to enhance internal efficiencies in production and operations. Their main objective is to prevent waste and emissions, rather than cleaning them up at the “end of the pipe”. By removing pollutants from the production process, pollution prevention innovations allow cost reductions by (a) reducing the inputs required, (b) simplifying the process, and (c) cutting compliance and liability costs (Hart and Dowell, 2011). Through lowering operational costs, pollution prevention innovations may improve competitiveness.

Product stewardship innovations focus beyond the firm's processes by integrating environmental concerns into product design decisions. The overall objective is to minimize the life cycle ecological impacts of products. Thus, through product stewardship innovations, firms can (a) minimize environmentally hazardous processes, (b) redesign existing product systems to reduce liability, and (c) develop products with lower life-cycle costs. The relative priorities among these three targets can vary according to the nature of the firms’ existing business approach. However, the starting point for these innovations is usually to identify opportunities for incremental improvements in the existing product portfolio, with limited effort spent on identifying more radical solutions.

Finally, clean technology innovations are distinct from product stewardship innovations because they are not focused on incremental product improvements, but on leapfrogging existing routines to achieve new standards of clean tech performance. These technologies preserve ecosystem resources and reorient energy use and industry in ecologically sustainable directions. A firm pursuing clean technology strategies works, over an extended period, to develop and deploy low-impact technologies that will be sold in emerging markets. For example, companies can obtain energy entirely from renewable sources, such as wind and solar power, or use conversion technologies, such as fuel cells, that minimize ecological footprints.

Focusing on the last two categories of technology innovation, conceptually, product stewardship and clean technology can be related to two distinct product innovations. Product stewardship innovation refers to incremental product innovations, and clean technology to radical product innovations. Incremental innovations are minor improvements or adjustments to the current technology, whereas radical innovations produce fundamental changes in the technology (Dewar and Dutton, 1986; Ettlie et al., 1984). Product stewardship innovation can refer to eco-design innovation strategies, which integrate environmental concerns into product design without introducing disruptive changes in the core concept of products (Five-Winds-International, 2003; Gupta, 1995). Companies investing in these innovations might have to develop new knowledge in each stage of the product development process; for example, to use alternative materials or components. However, these materials or components themselves are largely known in the industry (Orsato and Wells, 2007). Additionally, product stewardship can be concerned with architectural innovation, which refers to changes in the components of a product to create new interaction with other components in the established product. Architectural innovation does not change the core concept of a product, it only modifies components and linkages among product components (Bhoovaraghavan et al., 1996; Henderson and Clark, 1990). Product stewardship innovations, further, do not change consumer patterns; consumers do not perceive changes resulting from product stewardship innovations (Gerrard and Kandlikar, 2007). Conversely, clean technology innovations can be considered radical because they are new for both the firm and the market. A radical product innovation requires the creation of new infrastructures for companies and new levels of functionality to customers (O’Connor, 1998). Radical product innovations involve novelty in the technological and market domain; i.e., they are technologically very different from existing products. Thus, they address unfamiliar markets and often require changes in consumer behavior (Danneels and Kleinschmidtb, 2001).

3.1 Product stewardship and clean technology innovations in the automobile industry

For automobile companies a first option for potentially reducing CO_2 emissions through product stewardship innovation can be to redesign products using lighter materials, such as plastic, aluminum and magnesium (Kim et al., 2010; Orsato and Wells, 2007). Lighter materials reduce the weight of vehicles, improving their fuel economy and thus reducing CO_2 emissions (Tharumarajah and Koltun, 2007). These innovations do not change drastically the core concept of vehicles, and can fit well with existing social and infrastructural systems. They do not require new manufacturing and distribution infrastructure, and above all they do not affect consumers’ perceptions (Gerrard and Kandlikar, 2007). Unchanged perceptions mean low uncertainty in consumers’ minds, and a positive market assessment of these products (Bhoovaraghavan et al., 1996). A second option for companies attempting to reduce CO_2 emissions through product stewardship innovations is to redesign products with minimal changes in the power train which enable them to use alternative fuels such as methane and ethanol. These fuels are less carbon intense than gasoline and diesel. According to the literature, undertaking such product innovations does not require different manufacturing systems, or changes in the distribution infrastructures (Zapata and Nieuwenhuis, 2010). Consumers consider ethanol-fueled vehicles to be an engine variant of traditional vehicle models, so this innovation does not require substantial changes in consumer behavior (Williander, 2007). As a third option, hybrid technologies can also be considered product stewardship innovations. Hybrid technologies incorporate an electric drive alongside the traditional internal combustion engine, enabling reduced fuel consumption and emissions. These electric drive elements are similar to those found in a battery-electric vehicle. Hybrid technologies do not require an entirely new infrastructure, as the energy source of hybrid cars is based on traditional fuels, and consumers' perceptions do not change (Dijk and Yarime, 2010).

With reference to clean technology innovations, the automobile industry has two primary options for all-electric vehicles: batteries or fuel cells. Battery-electric vehicles obtain all their energy from batteries that are charged on the electrical grid. Batteries can utilize lead acid, Ni-MH or Li-ion technologies. Fuel cells are based on electrochemical devices that convert fuel energy directly into electrical energy. Fuel energy can be diverse, even gasoline-based, but most prominently used are alternative fuels such hydrogen, which can be derived from natural gas or renewable energy. The most suitable of the two main options – batteries and fuel cells – depends on the criterion of assessment. In terms of mass, volume, fuelling time, fuelling infrastructure, energy efficiency, and costs, fuel cells have the highest potential for reducing CO_2 emissions (Thomas, 2009). However, clean technology requires changes in the core vehicle concept (Pilkington and Dyerson, 2006; Zapata and Nieuwenhuis, 2010), which in turn require disruptive changes both in the companies' manufacturing processes (Magnusson and Berggren, 2001) and in the minds of consumers (Egbue and Long, 2012; Johansson and Magnusson, 1998). Consumers need to be re-educated about new vehicle concepts (i.e. for new driving patterns), with the consequent risk that they might not appreciate their improved environmental performance. Changes in customers' patterns could negatively affect the product diffusion. Besides, clean technologies require a long-term vision, shared among all relevant stakeholders, and strong cooperation along the supply chain (Lee, 2011; Smith, 2001). Since clean technologies are complex, companies must cooperate not only with their component suppliers, but also with other stakeholders such as institutions. The development of fuel cell vehicles, for instance, relies on the chemical and energy industries; the automobile industry is not able to supply hydrogen itself. Therefore, if suppliers controlling traditional fuel production and infrastructures seek to protect their rents, the introduction of fuel cell vehicles in the market can be further hampered (Hoffman, 2005).

Referring to the above descriptions, Table 1 illustrates how product stewardship and clean technology innovations, considered under the NRBV, can be applied in the automobile industry.

<<Insert Table 1 about here >>

3.2 Hypothesis development

Behind the rationale of the NRBV, the evolution of product stewardship and clean technology innovations follows an iterative process (Tushman and Anderson, 1986; Utterback and Abernathy, 1975) where each innovation occurs at a different stage in the product life cycle (Rogers, 2003). At the advanced stages of the product life cycle, firms may tend to focus on incremental environmental improvements by implementing product stewardship innovations. While such incremental improvements become the business practice, firms start looking for more radical solutions in order to attain substantial emission reductions from their products. Thus, they consider innovative ways to reinvent their products and position them in the markets. This process requires significant R&D efforts and is based on trial and error. Hence, product stewardship innovations can be slowly complemented by clean technology innovations in a transition period, especially if institutional pressures are materialized through voluntary agreements, not carbon regulation, and the demand for clean technologies is still not mature.

