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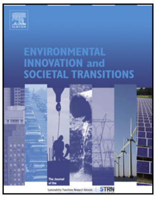

Electrifying the automotive industry: The geography and governance of R&D collaboration

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ABSTRACT

The automotive industry is subject to various pressures that may result in a transition to more eco-friendly technologies. Electrified vehicles represent a potential means to shift road transport onto a new technological path. However, incumbent automakers face several challenges related to vehicle electrification. One challenge is that vehicle electrification requires competences different to those associated with the internal combustion engine. Automakers can access competences and knowledge that can benefit innovation via collaborative R&Dwith external organisations. This paper uses patent and bibliometric data to examine geographical and organisational aspects of R&D collaboration in the automotive industry. We distinguish between two modes of organisation for R&D collaborations between automakers and external partners (hierarchies and networks) and compare R&D collaborations for electric vehicle technologies with traditional R&D partnerships. We show that automakers collaborate with foreign partners when they are linked viahierarchies and are embedded in local R&D networks with academic partners.

1. Introduction

The global automotive industry is unsustainable in many respects, and is subject to various pressures that may force road transport onto a new technological path. First, the recent economic

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downturn caused substantial losses in sales for numerous automakers (Dooley et al., 2010). Governments were forced to intervene with recovery packages to save jobs, the most notable being the salvation of General Motors by the US Obama administration. Second, the global reconfiguration of the automotive industry that followed the rapid economic development of Asian economies has resulted in the emergence of new markets (Abrenica, 1998; Humphrey and Memedovic, 2003) and new automotive companies in India and China that are competing with previously incumbent automakers. Third, increased global demand for automobility has driven fuel prices upwards and refocused attention to the fact that oil is a finite and geopolitically sensitive resource (Wells, 2010). Fourth, the conflation of these factors with ecological issues such as global warming has resulted in environmental legislation that forces automakers to improve vehicles' fuel efficiency and utilise alternative technologies and fuels.

Several automakers have developed electrified road vehicles in response to these 'megatrends' (Conrady, 2012). Electric vehicles have regained popularity in the last two decades and vehicles with various configurations of internal combustion engines (ICE) and electric motors have been developed. Toyota was an early mover in the electrification upswing with the Prius, first sold in 1997 (Magnusson and Berggren, 2001). Since the late 1990s other automakers have introduced hybrid and fully electric cars, buses and trucks. Hydrogen fuel cells represent another alternative for electrification.

Staying abreast of this trend poses challenges for automakers. One challenge is that electrification requires knowledge and competences that are notably different from those inherent to the ICE (Aggeri et al., 2009). Integrating electric motors, batteries and regenerative braking systems into vehicles means that automakers must develop more complex control systems to control and monitor electrical subsystems and components, and requires competences in fields such as electronics and computing. Connecting electric vehicles to the electricity grid via charging stations or 'slide-in' technology requires developments in ICT and utilises competences from electric power engineering. In other words, the potential for a transition to electrified vehicles means that automakers must draw on knowledge and skills that are beyond their traditional competence bases. Hence automakers may find it useful to seek out external partners with competences that can assist in an electromobility transition. The strategic alliance between Renault and Nissan, for instance, aims in part to develop 'zero-emission' transportation (Nissan, 2012). The alliance encompasses R&D collaboration on various key technologies for electrification, realised via joint venture activities such as the Automotive Energy Supply Corporation, which aims to develop and mass-produce lithium-ion batteries. The alliance is designed to help develop and access competences relevant for innovation and boost competitive advantage.

These types of partnerships represent credible ways of boosting innovation. Generally speaking, the generation of new ideas and knowledge for innovation is increasingly recognised as an outcome of creative interactions between actors with complementary knowledge bases and competences (Gilsing et al., 2008). Hence innovation management scholars tend to advocate open innovation strategies that blend external sources of innovation with company-level competences and assets (Chesbrough, 2006). The benefits of collaborations between companies and external partners are widely known. Companies can gain access to key markets, technologies, competences and skills that are useful for innovation (Mariti and Smiley, 1983; Lynn, 1988; Eisenhardt and Schoonhoven, 1996; Powell et al., 1996; Hagedoorn and Duysters, 2002). Through collaboration, companies can become better equipped to boost their competitive advantage, especially where increasing product complexity makes it difficult to maintain a workforce with the human capital necessary for innovation (Porter and Fuller, 1986; Hagedoorn and Schakenraad, 1990). Furthermore, R&D collaboration is important when industries undergo transitions to new technologies, especially where market incumbents do not possess the requisite competences and skills.

However, there are various factors that can inhibit R&D collaboration, including the structure and dynamics of competitive markets, a lack of social capital, cultural differences between skilled practitioners and even the types of knowledge shared between partners (Polanyi, 1967; Powell et al., 1996; Lundvall et al., 2002). Together these elements can inhibit the forces of globalisation as regards R&D collaboration, which is in some instances more suited to a local geographical scale (Martin and Moodysson, 2011).

Examining patterns of R&D collaboration can thus provide nuanced information for practitioners and policymakers that seek to boost industrial development. It can also provide an indication of companies' technological readiness for a transition to new technologies (Glenn Richey and Autry, 2009). This paper utilises quantitative methods based on analysis of bibliometric and patent data to examine R&D collaborations between automakers and external partners. In particular, the paper seeks to address two research questions. The first question addresses the 'openness' of R&D collaborations within the automotive industry and is formulated as: What types of organisational structures underpin collaborative partnerships between automakers and external partners? The second focuses on the geography of R&D collaboration, formulated as: What is the geography of R&D collaborations in the automotive industry? The next section further describes the rationale that underpins these lines of investigation by reviewing the literature on the electrification of road vehicles and R&D collaboration. Section three describes the methods used to access and analyse data, and results are presented in section four. Section five discusses the relevance and importance of the findings and concludes with suggestions for policymakers and practitioners.

2. Background and theoretical considerations

In very general terms, collaboration is critical to innovation. Innovation scholars commonly describe actors, networks and institutions as the three main elements of innovation systems (Lundvall, 1992; Nelson, 1993; Edquist, 2001). The actor-network core of an innovation system, whilst situated within an institutional framework, reflects the importance of actors such as companies, suppliers, universities and consultancies working together to make innovation possible. The importance of collaboration, or 'interconnectedness', also underpins cluster theory (Porter, 1990) and dates back to Alfred Marshall's (1890) work on agglomeration economies. Marshall argued that innovation is a collective act, having noted that internal processes within companies account for only a fraction of their development.

From a management perspective, collaborations with external partners can be beneficial for innovation for various reasons. This list of reasons can be crudely divided into two categories: access to markets and access to technology (Tidd et al., 2005). As regards access to markets, companies collaborate to gain access to new or foreign markets; to monitor market opportunities; to benefit from partners' complementary assets; and to increase economies of scale in production (Porter and Fuller, 1986; Harrigan, 1988; Obleros and MacDonald, 1988).

As regards access to technology, companies engage in collaborations in order to reduce and share the costs and risks of R&D activities (Mytelka and Delapierre, 1987; Mowery, 1988; D'Cruz and Rugman, 1994; Grandori, 1997; Ahuja, 2000). R&D collaboration also facilitates technology transfer and allows companies to access the tacit elements of partners' technologies, knowledge and competences (Mariti and Smiley, 1983; Lynn, 1988; Eisenhardt and Schoonhoven, 1996; Powell et al., 1996; Hagedoorn and Duysters, 2002). Moreover, given technology's increasing complexity, R&D collaboration allows companies to access interdisciplinary sources of knowledge and to monitor technological developments in different fields (Porter and Fuller, 1986; Hagedoorn and Schakenraad, 1990). In more general terms, a collaborative approach to innovation can also boost the development and diffusion of innovations both within and between industries (Almeida and Kogut, 1999; Nooteboom, 2000; Erickson and Jacoby, 2003).

The importance of R&D collaborations with different types of external actors is reflected in studies that focus on private–private partnerships (e.g. Hagedoorn et al., 2000); collaborations with suppliers (e.g. Harabi, 1998); and public–private partnerships (Stiglitz and Wallsten, 1999). Moreover, scholars increasingly recognise that industries should have strong ties with public research institutions and national research systems (Lundvall, 1992; Nelson, 1993; Edquist, 2001). Hence policymakers commonly aim to improve industry–academia ties by promoting 'translational research' that can boost national economic performance (Zerhouni, 2003). Such efforts are also reflected in increased academic patenting (Nelson, 2001); academic technology licensing (Thursby et al., 2001); academic entrepreneurship (Shane, 2005); and the diffusion of 'technology transfer' mechanisms (Siegel et al., 2003). As regards the automotive industry, there is evidence to show that successful collaboration with academic partners has various outcomes, including technological innovation; scientific publications; patents and other forms of IPR; research funding and student recruitment (Barnes et al., 2002).

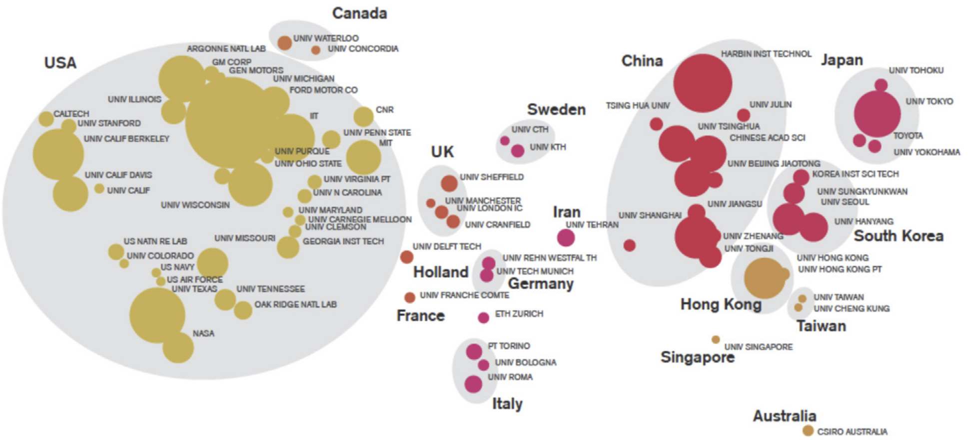

Fig. 1. Scientific journal publications on electric and hybrid electric vehicles per institution.
Source: author'sown calculations based on WoS data.

Companies can thus boost their innovative potential via R&D collaborations with external partners, both public and private. There are several reasons to focus on R&D collaboration as regards a transition to electrified vehicles in the automotive industry. One major reason is that the development of knowledge and competences for electrification appears to be unevenly dispersed across the globe, with some companies, countries and regions taking the lead. This is perhaps because countries with strengths in the automotive industry spend varying amounts on R&D for electrification and prioritise different areas. Government R&D funding in Sweden, for instance, has prioritised hybrid powertrains and control systems for vehicles; but funding for research on batteries, fuel cells and hydrogen infrastructure is lacklustre when compared with Japan and the USA (Arnold et al., 2007). Bibliometric data suggests that the USA and some East Asian countries are the most active in terms of electrification R&D (in absolute terms) (Fig. 1).

Furthermore, Japanese automakers own far more of the intellectual property associated with electrification compared to companies located elsewhere (Fig. 2). To the extent that this data reflects

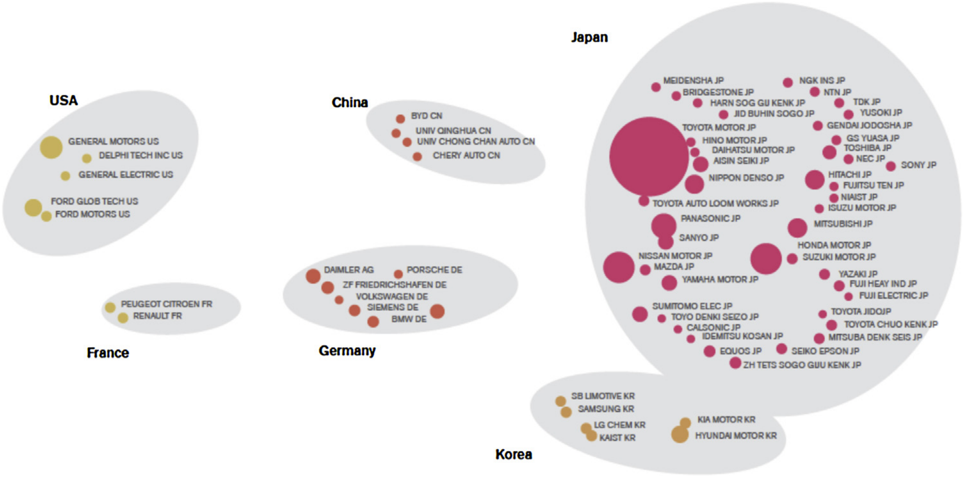

Fig. 2. Electric and hybrid electric vehicle patents per institution.
Source: author'sown calculation based on WoS data.

technological leadership in the field of electrification, it appears to be the case that European automakers are laggards in comparison to their counterparts in Japan, China and the USA. This is also supported by previous studies on patent data, which demonstrate that Japanese and American companies own the majority of 'significant' patents related to vehicle electrification (Pilkington et al., 2002; Lloyd and Blows, 2009).

The European automotive industry would perhaps benefit from R&D collaborations with foreign partners boasting electrification expertise, simply as a means to access the technology and competences required to build electrified vehicles. It is of course possible for European automakers to simply purchase key subsystems and components, such as batteries for electric vehicles, from specialised suppliers. However this type of strategy appears to be inherently risky for the following reasons.

Generally, R&D collaboration is important for complex product innovations such as automobiles. Road vehicles contain thousands of components that are designed and manufactured in a complex tiered system of suppliers. Within this value chain, automakers typically boast architectural competences – the skills and know–how required to integrate various systems and subsystems of components and ensure that they function as a whole (Henderson and Clark, 1990; Batchelor, 2006). This approach, whereby automakers collaborate with the value chain, is known as modularisation (Hsuan, 1999).[1] Modularisation is a type of open innovation (Chesbrough, 2006), as the responsibility for designing key components and subsystems is outsourced via R&D collaborations with suppliers (Howard and Squire, 2007). One advantage of modularisation is that automakers can utilise value chain competences to boost their own competitive advantage (Morris and Donnelly, 2006).