Research suggests that, in general, companies are agnostic about the science of climate change and the social responsibility for protecting the global climate (Hoffman, 2005; Rothenberg and Levy, 2012). If this perception of climate change is added to the presence of voluntary agreements, companies likely decide to reduce CO_2 emissions mainly for two reasons: 1) to be prepared for mandatory GHG emission reductions, and 2) to reap near-term economic and strategic benefits (Hoffman, 2005). Voluntary agreements seem to trigger improvements that conform to the dominant practices in the industry (Delmas and Montes-Sancho, 2010). This leads to the supposition that, under uncertainty due to the absence of carbon regulation, companies such as those in the automobile industry do not reduce CO_2 through clean technology innovations. Indeed, several studies show that a typical innovation approach of automobile companies is an early rejection of new technologies due to an unattractive unit production cost (Morgan and Daniels, 2001). Complex operations, low margins and high risks would lead automobile companies to favor more incumbent than new innovations (van den Hoed, 2007). Although automobile companies see new innovations as crucial to long-term success, their adoption is hindered by the traditional unit-cost-based adoption criteria (Morgan and Daniels, 2001). Besides, this is an industry where a new innovation may need a hype period to gain legitimacy and credibility in its early stages. The creation of expectations of technological progress helps to stimulate, steer and coordinate collective action by researchers, engineers and firms to make the innovation work in the market. This is just the case for hydrogen vehicles (Walker et al., 2013). For all these reasons, it is possible that CO_2 emission reductions under regulatory uncertainty have been mainly due to the implementation of product stewardship innovations rather than clean technology innovations. Hence, the first hypothesis is:

Hypothesis 1: *Under regulatory uncertainty, reduction of product-related* CO_2 *emissions can be due to product stewardship rather than clean technology innovations.*

The second hypothesis is concerned with the complementarity between product stewardship and clean technology innovations. In this regard, there are two contrasting views in the literature. One suggests that firms are likely to choose a combination of alternative strategies rather than focusing on a single strategy to reduce emissions (Petkova et al., 2013; Wakabayashi, 2013; Weinhofer and Hoffmann, 2010). Another view argues that firms focus only on specific carbon practices to enhance environmental performance (Cadez, 2016; Delmas and Toffel, 2008). Other findings are inconclusive in this regard (Okereke and Russel, 2010; Slawinski and Bansal, 2012; Wahyuni and Ratnatunga, 2015). Organizational literature, however, suggests that simultaneous strategies can produce positive interaction effects on performance (Gibson and J., 2004; He and Wong, 2004; Rothaermel and Alexandre, 2009). R&D to improve existing technologies can economically support firms' development of new technologies and, simultaneously, R&D to develop new technologies can enhance the ability of companies to engage in successful innovations (Cao et al., 2009). Firms that experiment with different types of innovations can increase their ability to introduce new variations of products in the market, with the advantage of solving existing and future problems between innovations (Katila and Ahuja, 2002).

Applying this mutual benefit mechanism to the case of product stewardship and clean technology innovations, it is possible that automobile companies, by simultaneously developing capabilities in both types of innovation, may benefit from increased reduction of CO_2 emissions. This is because they are able to quickly resolve specific problems that each innovation may present. For example, although clean technologies have great potential to reduce CO_2 emissions, the best outcome is actually realised by the selection of appropriate fuels and technologies (National Research Council, 2008; Offer et al., 2010; Thomas, 2009). Thus, clean technologies need technical improvements (Eberle et al., 2012; Offer et al., 2010) and product stewardship innovation can be useful for this purpose.

The challenge for battery-electric vehicles, for instance, is to achieve a relatively low energy density (i.e., a significant reduction of the volumetric energy density) to increase the actual driving range (Eberle et al., 2012). In the case of hydrogen-fuel-cell electric vehicles, the use of a hydrogen tank can achieve a similar driving range to a conventional vehicle. However, the energy density of the hydrogen tank stills needs further improvements, because the volume of hydrogen gas limits the amount of hydrogen that can be stored on board (Mori and Hirose, 2009; Offer et al., 2010). In these cases, product stewardship innovations can improve clean technologies; for example, by designing hydrogen tanks with greater capacity but bringing down the total vehicle weight by using lithium-ion cells, as in the case of hybrid vehicles. Another problem with fuel-cell vehicles is the recycling of materials used in the batteries. Product stewardship innovations can solve this problem by using materials that are more suitable for this purpose.

Hence, it is possible that CO_2 emission reductions happen under regulatory uncertainty when clean technologies and product stewardship innovations work together:

Hypothesis 2: *Under regulatory uncertainty, reduction of product-related* CO_2 *emissions can be due to interactions between clean technology and product stewardship innovations.*

4. Method

4.1 Data collection and sample

Data were collected using several data sources (see Table 2): the Vehicle Certification Agency (VCA)[3], the European Patent Office (EPO)[4], *Parkers Car Guide*[5], Osiris, Amadeus and Compustat[6]. VCA is the official Vehicle Type Approval Authority of the Department for Transport in UK; it provides expert international tests and certification services for vehicles and vehicle parts based on the official fuel consumption procedures established in the European Union Directive (80/1268/EEC). Thus, this authority ensures that vehicles and vehicle parts in Europe are designed and constructed to meet international safety and environmental protection standards, and provides reliable data about emissions and fuel consumption for vehicle models. EPO, through Espacenet search service, provides information on worldwide patents. The Espacenet service allows users to search patents by technology codes, company name and date. *Parkers Car Guide* is a monthly magazine that provides information about new and used cars in the United Kingdom. All data referring to new cars were downloaded taking into account the production date range of vehicles. Finally, the Osiris and Compustat datasets provide financial data for major listed companies around the world and the Amadeus dataset supplies financial information for more than 20 million companies in Europe. Thus, Amadeus provides information about companies that are not included in either Osiris or Compustat.

<< Insert Table 2 about here >>

Data from VCA and Parkers were merged by vehicle model type and aggregated at the level of automaker. Then, these were merged with patent and financial data provided at the level of automaker. After this procedure, we retained a total of 38 automakers[7].

---

[3] We used Access and SAS to merge and analyze data: http://carfueldata.direct.gov.uk/downloads/default.aspx (last accessed on December 2013).

[4] We used Espacenet patent search and STATA to merge data: http://www.epo.org/searching-for-patents/technical/espacenet.html#tab (last accessed on February 2014).

[5] We used facts and figure car research to collect data: http://www.parkers.co.uk/cars/reviews/facts-and-figures/ (last accessed on March 2014).

[6] The access to these databases is not free of charge (last accessed on January 2014).

[7] The automakers included in the study are: Aston Martin, Audi, BMW, Chrysler, Citroën, Daihatsu, Ferrari, Fiat, Ford, Honda, Hyundai, Jaguar, Kia, Lamborghini, Lotus Cars, Mazda, Mercedes-Benz, Mitsubishi, Nissan, Peugeot, Porsche, Proton, Renault, Saab, SEAT, Škoda, Subaru, Suzuki, Toyota, Vauxhall-Opel, Volkswagen, Volvo, Land Rover, Morgan, Rolls-Royce, SsangYong, Bentley, Smart.

4.2 Variable measurement

4.2.1 Dependent variable

The variable *CO_2 emission* (grams per kilometer — g/km) was measured using data from the VCA dataset for the period 2000-2011. Two dependent variables were computed to examine whether the firms' efforts to reduce CO_2 emissions were focused on one vehicle model (i.e., one production line), or on all produced models (i.e., all production lines). The dependent variables are (1) the *minimum amount of CO_2 emissions* from vehicle models and (2) the *average amount of CO_2 emissions* of all vehicle models. Both measures are important because they reflect the company's strategy about CO_2 emissions from vehicles. The minimum CO_2 is the lowest level of emissions that a firm holds across its models in a given year. The average CO_2 is the ratio between the sum of all CO_2 emissions of all vehicle models and the total number of models per firm and year. Let M_i be the total number of vehicle models that the firm "i" holds in a given year, and h=1,…,n be the type of model, then for each year, the average CO_2 is the ratio between the sum of the CO_2 emissions by vehicle model and year and the total number of vehicle models in that year:

$$\text{Average CO2 emission}_{\,i} = \frac{\sum_{h=1}^{n} vehicle\ model_{hi}}{\mathrm{M_i}}$$

4.2.2 Independent variable

Patent data are used as a proxy for the level of technological innovation of the automobile companies. The use of patent information has gained increasing attention in the fields of innovation and technology management (Penna and Geels, 2015; e.g. Pilkington and Dyerson, 2006). Patents were downloaded by publication date during the period 2000-2011. The resulting dataset was cleaned of duplicate patents and ordered according to their priority date, which is the date of the first filing of a similar claim in any patent office, in order to better reflect the timing of the invention. Since the lag between priority date and publication date is approximately two years, collecting the data between 2000 and 2011 ensured the collection of all the patents for the period 2000–2008, the target period of this study. In this period, CO_2 emission regulation was not in force. Consequently, the patents were obtained under an uncertain context. Given the dataset, the retained patents were those wherein the applicant was an automaker. Then the classification of the patents into the two innovation categories — product stewardship and clean technologies — was performed by content analysis.