Effective modularisation is facilitated when automakers possess technical competences to complement those of key suppliers (Morris and Donnelly, 2006). Electromobility poses a challenge to automakers in that the competences linked to lithium-ion battery systems, for instance, are not associated with the traditional internal combustion engine (ICE). As mentioned above, automakers can circumvent this problem by purchasing such technologies from suppliers without developing the competences required to facilitate research-intensive collaborations. However this type of strategy is risky because automakers that do not retain competences related to outsourced activities risk their competitive advantage (Takeishi, 2002). In other words, automakers that seek to derive competitive advantage from electromobility must undergo a process of organisational learning, where they (1) develop internal competences related to electric drivetrains and (2) enter into R&D intensive collaborations with key suppliers (and other organisational actors with key competences). The extent to which automakers pursue such strategies can be treated as, among other things, an indicator of technological readiness vis-à-vis a transition to electromobility (Glenn Richey and Autry, 2009).

2.1. *Modes of collaboration*

Some scholars advocate a collaborative approach to innovation via the 'open innovation' idiom, which refers to companies that seek to blend external sources of innovation with company-level competences and assets (Chesbrough, 2006). 'Open innovation' implies that companies must look beyond their value chains to partner with actors that can assist in both generating ideas and knowledge for innovations and their distribution via new market channels (Langlois, 2003; Christensen, 2006). Adopting an open approach to innovation is not simple. By seeking to access technology via R&D collaboration, automakers must decide on how to structure collaborations in a way that best suits their interests. In other words, automotive companies must implement an appropriate governance structure – or mode of collaboration – that underpins efforts to innovate with external partners. Modes of collaboration between automotive companies and external organisations are examined here in terms of two ideal types: hierarchy and network.

Williamson (1975) utilised Coase's (1937) transaction cost theory to elaborate on the economics of organisation and describe organisational governance structures in terms of markets and hierarchies. This approach is based on the notion that the opportunity to economise on transaction costs is

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[1] There are various forms of modularisation, which is not a standardised practice. For an overview see Takeishi and Fujimoto (2001).

central to the study of organisations (see also Williamson, 1981). Stated briefly, Williamson's (1975) argument is that transactions which are relatively straightforward and have low asset specificity are easily managed via markets. When companies can perform transactions with high degree of confidence and certainty, they are likely to interact with external partners via market exchanges. Hence market relationships are typically arm's length.

In contrast, Williamson (1975) argues that transactions with higher levels of uncertainty and asset specificity are better managed via hierarchies. Hierarchies are better suited to conditions whereby companies are limited by bounded rationality, or transactions are risky due to a partner's opportunistic behaviour. In such circumstances a company may wish to reduce these risks by internalising such transactions (in the form of a merger or acquisition, for instance). Alternatively, companies can reduce risks by entering into a more formal, legal agreement with a partner, such as a joint venture or a strategic alliance. In practice, such agreements make partnerships subject to managerial authority. These ideal types exist at opposite ends of a continuum – hence the term 'market-hierarchy dichotomy'. Scholars have utilised Williamson's approach to identify various hybrid forms that reside somewhere between the market-hierarchy poles of this continuum (Eccles and White, 1986; Thorelli, 1986; Powell, 1987; Koenig and Thietart, 1988).

As mentioned previously, to gain access to technology an automotive company can purchase systems, subsystems and components from suppliers. Whilst such transactions can require automakers to provide technical specifications to suppliers regarding the technology they wish to purchase, these types of market exchanges comprise little in the way of R&D collaboration. The automaker merely states technical criteria, which a supplier must then fulfil (Batchelor, 2006; Christensen, 2006). For this reason, this paper does not examine market modes of collaboration.

As an alternative to sourcing technology via markets, automotive companies can enter into formal (hierarchical) agreements with suppliers or other external partners (such as joint ventures and strategic alliances), which can facilitate more fruitful R&D collaborations aimed at developing technologies in partnership. A hierarchical mode of R&D collaboration is one means for automotive companies to access technology via external organisations in a manner that can help to boost their competitive advantage. This is because (1) companies must develop competences and skills in order to benefit from such agreements; and (2) interactions between actors with complementary knowledge and competences are beneficial for innovation (Cohen and Levinthal, 1990; Lane et al., 2001).

A further alternative means to structure R&D collaborations is for companies to work with partner organisations via innovation networks. Powell (1990) argues that networks are an organisational mode that stands apart from the traditional market-hierarchy dichotomy described above. Powell describes networks as more relational and trust-based than markets and hierarchies, and argues that actors collaborate in networks due to mutual benefits and complementary strengths. In networks, actors are not governed by administrative fiat or by market haggling. Instead, networks operate according to a 'norm of reciprocity', whereby reputational assets are valued (Powell, 1990, p. 300). The sizeable literature on innovation networks shows that creating and maintaining knowledge networks requires considerable time and nurture (Powell et al., 1996).

In sum, hierarchies appear to be useful fundaments of collaborative R&D collaborations between automakers and external partners. Whilst innovation networks may be more beneficial than hierarchies, they can be more difficult to establish and manage. The following section examines factors that influence the geography of R&D collaboration.

2.2. *The geography of R&D collaboration*

Knowledge and information are the main resources that travel between partners that adopt a networked approach to innovation (Porter, 1990; Gordon and McCann, 2000; Martin and Sunley, 2003). This facet of innovation networking can boost companies' prospects of long-term survival (Shaw, 1993; Siegel and Shaw, 1998), enables companies to learn of others' innovative work practices (Biemans, 1991; Erickson and Jacoby, 2003) and promotes the early adoption of new technology (Almeida and Kogut, 1999). A further key element of innovation networks is that they allow companies to access the tacit elements of partners' technologies and competences (Lynn, 1988; Mariti and Smiley, 1983).

These factors add credence to the presumption that networks are a favourable means of structuring R&D collaboration.

However, tacit knowledge refers to competences or 'know-how' that are hard to codify, such that tacit knowledge transfer requires face-to-face interaction. In contrast, codified knowledge can be exchanged more freely between individuals without interpersonal contact (Polanyi, 1967). This can influence the geography of innovation in that industries operating primarily on tacit knowledge pursue collaboration on a more localised scale (Martin and Moodysson, 2011). Despite the fact that developments in information technologies and reduced costs of travel can boost the flow of information between actors over long distances (Lang, 2001; Mirghani and Mohamed, 2007), other factors reinforce the importance of the local scale. These include the costs of long-distance collaboration, language and cultural/institutional barriers.

Technological externalities are another factor that can inhibit a networked approach to innovation. A technological externality is, in basic terms, a disincentive to innovation created by the mobility of ideas and knowledge. The risk to a company is that a rival may benefit from its innovative efforts without having invested in R&D, hence the need for corporate secrecy and intellectual property rights. The social capital of an innovation network can help to overcome this problem (Uzzi, 1997). However, nurturing social capital requires considerable time and effort (Powell et al., 1996; Lundvall et al., 2002), which is one reason for companies to network according to traditional patterns of collaboration (Granovetter, 1985; Ahuja, 2000; Kash and Rycroft, 2000). Furthermore, companies may not be aware of networking opportunities because of their bounded rationality (Simon, 1957). Even where individuals within companies are aware of opportunities, they may lack personal contacts with relevant individuals in potential partner organisations. It is here that 'know-how' must be complemented with terms like 'know-who' to describe the range of competences necessary for effective network collaboration (Lundvall and Johnson, 1994). Know-who means that individuals' social ties are important for collaboration, which reinforces the point that innovation networks may be better suited to a local scale.

3. Methods

This study utilises quantitative methods to map R&D collaborations in the automotive industry using two indicators: patents and bibliometric data. Both patent and bibliometric data analysis have previously been used to examine R&D collaborations. An alternative and common measure of R&D activity is, for instance, R&D expenditure. It is however a less reliable method because it is difficult to ensure that (1) expenditures are measured in a consistent way across time and for different companies and (2) such data is not widely accessible – it is mostly available for larger companies and for more recent time periods (Lanjouw et al., 1998). Accessibility to broad, comprehensive and commensurable datasets is one of the main advantages of using patent and bibliometric data.

Patent analysis has been used to examine R&D collaborations in a range of industrial contexts. For example, patents have been used to examine developments in lead-free solders in the electric and electronic industry in Japan, Europe, and the United States (Yarime, 2009). Patents have also been used to examine multinationals' international R&D collaborations (Guellec and van Pottelsberghe de la Potterie, 2001); the spatial distribution of innovations in different technological fields (Engelsmen and van Raan, 1994; Lanjouw and Mody, 1996); and the distribution of innovations between industry sectors and other actors such as government agencies and universities (Nameroff et al., 2004; Sun et al., 2004). Taken together, these studies demonstrate the utility of patent analysis for examining R&D collaborations between different types of organisational actors and the geography of R&D collaboration.

Generally, patents are regarded as a good indicator of R&D activities, especially since patent applications are usually filed early in the research process (Griliches, 1990; Popp, 2005). They comprise "a rich indicator of technological development" in that R&D activities are inherent to all patented inventions (Pilkington et al., 2002, p. 5). Patents also provide coverage over a long time period and for a comprehensive range of individuals and organisations, and cover the inputs and outputs of R&D activities (Lanjouw et al., 1998). Patents with 'cross-border ownership' (shown in applicants' addresses) can be used to discern the locations of R&D activities that led to the invention in question (Guellec and van Pottelsberghe de la Potterie, 2001).

However, patents are by no means a perfect indicator of R&D activities. One reason for this is that not all R&D efforts are patented (Engelsmen and van Raan, 1994; Popp, 2005). This may be because not all R&D efforts produce potentially successful inventions, or because inventors may choose to keep an invention secret and thus not patent it (Popp, 2005). The propensity to patent also varies across industries (Levin et al., 1987), although this shortcoming is minimised in studies that focus on a single industry (Popp, 2005). Another problem is that some countries and regions in the US and Asia are subject to a higher propensity to patent than in Europe (Engelsmen and van Raan, 1994; Arundel and Kabla, 1998; Hu and Jefferson, 2009) with the implication that patent data may be skewed and not fully reflect the scale of countries'/companies' R&D activities. Furthermore, some patent databases include patents written only in English, which may obscure patents written in other languages. A further problem is that R&D collaborations are not always fully detailed in patent data, especially industry–academia collaborations. Academic patenting is understated in Europe, where scientists are "less likely to reclaim the property of the patents they produce" than in the US, mainly because of institutional differences that allow private companies to own more IPR (Lissoni et al., 2009, p. 212). Overall, the role of academia as a partner to industry is often understated in patent data.

In order to examine linkages between the automotive industry and national research systems, this study uses bibliometric analysis to examine co-authorship of scientific journal publications. Co-authorship is a means of assessing networks containing authors with joint publications (Yin et al., 2006) that are built on other formal and informal structures (Abbasi et al., 2012). A paper is co-authored if it has more than one author, and the term 'institutional co-authorship' refers to authors from different organisations (Melin and Persson, 1996). Similar to patent analysis, bibliometric analysis is useful because of the availability of comprehensive and commensurable datasets. Co-authorship is a means to examine informal networks between researchers and demonstrates the diffusion of knowledge and skills between partners (Lundberg et al., 2006; Butcher and Jeffrey, 2005; Wang et al., 2005; Tussen, 2004; Tijssen et al., 1996; Luukonen et al., 1993).

However, similar to patents, bibliometric data cannot provide a full and exhaustive account of R&D activities (Engelsmen and van Raan, 1994) and are not a perfect indicator of R&D collaborations. There are various reasons for this. R&D collaboration can take many forms that are not evident in bibliometric data. As regards industry–academia collaboration, for instance, partners can make various inputs to R&D including experimental design, provision of scientific labour, access to data and instrumentation and provision of advice on a research project (Sylvan Katz and Martin, 1997; see also Laudel, 2002). In some instances academic researchers may omit industrial partners names from scientific publications (Tussen, 2004), but collaboration is generally overstated in bibliometric data (Melin and Persson, 1996). One reason for this is that authors move from one organisation to another, or have more than one affiliation, such that what appears to be co-authorship is really just a single author (Lundberg et al., 2006). Furthermore, the extent to which co-authorship fully reflects R&D collaborations between industry and academia is likely skewed by the fact that the entire scientific enterprise is geared towards publication whereas industrial and technological institutions focus more on economic rewards for R&D (Moed, 1996; Murray, 2002).

Hence despite the fact that patent and bibliometric data are widely used to examine R&D collaboration, neither are perfect indicators of R&D activities. Scholars typically aim to circumvent the problems described above by triangulating between different data sources (e.g. Lundberg et al., 2006). This study follows this tradition by triangulating between patent and bibliometric data. Triangulation is used here to strengthen the validity of the results, but also to examine different types of networks within which automakers are embedded. It must be noted, however, that this study does not provide an exhaustive account of automakers' network activities owing to the fact that there is no single indicator, or set of indicators, that can fully reveal R&D collaborations.