Content analysis is a way of codifying the text of written narratives into groups or categories based on selected concepts, thereby converting qualitative information into quantitative scales that permit further analysis (Weber, 1988). This process requires the selection of concepts based on a theoretical foundation (Stemler, 2001). For this reason, we selected concepts associated with product stewardship and clean technology by reading academic and practitioner-oriented literature. The resulting concepts associated with product stewardship were: reverse logistics, end-of-life treatment, recovery / recyclable materials, eco-design, efficiency (usage phase), hybrid, and natural gas. The concepts associated with clean technology were: electric, hydrogen, fuel cell, zero-carbon, car-related solar energy systems, and plug-in systems (see Table 3). These concepts were used in the research string key words applied to the title of patents. To ensure an objective codification process, Marshall and Brown's (Marshall and Brown, 2003) methodology was followed, in which two data coders manually examined and classified each patent independently, achieving an inter-coder reliability of 90%. Although 63% agreement between two examiners is considered "substantial agreement" (Landis and Koch, 1977), a third coder assessed the 10% of discrepancies between the two initial coders.

<<Insert Table 3 about here>>

After classification, the accumulated number of patents classified as product stewardship and clean technology innovations for each firm and year was calculated, as well as the total number of patents by firm and year. The independent variables were then measured as coefficients between the accumulated number of patents in product stewardship or in clean technology innovations until a given year, over the total patents until that year.

4.2.3 Control variables

Several control variables were also considered in the analysis. These variables are *anticipation of Euro standard legislation*, *model restyling*, *vehicle weight*, *firm size* and *firm profitability*.

The Euro standard is a legislation imposed in European Union directives to reduce toxic emissions (96/69/EC; 98/69/EC)[8] which are not directly related to climate change but can harm human health. This legislation has imposed more stringent targets over years through Euro 3 (fully effective in 2000), Euro 4 (fully effective in 2005) and Euro 5 (fully effective in 2009). Firms have, therefore, to take into account Euro standard legislation in their plans to reduce CO_2 emissions, and during the period 2000–2008 they had the opportunity to anticipate this legislation. A proactive behavior of firms toward Euro standard legislation thus could positively affect other environmental performance such as the reduction of CO_2 emissions. By using VCA data, *anticipation of Euro standard legislation* was computed as the ratio of the number of models that comply with Euro standards that were not fully effective in analyzed period, over the total models produced in the same period.

Restyling of vehicle models was controlled for because it is possible that firms redesigning their vehicle models for pure marketing interests could include little design modifications that also enhance CO_2 emissions. Using data from Parker's car guide, the variable *model restyling* was computed as the number of vehicle models that companies restyle each year over the total number of models produced in that year.

Vehicle weight also can affect CO_2 emission. It is viewed that automobile companies are doggedly pursuing a virtuous cycle where lightweight body structures, right-size powertrain and chassis, and electrification deliver improved CO_2 performance (SupplierBusiness, 2014). Hence, companies that produce prevalently heavy vehicle models may have some difficulties in reducing CO_2 emissions. *Vehicle weight* was calculated as the ratio of the sum of all vehicles' weight by firm and year over the total number of models by firm and year reported in Parkers.

Finally, firm size and profitability were calculated using data from Osiris, Amadeus and Compustat. *Firm size* is the logarithm of total assets, and *firm profitability* is calculated as the return on assets (ROA). Dummy variables for individual years are included in the models to control time effects.

5. Findings

---

[8] Toxic emissions are nitrogen oxides (NO_x), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM).

Table 4 shows the descriptive statistics and the correlation matrix of the variables used in the analyses. The collinearity diagnostic, including variance inflation factors (VIF), indicates that multicollinearity is not an issue (Hair et al., 1998)

<<Insert Table 4 about here>>

To test the hypotheses, several panel regression models were performed, with one year lagged (Tables 5 and 6) and two and three year lagged (Tables 7 and 8). In Tables 5 and 6 the independent variables refer to the time period 2000–2008, whereas the dependent variables are tested one year after, covering the time period 2001–2009. In Tables 7 and 8, the independent variables always refer to the time period 2000–2008, but the effects on CO_2 emissions are tested two years after that period, in 2010 and 2011. In addition, Tables 5 and 7 show the results for the model testing the hypotheses when the dependent variable is *CO_2 emissions of the vehicle model with minimum emissions*. Tables 6 and 8 display the results for the model when the dependent variable is the *average CO_2 emissions of all vehicle models*. Given the formulation of the dependent variables (CO_2 emission levels), the predicted relationship between each innovation strategy and CO_2 emission reductions will be reflected by a negative sign in their coefficients.

For all models, the *p*-values of the *F*-test and the Breusch-Pagan test (Breusch and Pagan, 1980) indicate that fixed-effects and random-effects models are better than pooled models. The Hausman test then suggests that random-effects models are consistent and more efficient than fixed-effects models. We tested for heteroskedasticity and autocorrelation using the modified Wald test and Wooldridge test respectively. We found the homoskedastic specification does not hold. Therefore, we used GLS random-effects regression with the option of cluster-robust standard errors, which allowed weaker assumptions of errors, especially for small cross-section dimensions and panels (Cameron and Trivedi, 2009).

<<Insert Table 5 about here>>

The coefficient for product stewardship is not significant in Tables 5 and 6. Thus, Hypothesis 1, that automobile companies can reduce CO_2 emissions from vehicles through product stewardship innovations, is not supported. The variable *clean technology* is negative and significant in Table 5 and in Table 6. These results imply that automobile companies can significantly reduce CO_2 emissions from vehicles through clean technology innovations. The interaction term between product stewardship and clean technology is negative and significant only in Table 6 (Model 4: -0.340 and p-value<0.05). This result suggests firms that innovate in both product stewardship and clean technology can amplify CO_2 improvements in their vehicles. However, this finding only holds for average reduction of CO_2 across all vehicles models, not for the formulation of the vehicle model with minimum emissions. Hence, Hypothesis 2 is partially supported. This result is consistent with the idea that innovations in both product stewardship and clean technology can accelerate CO_2 emissions reductions.

<<Insert Table 6 about here>>

In addition, there is some uncertainty about when exactly the automakers will implement patented innovations in their vehicles models. In Tables 5 and 6, it is assumed that the effect of such innovations will become tangible in the next year. For robustness, hypotheses were tested over the next two years and the next three years (Tables 7 and 8). For Hypothesis 1, results in both timelines are consistent with prior findings: clean technologies have long-term effects on CO_2 emission reduction. Conversely, Hypothesis 2 cannot be confirmed when extending the time frame: the interaction effects have short-term paybacks on CO_2 emissions reduction, and continuous innovations in product stewardship are therefore necessary to obtain long-term effects. Furthermore, the same results are obtained when Volkswagen group is dropped out of the sample (see Table A in the appendix).

<<Insert Table 7 about here>>

<<Insert Table 8 about here>>

6. Discussion

6.1 Research contribution and implications

Despite the increasing interest in climate change and the multiple analyses on practices and strategies adopted by the companies to address it, few studies have adopted a socio-technical perspective to assess the type of innovations that companies can develop for addressing climate change challenges and how these innovations ultimately affect CO_2 emissions. While most studies have focused on climate change practices, which are not always explicitly related to CO_2 emission reductions, other researchers have started to analyze climate change mitigation by embracing a technological perspective and by taking into account the socio-political context in which these technologies are developed. These last studies, however, only provide qualitative and descriptive analyses of the technological innovation process of companies within a certain socio-political context; a more comprehensive and sophisticated empirical analysis is required.

The adoption of a socio-technical perspective to assess product-related CO_2 emission reduction is particularly consistent with the challenges faced in the automobile industry, which is the source of one-fourth of carbon emissions. Indeed, a reduction of CO_2 emissions from vehicles is critical to avoid dangerous anthropogenic interference with the climate. In addition, the automobile industry deals with several barriers to the introduction of new technology to lower emissions. Some of these barriers are related to consumer values and attitudes towards green vehicles, and others with conflicts of interest within the supply chain. Hence, analyzing technology development under a multi-dimensional perspective can help with understanding the innovation process of automobile companies and their effects on performance.