3.1. Data sample and analysis

We gathered data using two online sources provided by Thomson Reuters. Bibliometric data was accessed via Web of Science (WoS) and patent data via Derwent Innovations Index (DII). WoS accesses

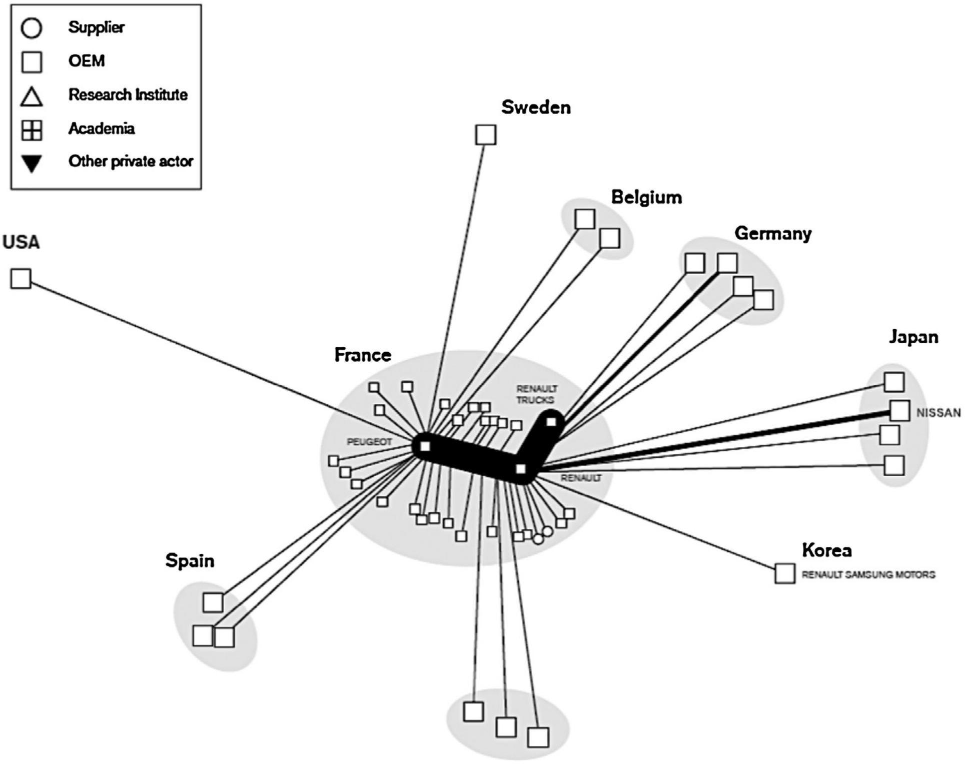

Fig. 3. Network map for Renault (EV and non-EV patents).

“over 12,000 of the highest impact journals worldwide. . .and over 150,000 conference proceedings” (Reuters, 2012). One advantage of DII is that it provides information on patent families (i.e. records of inventions whose patents have been renewed or assigned in different jurisdictions) under a single record. This is important methodologically in that it reduces the ‘noise’ that features in many studies on patent data created by patent renewals and applications (Lanjouw et al., 1998). DII also accesses patents written in different languages.

WoS coverage includes the years between 1899 and present, and DII includes patent coverage from 1963 onwards from 47 patent authorities worldwide. We chose to include all publications and patents for these periods in order to identify cumulative patterns of automakers’ network strategies. Whilst this method produced the most comprehensive dataset, it is important to note that the automakers examined here have not all existed for the same length of time. In addition, most R&D on EV technology has occurred after 1990. This is because of various institutional changes that have encouraged automakers to develop alternatively fuelled vehicles since 1990 (Fogelberg, 2000; Pilkington et al., 2002). Hence our data on R&D collaborations for EV technologies apply mainly to the period 1990–2013.

The automakers included in the study are Fiat, Ford Motors, General Motors, Renault, Toyota, Volvo Cars and Volkswagen (passenger cars) and Scania, Iveco and Hino Motors (busses and trucks). These automakers were chosen because they design and manufacture different types of vehicles, thus covering different applications of EV technology. The findings of this study are thus more generalisable than if it had focused on only one application of EV technology (e.g. passenger cars). These automakers were also chosen because of their locations, which span three continents. This is important given the regional differences in patenting described in the above sections, and because of uneven levels of R&D activity related to EV technology as shown in Figs. 3 and 4. It must be noted that Scania, Iveco and Hino

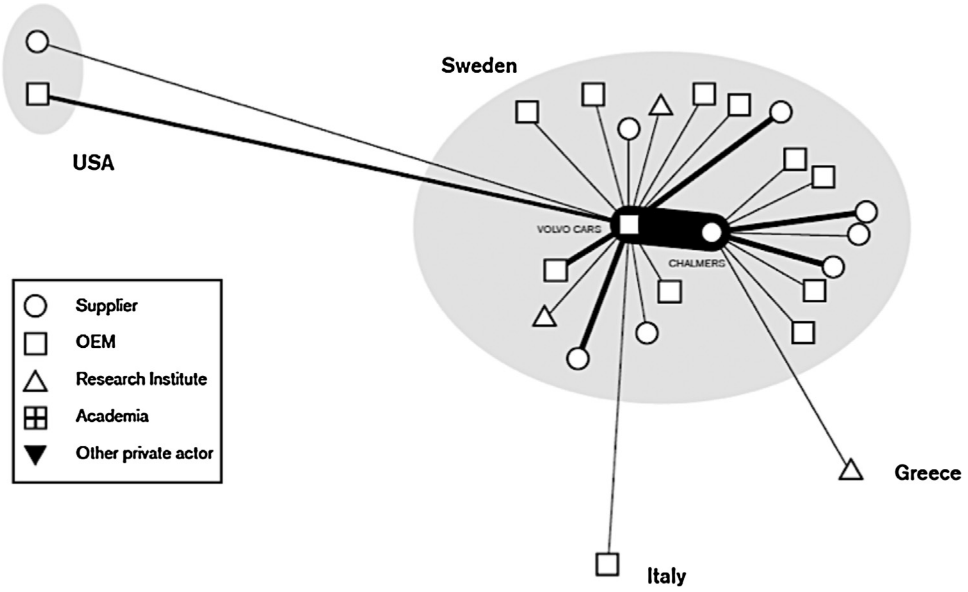

Fig. 4. Volvo's R&D collaborations vis-à-vis scientific publications (non-EV technologies).

Motors are subsidiaries of the Volkswagen Group, the Fiat Group and Toyota Motors respectively. We thus treat any links between these companies and others that are part of the same family of companies as hierarchical.

Data was collected on automakers' R&D activities in the following way. Firstly, bibliometric and patent data were gathered to examine how automakers collaborate by searching for publications and patents using the names automakers and the addresses of their main operational hubs as Boolean search terms. As regards patents, we used a code provided by DII (X21) to select the range of technologies associated with electric vehicles as a Boolean search term, alongside the name/address terms described above. This allowed us to produce two sets of patent data: one that encompasses automakers' patents on EV technologies and one for 'non-EV technologies'. We made a similar distinction for scientific publications by firstly removing non-technical publications from our sample and then by categorising publications using the same terms (EV and non-EV technologies). This was done by examining the title and abstract of each publication.

Both patent and bibliometric data was then collated and analysed in terms of organisational partners that appear as co-authors in publications and co-assignees in patents.[2] Information regarding partner organisations' was then added as codes to the dataset. The first code describes the address of partner (as described in the publication/patent) in the form of a country code. The second describes the type of partner organisation according to the following criteria. Academic organisations were coded as a single category. Publicly floated companies were coded as a second category, regardless of state or private ownership. Organisations that focus exclusively on research activities such as research institutes and laboratories but with no focus on higher education were coded in a third category, again regardless of public or private ownership. Government agencies and third sector organisations such as industry associations were coded in a fourth category.