The main contributions of this study build on assessing technological innovation for climate change mitigation under the NRBV. The relative novelty of this framework provides the opportunity to categorize technological innovation under a hierarchical conceptual framework, identifying product stewardship innovation as a first option for companies looking to reduce CO_2 emissions without altering the core product concept and, consequently, the market status quo. Furthermore, firms could develop clean technology innovations with strong implications for manufacturing processes and market acceptance. In this way, a practical application of the NRBV is provided for the automobile industry and a new methodological approach, different from the engineering studies, is proposed. In addition, research based on NRBV has extensively focused on pollution prevention innovations (e.g., Christmann, 2000; King and Lenox, 2002; Klassen and Vachon, 2003; Klassen and Whybark, 1999; Russo and Fouts, 1997), leaving analysis of product stewardship and clean technology innovations virtually unexplored (Hart and Dowell, 2011). Only a few studies have investigated these last innovation strategies (Bansal, 2005; Sharma and Henriques, 2005; Sharma and Vredenburg, 1998), but they have not empirically tested the effects of product-based environmental performance. This work contributes to this area of research by analyzing product stewardship and clean technology and their effect on product-related CO_2 emissions. Furthermore, this study explores the interaction effects of these innovations on product performance by considering that product stewardship and clean technology innovations are not mutually exclusive and that the innovation process of the automobile industry is not characterized by quick, drastic jumps.

The data analysis for this study focused on a time period where companies were not yet subjected to CO_2 regulation, with the objective of assessing the technological innovation process of companies under regulatory uncertainty, making it possible to observe heterogeneous companies' strategies (Hoffman, 2005). In this context, it is hypothesized that companies will try to reduce CO_2 emissions through incumbent innovations; i.e., through product stewardship innovations. Results contradict this prediction, suggesting that companies that significantly reduced product-related CO_2 emissions were those that innovated in clean technologies. Conversely, by just focusing on product stewardship innovations, companies had not been able to significantly reduce CO_2 emissions from vehicles. However, this last outcome does not imply that firms should fully neglect product stewardship innovations. Indeed, companies that embark on a strategy that pursues both product stewardship and clean technology innovations may amplify the reduction of CO_2 emissions from vehicles. While clean technology innovation seem to have an effect on CO_2 emission reduction in the long run, the interactive effects of product stewardship and clean technologies do not seem to persist over time.

Hence, a managerial recommendation to enhance CO_2 emission reductions from vehicles over time is to continue innovating in both product stewardship and clean technology. Although innovation in clean technologies is crucial for reducing CO_2 emissions and so remaining competitive in a carbon-constrained market, product stewardship innovations can amplify the positive effects of clean technology, since they still require further technological advantages. In particular, product stewardship innovations could help to manage rebound effects that could be generated by changes in the powertrain.

6.2 Limitations and future research

This study is subject to several limitations. First, the analysis focused on a period (2000–2008) when companies were not subject to CO_2 emission regulation, in order to capture companies' innovation strategies in an uncertain context. Only in this period is it possible to understand the combined innovation approaches companies can adopt for tackling climate change challenges. Since 2008, clean technologies have been substantially driven by regulation; future studies could focus on analyzing the alternatives companies have in developing clean technologies, as well as their effects on vehicle performance.

In addition, this study does not estimate the optimal balance between product stewardship and clean technology innovations for reducing product-related CO_2 emissions. Future empirical studies could adopt a different empirical technique to verify which combinations, over time, are the best in terms of enhanced environmental product performance.

Furthermore, this work focuses on CO_2 emissions from vehicles, while other environmental issues related to the production process are neglected. A number of comparative life cycle analyses indicate that fully electric vehicles are not necessarily better than conventional cars with internal combustion engines, due to the high environmental impact of battery manufacture during the stages of raw extraction, processing and production (Hawkins et al., 2012; Nordelöf et al., 2014). Thus, it is important to analyze the entire product life cycle from cradle to grave. Future research could build on the Greenhouse Gas Protocol (WBCSD and WRI, 2004) and analyze car manufacturers from a holistic perspective including all life-cycle-wide emissions. Finally, since in the automobile industry the locus of innovation has moved upstream for at least a decade (Rothenberg and Ettlie, 2011) and the level of technological outsourcing is quite high, the role of suppliers in contributing to reduce vehicle CO_2 emissions could be relevant. Toyota's gas pedal scandal, which resulted in the biggest recall in the company's history, shows that the performance of firms' products also depends on suppliers' activities. In line with this, it is possible that firms can produce products with lower carbon emissions by establishing relationships with suppliers who have already moved toward clean technology innovations. An interesting area for future research, in consonance with the recent contribution by Nair *et al.* (2016), could be to empirically analyze how R&D cooperation between automakers and suppliers can contribute to reducing CO_2 emissions from vehicles.

And finally, our results should be read with caution considering the latest development and discoveries regarding emissions testing, which seem to go beyond Volkswagen group.

7. Conclusion

The motivation for this study was to better understand how companies face climate change challenges, through a socio-technical analysis of innovations and their impact on CO_2 emissions. Although many companies today are aware of the business opportunities that climate change can offer, they also recognize that climate change may pose commercial risks (Beale and Fernando, 2009). Firms that offer products producing carbon emissions and depend on consumer behavior, such as those of the automobile industry, are particularly sensitive to these opportunities and risks. The complexity of the technologies, the high costs of their production and the parallel need to create the adequate refueling infrastructures, are critical in their innovation process and so in their capacity to reduce CO_2 emissions(UNEP, 2002). Although customers now increasingly consider the fuel consumption of cars as a purchase criterion (Dijk and Yarime, 2010; Hardman et al., 2016), before CO_2 regulation, automobile companies faced strong market and technological uncertainty. In this context, they had the opportunity to enter in a new market segment, while needing to continue to satisfy the mainstream market segment. The objective of this study was to understand how companies could overcome this dilemma. This paper makes an important step to this end, showing that companies could achieve significant CO_2 emissions reduction by deploying resources and capabilities in clean technology innovations, and above all by combining these technologies with product stewardship innovations.

References

Backman, C.A., Verbeke, A., Schulz, R.A., 2015. The Drivers of Corporate Climate Change Strategies and Public Policy: A New Resource-Based View Perspective. Business & Society. doi:10.1177/0007650315578450

Bansal, P., 2005. Evolving sustainably: A longitudinal study of corporate sustainable development. Strategic Management Journal 26, 197–218. doi:10.1002/smj.441

Barney, J., 1991. Firm Resources and Sustained Competitive Advantage. Journal of Management 17, 99–120.

Beale, F., Fernando, M., 2009. Short-termism and genuineness in environmental initiatives: a comparative case study of two oil companies. European Management Journal 27, 26–35. doi:10.1016/j.emj.2008.05.002

Benhelal, E., Zahedi, G., Shamsaei, E., Bahadori, A., 2013. Global strategies and potentials to curb CO2 emissions in cement industry. Journal of Cleaner Production 51, 142–161. doi:10.1016/j.jclepro.2012.10.049

Berrone, P., Fosfuri, A., Gelabert, L., Gomez-Mejia, L.R., 2013. Necessity as the mother of “green” inventions: institutional pressures and environmental innovations. Strategic Management Journal 34, 891–909.

Bhoovaraghavan, S., Vasudevan, A., Chandran, R., 1996. Resolving the Process vs. Product Innovation Dilemma: A Consumer Choice Theoretic Approach. Management Science 42, 232–246. doi:10.1287/mnsc.42.2.232

Boiral, O., 2006. Global Warming: Should Companies Adopt a Proactive Strategy? Long Range Planning 39, 315–330. doi:10.1016/j.lrp.2006.07.002

Boiral, O., Henri, J.F., Talbot, D., 2012. Modeling the Impacts of Corporate Commitment on Climate Change. Business Strategy and the Environment 21, 495–516. doi:10.1002/bse.723

Breusch, T., Pagan, A., 1980. The Lagrange multiplier test and its applications to model specification in econometrics. Review of Economics Studies 47(1): 239-253. 47, 239–253.

Budde, B., Alkemade, F., Weber, K.M., 2012. Expectations as a key to understanding actor strategies in the field of fuel cell and hydrogen vehicles. Technological Forecasting & Social Change 79, 1072–1083. doi:10.1016/j.techfore.2011.12.012

Busch, T., Hoffmann, V.H., 2009. Ecology-Driven Real Options: An Investment Framework for Incorporating Uncertainties in the Context of the Natural Environment. Journal of Business Ethics 90, 295–310.

Busch, T., Hoffmann, V.H., 2007. Emerging carbon constraints for corporate risk management. Ecological Economics 62, 518–528. doi:10.1016/j.ecolecon.2006.05.022

Cadez, S., 2016. Climate change mitigation strategies in carbon-intensive firms. Journal of Cleaner Production 112, 4132–4143. doi:10.1016/j.jclepro.2015.07.099

Cameron, C., Trivedi, P.K., 2009. Microeconometrics using Stata, Stata Pres. ed.

Cao, Q., Gedajlovic, E., Zhang, H., 2009. Unpacking Organizational Ambidexterity: Dimensions, Contingencies, and Synergistic Effects. Organization Science 20, 781–796. doi:10.1287/orsc.1090.0426

Christensen, C.M., 1997. The innovator’s dilemma: When new technologies cause great firm to fail. Harvard Business, Boston, MA.

Christmann, P., 2000. Effects of “best practices” of environmental management on cost advantage: The role of complementary assets. Academy of Management Journal 43, 663–680.

Cousins, S.H., Garcia Bueno, J., Palomares Colorado, O., 2007. Powering or de-powering future vehicles to reach low carbon outcomes: the long term view 1930-2020. Journal of Cleaner Production 15, 1022–1031.

Croci, E., 2003. Voluntary Agreements for CO2 Emission Reduction: Evaluation and Perspective. Energy & Environment 14, 663–676.

Danneels, E., Kleinschmidtb, E.J., 2001. Product innovativeness from the firm's perspective: Its dimensions and their relation with project selection and performance. Journal of Product Innovation Management 18, 357–373. doi:10.1111/1540-5885.1860357

Delmas, M., Montes-Sancho, M.J., 2010. Voluntary agreements to improve environmental quality: symbolic and substantive cooperation. Strategic Management Journal 31, 575–601.

Delmas, M., Toffel, M.W., 2008. Organizational responses to environmental demands: opening the black box. Strategic Management Journal 29, 1027–1055.

Dewar, R.D., Dutton, J.E., 1986. The Adoption of Radical and Incremental Innovations: An Empirical Analysis. Management Science 32, 1422–1433. doi:10.1287/mnsc.32.11.1422

Dijk, M., Orsato, R.J., Kemp, R., 2013. The emergence of an electric mobility trajectory. Energy Policy 52, 135–145. doi:10.1016/j.enpol.2012.04.024

Dijk, M., Yarime, M., 2010. The emergence of hybrid-electric cars: Innovation path creation through co- evolution of supply and demand. Technological Forecasting & Social Change 77, 1371–1390. doi:10.1016/j.techfore.2010.05.001

Doda, B., Gennaioli, C., Gouldson, A., Grover, D., Sullivan, R., 2015. Are Corporate Carbon Management Practices Reducing Corporate Carbon Emissions? Corporate Social Responsibility and Environmental Management. doi:10.1002/csr.1369

Eberle, E., Mueller, B., von Helmolt, R., 2012. Fuel cell electric vehicles and hydrogen infrastructure: status 2012. Energy & Environment 10, 8780–8798.

Egbue, O., Long, S., 2012. Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. Energy Policy 48, 717–729.

Ettlie, J.E., Bridges, W.P., O'Keefe, R.D., 1984. Organization Strategy and Structural Differences for Radical Versus Incremental Innovation. Management Science 30, 682–695. doi:10.1287/mnsc.30.6.682

Five-Winds-International, 2003. Product Stewardship Opportunities within the Automotive Industry. Five-Winds-International.

Galbreath, J., 2011. To What Extent is Business Responding to Climate Change? Evidence from a Global Wine Producer. Journal of Business Ethics 104, 421–432. doi:10.1007/s10551-011-0919-5

Gerrard, J., Kandlikar, M., 2007. Is European end-of-life vehicle legislation living up to expectations? Assessing the impact of the ELV Directive on “green” innovation and vehicle recovery. Journal of Cleaner Production 15, 17–27.

Gibson, C.B., J., B., 2004. The Antecedents, Consequences, and Mediating Role of Organizational Ambidexterity. Academy of Management Journal 47, 209–226.

Gupta, M.C., 1995. Environmental management and its impact on the operations function. International Journal of Operations & Production Management 15, 34–51.

Hair, J.F., Tatham, R.E., Black, W.C., 1998. Multivariate Data Analysis., Prentice H. ed. Englewood Cliffs, NJ.

Hardman, S., Chandan, A., Shiu, E., Steinberger-wilckens, R., 2016. ScienceDirect Consumer attitudes to fuel cell vehicles post trial in the United Kingdom. International Journal of Hydrogen Energy 41, 6171–6179. doi:10.1016/j.ijhydene.2016.02.067

Hart, S., 1997. Beyond Greening: Strategies for a Sustainable World. Harvard Business Review 75, 66–76.

Hart, S., 1995. A natural-resource-based view of the firm. The Academy of Management Review 20, 986. doi:10.5465/AMR.1995.9512280033

Hart, S.L., Dowell, G., 2011. Invited Editorial: A Natural-Resource-Based View of the Firm: Fifteen Years After. Journal of Management 37, 1464–1479. doi:10.1177/0149206310390219

Härtel, C.E., Pearman, G., 2010. Understanding and responding to the climate change issue: Towards a whole-of-science research agenda. Journal of Management and Organization 16, 16–47. doi:10.5172/jmo.16.1.16

Hawkins, T.R., Singh, B., Strømman, G.M.-B.A.H., 2012. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology 17, 53–64.

He, Z.L., Wong, P.K., 2004. Exploration vs. Exploitation: An Empirical Test of the Ambidexterity Hypothesis. Organization Science 15, 481–494.

Henderson, R.M., Clark, K.B., 1990. Architectural Innovation: The reconfiguration of Existing Product Technologies and Failure of Established Firms. Administrative Science Quarterly 35, 9–30.

Hoffman, A.J., 2005. Climate change strategy: The business logic behind voluntary greenhouse gas reductions. California Management Review 47, 21–46. doi:10.2139/ssrn.902357

Howard-Grenville, J., Buckle, S.J., Hoskins, B.J., George, G., 2014. Climate change and management. Academy of Management Journal 57, 615–623.

Huisingh, D., Zhang, Z., Moore, J.C., Qiao, Q., Li, Q., 2015. Recent advances in carbon emissions reduction: policies, technologies, monitoring, assessment and modeling 103. doi:10.1016/j.jclepro.2015.04.098

ICCT, 2015. The future of vehicle emissions testing and compliance. International Council on Clean Transportation, Berlin.

IEA, 2011. CO2 emissions from fuel combustion. International Energy Agency (OECD), Paris.

Jeswani, H.K., Wehrmeyer, W., Mulugetta, Y., 2008. How Warm Is the Corporate Response to Climate Change ? Evidence from Pakistan and the UK. Business Strategy and the Environment 17, 46–60. doi:10.1002/bse

Johansson, G., Magnusson, T., 1998. Eco-innovations - a novel phenomenon? The Journal of Sustainable Product Design 7 , 7–15.