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[2] Where individuals appeared as assignees in patent data they were removed. It was not possible to include data on individuals due to the large numbers of patents in the study. Whilst this problem likely skews the data in that academic individuals are likely removed, findings from patent data in this study represent organisational collaborations, mainly between private companies. There are databases such as KEINS that collate data on individual scientists precisely to alleviate this problem. However KEINS only has data for academic individuals in Sweden, France and Italy, and to the knowledge of the authors, no database exists with adequate global coverage. Constructing such a database was beyond the resource constraints of the study.

As regards patent data, we focused on the five partner organisations that appeared most frequently as co-assignees in each automakers' patent records. We chose only the top five partners for two reasons. First, analysing every partner would have entailed researching tens of thousands of organisations, which was beyond our resources. Second, we wanted to focus on significant and reciprocated partnerships between automakers and their external partners. Many of the records referred to R&D collaboration in the form of a single patent, which we interpreted to be insignificant given our aims.

We recorded the periods during which the patents with each partner were filed and then analysed the mode of collaboration for each partnership. To identify hierarchical modes of collaboration, we searched for records of mergers, acquisitions, strategic alliances and joint ventures using the Orbis database (BVD, 2013) and corporate histories available via company websites. We also browsed industry journals for reports of collaboration between each automaker and the partner in question. Where no information could be found regarding some form of hierarchical arrangement, we assumed that the patents in question had been produced via network modes of R&D collaboration.

As regards bibliometric data, we included all of the ties between automakers and external organisations in our analysis. This was possible given that the majority of partners were either universities or technical colleges. We observed that the automakers in our sample each have strong ties with a single university or technical college that is located closely to its main operational hub. For this reason we chose to include details of this partnership in the results section below.

We then converted our data into matrix form and fed it into Social Network Analysis software (UCINET). Matrices were created to reflect collaborations between automakers and their partners, with the number of publications/patents used to reflect the strength of ties between partners. As regards geographical aspects of patenting activities, mapping (cartography) is a useful means to present the complexity inherent to bibliometric and patent data (Engelsmen and van Raan, 1994). We thus converted our data into a network map using NETDRAW, with organisations grouped according to their location. Each map represents an automaker's ties with partner organisations, but not ties between partners. Each map is thus a simplified ego-network that aims to show the geographical aspects of collaborations and the diversity or partners. The strength of the tie between an automaker and a partner organisation is reflected in the width of the line between nodes on the map, and the type of partner organisation is shown in the colour/shape of the node.

4. Results

4.1. Patents and R&D collaboration

Table 1 shows data regarding automakers' R&D collaborations vis-à-vis patents. For means of comparison, the dataset includes patents on EV and non-EV technologies. The second column shows the five partners with which each automaker has collaborated the most. Information is provided as regards the dates of these collaborations, as shown by patent data. The fourth column describes the governance structure that underpinned collaborations with a given partner in terms of hierarchies and networks. The fifth column describes the geography of the R&D collaboration in question in terms of local (occurring within the same town or city); national (within the same country); and global (across two countries).

The data show that automakers collaborate primarily with other companies in the automotive industry. The data also show that some automakers have produced patents in collaboration with external partners to a greater extent than others. Ford and Volvo Cars, for instance, have collaborated on a much larger percentage of their patents (as shown in column 3) than the other companies in the dataset. In contrast, Scania produced none of its non-EV patents in collaboration with external partners.

As regards modes of collaboration, the data show that hierarchies between automakers and their partners facilitate an overwhelming majority (70%) of R&D collaborations. Moreover, all of the automakers examined here have collaborated repeatedly with their parent companies or subsidiaries (with the exception of Scania). To a lesser extent, hierarchical arrangements such as joint ventures and strategic alliances facilitate R&D collaboration (e.g. Fiat, Ford and Renault). In contrast, networks underpin much fewer R&D collaborations between companies (30%). Volkswagen and Volvo Cars

Table 1
Automakers' R&D partners for EV and non-EV patents.

1. Automaker		2. Main partners (patent dates)	3. % of patents	4. Mode	5. Geography of collaboration
Fiat auto	1957 non-EV patents	Alfa Lancia (IT) (1988–1993)	2.3%	Hierarchy (Subsidiary, Fiat acquired Lancia in 1969 and Alfa in 1986)	National
		GM Global Technology (US) (2004–2007)	0.7%	Hierarchy (JV between 2000–2005)	Global
		Fiat Research Centre (IT) (1987–1993)	0.5%	Hierarchy (Subsidiary, est. 1978)	Local
		Opel (DE) (2004–2006)	0.4%	Hierarchy (GM acquired Opel in 1931)	Global
		Stars (IT) (1988–1989)	0.3%	Network	National
	22 EV patents	None in collaboration			
Ford Motors	7867 non-EV patents	Ford (DE) (1972–2004)	15.8%	Hierarchy (Subsidiary, est. 1925)	Global
		Ford (FR) (1976–2004)	12.4%	Hierarchy (Subsidiary, est. 1907)	Global
		Ford (CA) (1988–2002)	10.2%	Hierarchy (Subsidiary, est. 1904, acquired 1948)	Global
		Visteon Global Technologies (US) (1993–2007)	2.4%	Hierarchy – network (Spun-off from Ford in 2000)	Local
	1328 EV patents	Daimler AG (DE) (2005–2013)	9.3%	Hierarchy (Joint venture between Daimler and Ballard Power Systems, joined by Ford in 1998)	Global
		Ecostar Electric Drive Systems (US) (1990–2002)	0.7%	Hierarchy (Former subsidiary, est. 1998, acquired by Ballard in 2001)	National
		Ford (DE) (1993–1995)	0.5%	Hierarchy (Subsidiary, est. 1925)	Global
		Ballard Power Systems (CA) (2001–2007)	0.5%	Hierarchy (Joint venture between Daimler and Ballard Power Systems, joined by Ford in 1998)	Global
		Ford (FR) (1993–1995)	0.4%	Hierarchy (Subsidiary, est. 1907)	Global
General Motors	13544 non-EV patents	Opel (DE) (1974–2002)	2.2%	Hierarchy (Subsidiary since 1929)	Global
		Delphi Technologies (US) (1994–2012)	1.6%	Hierarchy – network (Founded 1994, spun off from GM in 1999)	Local
		GM France (FR) (1968–1995)	0.5%	Hierarchy (Subsidiary since 1925)	Global
		Delco Electronics (US) (1989–2000)	0.3%	Hierarchy (Subsidiary 1918–1999)	National
		Electro-Motive Diesel (US) (1996–2005)	0.3%	Hierarchy (Subsidiary 1930–2005)	National
	520 EV patents	Daimlerchrysler (DE) (2005–2006)	2.1%	Hierarchy (Joint venture, Global Hybrid Cooperation, est. 2004)	Global
		Delco Electronics (US) (1996–1998)	1.5%	Hierarchy (Subsidiary, acquired in 1918 until 1999)	National
		General Electric (2004–2006)	1.2%	Network	National
		Hughes Aircraft (US) (1995–1997)	1.2%	Hierarchy (Subsidiary, acquired in 1985)	National