Katila, R., Ahuja, G., 2002. Something Old, Something New: a Longitudinal Study of Search Behavior and New Product Introduction. Academy of Management Journal 45, 1183–1194. doi:10.2307/3069433

Kim, H., Mcmillan, C., Keoleian, G.A., Skerlos, S.J., 2010. Payback for Lightweighted Vehicles Using Aluminum and High-Strength Steel. Journal of Industrial Ecology 14, 929–946. doi:10.1111/j.1530-9290.2010.00283.x

King, A., Lenox, M., 2002. Exploring the Locus of Profitable Pollution Reduction. Management Science 48, 289–299. doi:10.1287/mnsc.48.2.289.258

Klassen, R.D., Vachon, S., 2003. Collaboration and Evaluation in the Supply Chain: The Impact on Plant-Level Environmental Investment. Production And Operations Management 12, 336–352. doi:10.1111/j.1937-5956.2003.tb00207.x

Klassen, R.D., Whybark, D.C., 1999. The Impact of Environmental Technologies on Manufacturing Performance. The Academy of Management Journal 42, 599–615. doi:10.2307/256982

Kolk, A., Pinkse, J., 2008. A perspective on multinational enterprises and climate change: Learning from “an inconvenient truth”’. Journal of International Business Studies 39, 1359–1378.

Kolk, A., Pinkse, J., 2005. Business responses to climate change: Identifying emergent strategies. California Management Review 47, 6–20.

KPMG, 2010. The Transformation of the Automotive Industry: The Environmental Regulation Effect. KPMG International.

Landis, J.R., Koch, G.G., 1977. The measurement of observer agreement for categorical data. Biometrics 33, 159–174. doi:10.2307/2529310

Lane, B., Potter, S., 2007. The adoption of cleaner vehicles in the UK: Exploring the consumer attitude-action gap. Journal of Cleaner Production 15, 1085–1092.

Lee, K.H., 2011. Integrating carbon footprint into supply chain management: The case of Hyundai Motor Company (HMC) in the automobile industry. Journal of Cleaner Production 19, 1216–1223. doi:10.1016/j.jclepro.2011.03.010

Lee, S., 2012. Corporate carbon strategies in responding to climate change. Business Strategy and the Environment 21, 33–48. doi:10.1002/bse.711

Lee, S.Y., 2013. Existing and anticipated technology strategies for reducing greenhouse gas emissions in Korea's petrochemical and steel industries. Journal of Cleaner Production 40, 83–92. doi:10.1016/j.jclepro.2011.11.052

Lee, S.-Y., Klassen, R.D., 2015. Firms' Response to Climate Change: The Interplay of Business Uncertainty and Organizational Capabilities. Business Strategy and the Environment. doi:10.1002/bse.1890

Levy, D.L., Rothenberg, S., 2002. Heterogeneity and change in environmental strategy: Technological and political responses to climate change in the automobile industry. In Hoffman, M. (Eds), Organizations, Policy and the Natural Environment. Stanford.

Liou, J.J.H., 2015. Building an effective system for carbon reduction management. Journal of Cleaner Production 103, 353–361.

Magnusson, T., Berggren, C., 2001. Environmental innovation in auto development managing technological uncertainty within strict time limits. International Journal of Vehicle Design 26, 101–114.

Marshall, R.S., Brown, D., 2003. Corporate environmental reporting: What's in a metric? Business Strategy and the Environment 12, 87–106.

McKinsey&Company, 2009. Roads toward a low-carbon future: Reducing CO2 emissions from passenger vehicles in the global road transportation system. New York City.

Mildenberger, U., Khare, A., 2000. Planning for an environment-friendly car. Technovation 20, 205–214. doi:10.1016/S0166-4972(99)00111-X

Morgan, L.O., Daniels, R.L., 2001. Integrating product mix and technology adoption decisions: a portfolio approach for evaluating advanced technologies in the automobile industry. Journal of Operations Management 19, 219–238.

Mori, D., Hirose, K., 2009. Recent challenges of hydrogen storage technologies for fuel cell vehicles. International Journal of Hydrogen Energy 34, 4569–4574. doi:10.1016/j.ijhydene.2008.07.115

Nair, A., Yan, T., Ro, Y.K., Oke, A., Chiles, T.H., Lee, S.-Y., 2016. How Environmental Innovations Emerge and Proliferate in Supply Networks: A Complex Adaptive Systems Perspective. Journal of Supply Chain Management 52, 66–86.

National Research Council, 2008. Review of the Research Program of the Freedom CAR and Fuel Partnership.

Nordelöf, A., Messagie, M., Tillman, A.-M., Söderman, M.L., Mierlo, J. Van, 2014. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? International Journal of Life Cycle Assessment 19, 1866–1890.

O'Connor, G.C., 1998. Market Learning and Radical Innovation: A Cross Case Comparison of Eight Radical Innovation Projects. Journal of Product Innovation Management 15, 151–166. doi:10.1111/1540-5885.1520151

Offer, G.J., Howey, D., Contestabile, M., Clague, R., Brandon, N.P., 2010. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Policy 38, 24–29. doi:10.1016/j.enpol.2009.08.040

Okereke, C., Russel, D., 2010. Regulatory pressure and competitive dynamics: carbon management strategies of UK energy-intensive companies. California Management Review 52, 100–124.

Orsato, R.J., Wells, P., 2007. U-turn: the rise and demise of the automobile industry. Journal of Cleaner Production 15, 994–1006. doi:10.1016/j.jclepro.2006.05.019

Penna, C.C.R., Geels, F.W., 2015. Climate change and the slow reorientation of the American car industry (1979 – 2012): An application and extension of the Dialectic Issue LifeCycle (DILC) model. Research Policy 44, 1029–1048. doi:10.1016/j.respol.2014.11.010

Petkova, A., Wadhwa, A., Yao, X., Jain, S., 2013. Reputation and decision making under ambiguity: a study of U.S. venture capital firms' investments in the emerging clean energy sector. Academy of Management Journal 57, 422–448.

Pilkington, A., Dyerson, R., 2006. Innovation in distruptive regulatory environmens". European Journal of Innovation Management 9, 146–1060.

Pinkse, J., Kolk, A., 2010. Challenges and Trade-Offs in Corporate Innovation for Climate Change. Business Strategy and the Environment 272, 261–272.

Porter, M.E., Van-der-Linde, C., 1995. Green and competitive: Ending the stalemate. Harvard Business Review 73, 120–134.

PricewaterhouseCoopers, 2007. The automotive industry and climate change. Framework and dynamics of the CO2 (r)evolution. Stuttgart.

Reid, E.M., Toffel, M.W., 2009. Responding to public and private politics: Corporate disclosure of climate change strategies. Strategic Management Journal 30, 1157–1178. doi:10.1002/smj.796

Rietbergen, M.G., Rheede, A.V., Blok, K., 2015. The target-setting process in the CO2 Emission, performance ladder: does it lead to ambitious goals for carbon dioxide reduction? Journal of Cleaner Production 103, 549–561.

Rogers, E.M., 2003. Diffusion of innovations. Fifth Edition., Free Press. ed. New York.

Rothaermel, F.T., Alexandre, M.T.', 2009. Ambidexterity in Technology Sourcing: The Moderating Role of Absorptive Capacity. Organization Science 20, 759–780.

Rothenberg, S., Ettlie, J.E., 2011. Strategies to Cope with Regulatory Uncertainty in the Auto Industry. California Management Review 54, 126–144. doi:10.1525/cmr.2011.54.1.126

Rothenberg, S., Levy, D.L., 2012. Corporate Perceptions of Climate Science: The Role of Corporate Environmental Scientists. Business & Society 51, 31–61. doi:10.1177/0007650311427424

Rugman, A.M., Verbeke, A., 1998. Corporate Strategies and Environment Regulations: An Organizing Framework. Strategic Management Journal 19, 363–375.

Russo, M. V., Fouts, P.A., 1997. A resource-based perspective on corporate environmental performance and profitability. Academy of Management Journal 40, 534–559. doi:10.2307/257052

Sharma, S., Henriques, I., 2005. Stakeholder influences on sustainability practices in the Canadian forest products industry. Strategic Management Journal 26, 159–180. doi:10.1002/smj.439

Sharma, S., Vredenburg, H., 1998. Proactive corporate environmental strategy and the development of competitively valuable organizational capabilities. Strategic Management Journal 19, 729–753. doi:10.1002/(SICI)1097-0266(199808)19:8<729::AID-SMJ967>3.0.CO;2-4

Slawinski, N., Bansal, P., 2012. A matter of time: the temporal perspectives organizational responses to climate change. Organization Studies 33, 1537–1563.

Smith, M.T., 2001. Eco-innovation and market transformation. The Journal of Sustainable Product Design 1, 19–26.

Stemler, S., 2001. An overview of content analysis in practical assessment. Research & Evaluation 7, 1–9.

SupplierBusiness, 2014. Weight Reduction in Automotive Design & Manufacture. IHS Automotive SupplierBusiness,.

Tharumarajah, A., Koltun, P., 2007. Is there an environmental advantage of using magnesium components for light-weighting cars? Journal of Cleaner Production 15, 1007–1013. doi:10.1016/j.jclepro.2006.05.022

Thomas, C.E., 2009. Fuel cell and battery electric vehicles compared. International Journal of Hydrogen Energy 34, 6005–6020. doi:10.1016/j.ijhydene.2009.06.003

Tushman, M.L., Anderson, P., 1986. Technological discontinuities and organizational environments. Administrative Science Quarterly 31, 439–465.

UNEP, 2002. Industry as a partner for sustainable development: Automotive. United Nations Environment Programme - Paperback, 10 July 2002.

Utterback, J.M., Abernathy, W.J., 1975. A Dynamic Model of Process and Product Innovation. Omega 3, 639–656. doi:10.1016/0305-0483(75)90068-7

Van den Hoed, R., 2007. Sources of radical technological innovation: the emergence of fuel cell technology in the automotive industry. Journal of Cleaner Production 15, 1014–1021. doi:10.1016/j.jclepro.2006.05.032

Vergragt, P.J., Brown, H.S., 2007. Sustainable mobility: from technological innovation to societal learning. Journal of Cleaner Production 15, 1104–1115. doi:10.1016/j.jclepro.2006.05.020

Wahyuni, D., Ratnatunga, J., 2015. Carbon strategies and management practices in an uncertain carbonomic environment - Lessons learned from the coal-face. Journal of Cleaner Production 96, 397–406. doi:10.1016/j.jclepro.2014.01.095

Wakabayashi, M., 2013. Voluntary business activities to mitigate climate change: case studies in Japan. Energy Policy 63, 1086–1090.

Walker, H., Bakker, E., Schotanus, F., Harland, C., 2013. Collaborative Procurement: A Relational View of Buyer–Buyer Relationships. Public Administration Review 73, 588–598. doi:10.1111/puar.12048.studies

WBCSD, WRI, 2004. The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised version). Geneva, Washington DC, Washington DC.

Weber, R.P., 1988. Basic content analysis, Paper Series No. 07-049.

Weinhofer, G., Busch, T., 2013. Corporate Strategies for Managing Climate Risks. Business Strategy and the Environment 22, 121–144. doi:10.1002/bse.1744

Weinhofer, G., Hoffmann, V.H., 2010. Mitigating climate change – how do corporate strategies differ? Business Strategy and the Environment 19, 77–89. doi:10.1002/bse.618

Wernerfelt, B., 1984. A resource-based view of the firm. Strategic Management Journal 5, 171–180. doi:10.1002/smj.4250050207

Williander, M., 2007. Absorptive Capacity and Interpretation System's Impact when "Going Green": an Empirical Study of Ford, Volvo Cars and Toyota. Business Strategy and the Environment 213, 202–213. doi:10.1002/bse

Winn, M., Kirchgeorg, M., Griffiths, a., Linnenluecke, M.K., Gunther, E., 2011. Impacts from climate change on organizations: A conceptual foundation. Business Strategy and the Environment 20, 157–173. doi:10.1002/bse.679

Zapata, C., Nieuwenhuis, P., 2010. Exploring innovation in the automotive industry: new technologies for cleaner cars. Journal of Cleaner Production 18, 14–20. doi:10.1016/j.jclepro.2009.09.009

Table 1. Application of the natural-resource-based view on auto-industry innovations in the context of climate change

Innovation strategy	**Key characteristics**	**Innovations in the context of climate change**	**Related concepts in the automobile industry**
Product Stewardship	Minimize life-cycle-wide ecological impacts of products	Focus on redesigning existing products: • Incremental changes in product performance (no changes in the core concept) • Use of alternative fuels, lightweight materials to reduce CO_2 emissions • Require no completely new infrastructure • Depend on marginal changes in consumer behavior	• Reverse logistics • End-of-life treatment • Recovery / recyclable materials • Eco-design • Efficiency (usage phase) • Hybrid • Natural gas
Clean Technology	Leapfrog standard processes and products to implement clean-tech innovations	Focus on radical product innovations: • Significant changes in the core concept of the product • Use of alternative / clean technologies to eliminate / significantly reduce CO_2 emissions • May require completely new infrastructure • May depend on far-reaching changes in consumer behavior	• Electric • Hydrogen • Fuel cell • Zero-carbon • Car-related solar energy systems • Plug-in systems

Source: Derived from Hart (1995; 1997) and Hart & Milstein (2003).

Table 2. Variables and data sources

Variable	Database / Source
CO_2 emissions (minimum)	Vehicle Certification Agency (VCA)
CO_2 emissions (mean)	Vehicle Certification Agency (VCA)
Product stewardship	EPO – (Espacenet)
Clean technology	EPO – (Espacenet)
Euro standard anticipation	Vehicle Certification Agency (VCA)
Model restyling	Parkers Car Guide
Vehicle weight	Parkers Car Guide
Firm size	Osiris, Amadeus and Compustat
Firm profitability	Osiris, Amadeus and Compustat

Table 3. Key words used in content analysis

Innovation strategy	Product Stewardship	Clean Technology
Set of key words used to code patent title	Revers+ logistics	electric+ product
	End+cycle	electric+ car
	End+cycle+ treat	electric+ vehicle
	recover+ material	electric+ auto
	recycle+ material	hydrogen+ product
	eco+ design	hydrogen+ car
	Efficien+ Product	hydrogen+ vehicle
	Efficien+ car	hydrogen+ auto
	Efficien+ vehicle	fuel+ cell+ product
	Efficien+ auto	fuel+ cell+ car
	Hybrid+ PROduct	fuel+ cell+ vehicle
	Hybrid+ car	fuel+ cell+ auto
	Hybrid+ vehicle	zero+ carbon+ product
	Hybrid+ auto	zero+ carbon+ car
	Natural+ gas+ PROduct	zero+ carbon+ vehicle
	Natural+ gas+ car	zero+ carbon+ auto
	Natural+ gas+ vehicle	zero+ emission+ product
	Natural+ gas+ auto	zero+ emission+ car
	Reduc+ material+ product	zero+ emission+ vehicle
	Reduc+ material+ car	zero+ emission+ auto
	Reduc+ material+ vehicle	solar+ product
	Reduc+ material+ auto	solar+ car
	reduc+ weight+ product	solar+ vehicle
	reduc+ weight+ car	solar+ auto
	reduc+ weight + vehicle	plug+ product
	reduc+ weight + auto	plug+ car
	reduc+ combust+ product	plug+ vehicle
	reduc+ combust+ car	
	reduc+ combust+ vehicle	
	reduc+ combust+ auto	
	light+ material+ product	
	light+ material+ car	
	light+ material+ vehicle	
	light+ material+ auto	

Table 4. Descriptive statistics and correlations matrix

		Mean	SD	1	2	3	4	5	6	7	8
1	Min CO_2 emissions	175.64	60.12								
2	Average CO_2 emissions	230.22	87.59	***0.91***							
3	Product stewardship (%)	2.13	3.73	***-0.13***	***-0.13***						
4	Clean technology (%)	2.95	6.66	***-0.16***	***-0.18***	-0.07					
5	Vehicle weight	1436.28	351.82	***0.61***	***0.65***	***-0.14***	***-0.16***				
6	Euro standard anticipation	0.55	0.45	***-0.16***	-0.09	0.06	0.04	0.07			
7	Model restyling	0.17	0.15	0.00	-0.05	-0.07	0.02	0.03	-0.09		
8	Firm size	15.38	3.49	***-0.59***	***-0.53***	***0.19***	***-0.20***	***-0.12***	-0.01	0.06	
9	Firm profitability	2.03	5.63	***-0.18***	***-0.13***	***0.25***	-0.04	-0.04	-0.02	0.00	***0.13***

N = 327 observations. Correlations in bold, italicized values are significant at *p*-value <0.05.