		Mitsubishi Heavy Industries (JP) (2001)	0.6%	Network	Global
Hino Motors	5170 non-EV patents	Toyota (JP) (1997–2013)	2.2%	Hierarchy (Parent)	National
		Sankyo Radiator (JP) (1992–2013)	0.4%	Hierarchy (Subsidiary, N.D.)	Local
		Denso (JP) (1991–2011)	0.4%	Hierarchy (Affiliated via parent)	National
		Isuzu Motors (2010–2013)	0.4%	Hierarchy (Affiliated via parent since 2006)	Local
		Sawafuji Denki (JP) (1983–2002)	0.4%	Network (Noted affiliate)	National
		Hitachi Metals (JP) (1995–2008)	0.3%	Network	National
	151 EV patents	Toshiba (JP) (1988–2004)	6.6%	Network	National
		Toyota (JP) (2002–2009)	4.0%	Hierarchy (Parent)	National
		Aisin Seiki (JP) (2009)	0.7%	Hierarchy (Affiliated via parent)	National
		Daikin Seisakusho (JP) (2002)	0.7%	Network	National
		Denso (JP) (2005)	0.7%	Hierarchy (Affiliated via parent)	National
Iveco	541 non-EV patents	Fiat Powertrain Technologies (IT) (2005–2011)	2.4%	Hierarchy (Affiliated via parent)	Local
		Nissan Diesel Kogyo (JP) (1993–1996)	1.7%	Hierarchy (Joint venture, est. 1989)	Global
		Iveco Germany (DE) (1987–2010)	0.7%	Hierarchy (Subsidiary acquired in 1983)	Global
		ZF Friedrichshafen (DE) (1993–2011)	0.7%	Network (ZF supplier to Iveco)	Global
		Irisbus (IT) (1997–1998)	0.7%	Network (Joint venture between Iveco and Renault in 1999)	National
	9 EV patents	None in collaboration			
Renault	11152 non-EV patents	Renault & Peugeot (FR) (1970–1979)	5.3%	Hierarchy (Joint venture, est. 1969)	National
		Renault Trucks (FR) (2000–2013)	4.4%	Hierarchy – network (Subsidiary between 1978–2001)*	National
		Renault Samsung Motors (KR) (2004–2006)	1.3%	Hierarchy (Subsidiary since 2000)	Global
		Peugeot (FR) (1974–2002)	1.1%	Hierarchy (Joint venture, est. 1969)	National
		Nissan Motors (JP) (2003–2013)	0.6%	Hierarchy (Strategic alliance, est. 1999)	Global
	546 EV patents	Nissan Motors (JP) (2004–2013)	3.7%	Hierarchy (Strategic alliance, est. 1999)	Global
		Michelin (FR) (2011)	0.2%	Network	National
		Inria (FR) (2013)	0.2%	Network	National
Scania	1560 non-EV patents	None in collaboration			
	28 EV patents	Voith Turbo (DE) (2011)	3.7%	Network	Global
Toyota Motors	77965 non-EV patents	Denso (JP) (1996–2013)	3.4%	Hierarchy (Subsidiary to Toyota Group, est. 1949)	National
		Aisin Seiki Co (JP) (1996–2013)	2.8%	Hierarchy (Subsidiary to Toyota Group, est. 1949)	National

Table 1 (*Continued*)

1. Automaker		2. Main partners (patent dates)	3. % of patents	4. Mode	5. Geography of collaboration
	17157 EV patents	Toyoda Automatic Loom Works (JP) (1996–2013)	1.3%	Hierarchy (Subsidiary to Toyota Group, est. 1926)	National
		Soken Inc. (JP) (1996–2013)	1.1%	Hierarchy (Subsidiary to DENSO, est. 1970)	National
		Toyota Auto Body Co. (JP) (1997–2013)	0.9%	Hierarchy (Subsidiary to Toyota Group, est. 1940)	National
		Aisin Seiki Co (JP) (1974–2013)	3.8%	Hierarchy (Subsidiary to Toyota Group, est. 1949)	National
		Denso (JP) (1995–2013)	2.6%	Hierarchy (Subsidiary to Toyota Group, est. 1949)	National
		Soken Inc. (JP) (1995–2013)	1.0%	Hierarchy (Subsidiary to DENSO, est. 1970)	National
		Toyoda Automatic Loom Works (JP) (1995–2013)	0.7%	Hierarchy (Subsidiary to Toyota Group, est. 1926)	National
Volkswagen	13617 non-EV patents	Audi (DE) (1992–2013)	1.5%	Hierarchy (Subsidiary since 1964)	National
		Porsche (DE) (1986–2013)	0.3%	Network – hierarchy (Subsidiary since 2009)	National
		Skoda Auto (CZ) (2005–2011)	0.3%	Hierarchy (Subsidiary since 1994)	Global
		BMW (DE) (1992–2010)	0.3%	Network	National
		Daimlerchrysler (DE) (1995–2007)	0.3%	Network	National
		Bosch (DE) (1992–2013)	0.2%	Network	National
	391 EV patents	Skoda Auto (CZ) (2005–2010)	5.9%	Hierarchy (Subsidiary since 1994)	Global
		Audi (DE) (2012–2013)	2.0%	Hierarchy (Subsidiary since 1964)	National
		Volvo AB (SE) (2000)	0.8%	Network	Global
		Bosch (DE) (1984)	0.4%	Network	National
		Continental (DE) (2006)	0.4%	Network	National
Volvo Cars	310 non-EV patents	Volvo Group (SE) (1991–2001)	37.7%	Hierarchy (Acquired by Ford in 1999)	Local
		Ford Global Technologies (US) (2000–2011)	39.0%	Hierarchy (Owned by Ford 1999–2009)	Global
		Bosch (DE) (2010–2011)	2.3%	Hierarchy (Part of Ford's 'Aligned Business Framework' since 2005)	Global
		Conti Temic Microelectronic (DE) (2006–2007)	1.3%	Network	Global
		Volvo Trucks (SE) (2006)	1.0%	Network	Local
	14 EV patents	Ford Global Technologies (US) (2002–2009)	28.6%	Hierarchy (Owned by Ford 1999–2009	Global
		Volvo AB (SE) (2002–2004)	14.3%	Network (Volvo Cars sold to Ford in 1999)	Local
		Panasonic (JP) (1998–2013)	0.7%	Hierarchy (Joint venture, est. 1996)	National

appear to be exceptions in that they have collaborated with more partners via networks. However the frequency of such collaborations is much less than for hierarchies (see column 3), and as regards Volkswagen and Volvo Cars, several network collaborations represent just a single patent.

Three of the examined partnerships show that hierarchies can precede networked R&D collaborations. The partnerships between Ford–Visteon, GM–Delphi and Renault–Renault-Trucks each represent cases where automakers founded subsidiaries with whom they collaborated on R&D initially via hierarchies. However collaborations continued via networks after these subsidiaries were spun off. The one exception is Volkswagen–Porsche, who collaborated via network arrangements from 1986 until 2009, when the latter was acquired by VW. VW and Porsche then continued to collaborate via the hierarchical arrangements that followed.