Table 5. Random-effects regression results (Dependent variable = CO_2 emissions of the vehicle model with the minimum emissions)

	Min $CO_{2\ t+1}$							
	Model 1		Model 2		Model 3		Model 4	
Variables	Coefficient	RE	Coefficient	RE	Coefficient	RE	Coefficient	RE
Product stewardship			0.291	(0.385)	0.337	(0.374)	0.420	(0.384)
Clean technology					-0.628***	(0.151)	-0.617***	(0.151)
Product stewardship x Clean technology							-0.216	(0.185)
Vehicle weight	0.090***	(0.010)	0.090***	(0.010)	0.090***	(0.010)	0.089***	(0.010)
Euro standard anticipation	-9.313	(6.540)	-8.785	(6.761)	-8.556	(6.645)	-8.653	(6.666)
Model restyling	7.720	(10.416)	8.244	(10.462)	7.119	(10.172)	7.169	(10.145)
Firm size	-8.888***	(1.688)	-8.930***	(1.722)	-9.405***	(1.669)	-9.202***	(1.694)
Firm profitability	-0.036	(0.196)	-0.070	(0.205)	-0.248	(0.192)	-0.257	(0.194)
Years dummies	Yes		Yes		Yes		Yes	
Constant	168.860***	(30.380)	167.750***	(30.080)	178.432***	(28.618)	177.100***	(28.689)
Number of observations	327		327		327		327	
Number of firms	38		38		38		38	
R-squared	0.69		0.69		0.71		0.72	

*** $p<0.01$; ** $p<0.05$; * $p<0.1$. RE, Cluster-robust standard errors are in parentheses.

Table 6. Random effects regression results (Dependent variable = Average CO_2 emissions of all vehicle models)

	Av. $CO_{2\ t+1}$							
	Model 1		Model 2		Model 3		Model 4	
Variables	Coefficient	RE	Coefficient	RE	Coefficient	RE	Coefficient	RE
Product stewardship			-0.397	(0.396)	-0.352	(0.398)	-0.225	(0.424)
Clean technology					-0.555***	(0.141)	-0.539***	(0.139)
Product stewardship x Clean technology							-0.340**	(0.170)
Vehicle weight	0.115***	(0.013)	0.115***	(0.013)	0.116***	(0.014)	0.114***	(0.014)
Euro standard anticipation	-6.098	(5.326)	-6.846	(5.505)	-6.622	(5.402)	-6.744	(5.401)
Model restyling	-0.555	(8.799)	-1.240	(8.849)	-2.325	(8.669)	-2.212	(8.605)
Firm size	-9.614***	(2.212)	-9.549***	(2.226)	-10.029***	(2.159)	-9.628***	(2.178)
Firm profitability	-0.238	(0.215)	-0.190	(0.223)	-0.358	(0.224)	-0.375*	(0.227)
Years dummies	Yes		Yes		Yes		Yes	
Constant	197.032***	(45.731)	198.675***	(45.933)	206.799***	(45.263)	204.184***	(45.418)
Number of observations	327		327		327		327	
Number of firms	38		38		38		38	
R-squared	0.64		0.64		0.66		0.67	

*** $p<0.01$; ** $p<0.05$; * $p<0.1$. RE, Cluster-robust standard errors are in parentheses.

Table 7. Random effects regression results (Dependent variable = CO_2 emissions of the vehicle model with minimum emissions in t+1, t+2 and t+3)

	Model 1: Min $CO_{2\ t+1\ (2009)}$		**Model 2: Min $CO_{2\ t+2\ (2010)}$**		**Model 3: Min $CO_{2\ t+3\ (2011)}$**	
Variables	Coefficient	RE	Coefficient	RE	Coefficient	RE
Product stewardship	0.420	(0.384)	0.422	(0.384)	-0.121	(0.441)
Clean technology	-0.617***	(0.151)	-0.589***	(0.134)	-0.705***	(0.158)
Product stewardship x Clean technology	-0.216	(0.185)	0.060	(0.204)	0.130	(0.231)
Vehicle weight	0.089***	(0.010)	0.080***	(0.010)	0.107***	(0.015)
Euro standard anticipation	-8.653	(6.666)	-3.109	(6.386)	-3.843	(5.928)
Model restyling	7.169	(10.145)	5.049	(8.792)	-11.834	(10.151)
Automaker size	-9.202***	(1.694)	-9.070***	(1.554)	-13.331***	(2.087)
Automaker profitability	-0.257	(0.194)	-0.285	(0.206)	-0.174	(0.300)
Years dummies	Yes		Yes		Yes	
Constant	177.100***	(28.679)	175.691***	(27.173)	208.605***	(40.246)
Number of observations	327		327		327	
Number of automakers	38		38		38	
R-squared (overall)	0.72		0.71		0.73	

*** $p<0.01$; ** $p<0.05$; * $p<0.1$ RE, Cluster-robust standard errors are in parentheses.

Note: For convenience, we also display the results for the full model for CO_2 in t+1, previously displayed in Table 5.

Table 8. Random effects regression results (Dependent variable = Average CO_2 emissions of all vehicle models in t+1, t+2 and t+3)

	Model 1: Av.$CO_{2\ t+1\ (2009)}$		**Model 2: Av.$CO_{2\ t+2\ (2010)}$**		**Model 3: Av.$CO_{2\ t+3\ (2011)}$**	
Variables	Coefficient	RE	Coefficient	RE	Coefficient	RE
Product stewardship	-0.225	(0.424)	-0.089	(0.430)	0.369	(0.440)
Clean technology	-0.539***	(0.139)	-0.586***	(0.116)	-0.410**	(0.166)
Product stewardship x Clean technology	-0.340**	(0.170)	-0.099	(0.186)	-0.144	(0.202)
Vehicle weight	0.114***	(0.014)	0.107***	(0.013)	0.094***	(0.013)
Euro standard anticipation	-6.744	(5.401)	-6.522	(5.294)	-4.175	(5.368)
Model restyling	-2.212	(8.605)	-2.040	(7.789)	-4.038	(7.585)
Automaker size	-9.628***	(2.178)	-10.629***	(2.093)	-11.064***	(2.066)
Automaker profitability	-0.375*	(0.227)	-0.249	(0.199)	-0.116	(0.188)
Years dummies	Yes		Yes		Yes	
Constant	204.184***	(45.418)	223.703***	(41.860)	231.976***	(41.815)
Number of observations	327		327		327	
Number of automakers	38		38		38	
R-squared (overall)	0.67		0.67		0.65	

*** $p<0.01$; ** $p<0.05$; * $p<0.1$

RE, cluster-robust standard errors are in parentheses.

Note: For convenience, we also display the results for the full model for CO_2 in t+1, previously displayed in Table 6.

Appendix

Table A. Random effects regression results without Volkswagen group (Dependent variable = Average CO2 emissions of all vehicle models in t+1, t+2 and t+3)

	Model 1: Av. CO2$_{t+1\ (2009)}$		**Model 2: Av. CO2$_{t+2\ (2010)}$**		**Model 3: Av. CO2$_{t+3\ (2011)}$**	
Variables	Coefficient	RE	Coefficient	RE	Coefficient	RE
Product stewardship	-0.318	(0.590)	0.124	(0.524)	0.400	(0.734)
Clean technology	-0.539***	(0.072)	-0.595***	(0.065)	-0.423***	(0.065)
Product stewardship x Clean technology	-0.460**	(0.208)	-0.206	(0.173)	-0.236	(0.162)
Vehicle weight	0.117***	(0.018)	0.115***	(0.017)	0.101***	(0.016)
Euro standard anticipation	-3.693	(6.552)	-4.704	(6.599)	-2.722	(5.635)
Model restyling	-3.588	(7.780)	-3.584	(5.588)	-4.455	(6.439)
Automaker size	-9.830***	(3.407)	-10.622***	(3.227)	-10.922***	(2.929)
Automaker profitability	-0.434*	(0.236)	-0.335*	(0.194)	-0.215	(0.212)
Years dummies	Yes		Yes		Yes	
Constant	203.166***	(58.199)	213.761******	(57.588)	221.308***	(56.963)
Number of observations	292		292		292	
Number of automakers	34		34		34	
R-squared (overall)	0.67		0.67		0.66	

*** p<0.01; ** p<0.05; * p<0.1

RE, cluster-robust standard errors in parentheses.