As regards the geography of R&D collaborations, the data do not suggest that geographical factors play a significant role in terms of partner's locations. In fact the local scale is the most irrelevant, as fewer patents (12%) were produced via collaborations with local partners. On the contrary, the data suggest that automakers are capable of partnering with companies located both in the same country (54%) and across borders (34%). This is especially the case where hierarchical conditions support R&D collaborations. In contrast, geography does appear to be significant as regards network collaborations. Over 60% of the networked patents were produced with partners within the same country. These patterns of R&D collaboration are exemplified in Fig. 3.

All of the automakers in the dataset have fewer EV patents than non-EV patents, which is to be expected given that the current focus on electrified vehicles was not initiated until 1990. However, the data suggest that automakers demonstrate varying degrees of technological readiness as regards a transition to electrified vehicles. Automakers such as Ford and Toyota have patenting levels that are significantly above the rest, whereas Fiat and Iveco have relatively few EV patents and have not yet started to collaborate with partners vis-à-vis EV technologies. Furthermore, some of the automakers appear to be concentrating on EV patent collaborations with companies that do not appear as major partners in non-EV patents (e.g. Ford–Daimler, Ford–Ecostar, Ford–Ballard, Hino–Toshiba). Again, this is to be expected given that EVs require different knowledge and competences than the ICE.However, some of the automakers in our sample have retained a similar level of patenting with traditional partners as regards EV technologies. For example, significant levels of collaborationcan be noted across both EV and non-EV patents: between Ford Motors and its German subsidiary, Ford DE; between Hino Motors and Toyota and Denso; between Renault and Nissan; between Toyota Motors and Denso, Aisin Seiko, and Toyoda Automatic Loom Works; between Volkswagen and Audi, Skoda, and Bosch; and between Volvo Cars and Ford.

4.2. *Bibliometric data and R&D collaboration*

Bibliometric data tells a different story to that of patents. Whilst patent collaborations show that automakers typically partner with private organisations via hierarchies, bibliometric data suggests that automakers are embedded in local and national networks where they typically collaborate with universities. Moreover, each of the automakers included in our sample maintains reciprocal relationships with a single university or technical college that is geographically close to their main operation al hub. Both Ford and GM, for instance, have collaborated extensively with the University of Michigan, whose main campus is located in Ann Arbor. The latter neighbours Detroit and Dearborn, which are home to GM and Ford respectively. Automakers' partner universities are listed in Table 2.

Overall, bibliometric data shows that automakers' collaborate mainly with local academic partners vis-à-vis scientific publications (Table 3). Approximately three quarters of their R&D collaborations occur with academic researchers from local universities and technical colleges.

Automakers have collaborated to a much lesser extent as regards scientific publications on EV technologies. However, where automakers have co-published scientific papers, they have done so in collaboration with the same partners for non-EV technologies (Table 2). For instance, Ford's main partners in terms of EV technology publications are the University of Michigan (6.3% of 79 publications) and Wayne State University (3.8%). Similarly, Fiat has collaborated mainly with the Polytechnic University of Turin (20% of 10 publications). Volkswagen's main partner is the University of Leibniz (19% of 21 publications), with whom Volkswagen collaborated on 5.3% of its non-EV publications. Hence

Table 2
Automakers' main R&D partners for scientific publications (EV and non-EV technology).

Automaker	Main partners	% of publications	Location
Fiat Auto (509 publications)	Turin Polytechnic University	9%	Local
Ford (6749)	University of Michigan	7.5%	National
General Motors (2639)	University of Michigan	12%	National
Hino (44)	Toyota Technological Institute	14%	National
Iveco (19)	University of Turin	43%	Local
Renault (554)	French National Centre for Scientific Research (CNRS)	12.1%	National
Scania (198)	Royal Institute of Technology Stockholm	16.7%	Local
Volkswagen (170)	Brunswick Technical University	20.5%	National
Volvo Cars (288)	Chalmers University of Technology	25%	Local
Toyota (7470)	Toyota Technological Institute	33%	National

Table 3
Automakers' R&D collaborations for scientific publications (EV and non-EV technology).

Automaker	Geography of collaboration			Type of partner			
	Local	National	Global	Academia	Corporate	Research institute	Gov't/other
Fiat Auto	253	240	46	297	104	79	59
Ford	2453	113	717	2662	260	191	154
General Motors	1970	237	432	2003	274	213	149
Hino	31	0	1	12	12	10	9
Iveco	8	7	3	11	2	4	2
Renault	472	33	13	313	47	156	2
Scania	100	9	8	96	16	1	4
Volkswagen	266	67	25	184	94	71	4
Volvo Cars	187	4	7	152	38	8	0
Toyota	5553	683	1234	5498	806	831	429
Total	11,293	1393	2486	11,228	1653	1564	812
Percentage	74%	9%	16%	74%	11%	10%	5%

despite the fact that automakers have produced much less in the way of scientific research on EV technologies, they appear to collaborate with partners that are part of their traditional networks of universities and technical colleges located close to their main operational hubs. An example of such a network is shown in Fig. 4.

5. Conclusions

This paper examines R&D collaborations in the automotive sector with attention given to technologies for the electrification of road vehicles. A number of conclusions can be drawn from bibliometric and patent data. First, as regards publications, automakers tend to collaborate with academic institutions that are geographically close their main operational hubs. However, the importance of academy–industry collaborations for innovation warrants further investigation. The valorisation of academic research currently receives much attention in both policy circles and within the management of academia. It appears to be the case that academic institutions are key partners for automakers. It may be the case that academia acts as a supplier of skilled labour to the automotive industry, as a source of ideas and/or as a site for experimentation. Academia is perhaps even an indirect source of innovation for automakers even though this is difficult to evaluate using patent records. Further research should focus on the role of academy–industry vis-à-vis innovation in the automotive industry and a good starting point is to follow the methodology outlined in Lissoni et al. (2009). Further research should also examine the mechanisms that support knowledge transfer between academic institutions and industry. Despite the expansion of technology transfer offices and licensing practices that seek to create incentives for (1) university-based invention and (2) university–industry collaboration; there is evidence to suggest that academic researchers rely more on their personal social networks than formalised technology transfer practices for collaborations with industry (Siegel et al., 2003).

One implication for policymakers is that the provision of targeted and strategic funding for academic research may be of benefit for automakers in terms of competence enhancement and innovation. Here it may be beneficial to sponsor research on vehicle electrification within academic institutions that are based in the same localities as major automakers. Whilst the exact impacts of such research are unknown, some sort of positive spillover is likely given the strong ties between these two sets of actors. Furthermore, this type of policy intervention may be of importance for the European automotive industry given that Japan and the US appear to leaders in the field of electrification. The provision of funding of academic institutions that have a history of collaboration with automakers should perhaps be complemented by mechanisms that stimulate knowledge transfer between academic partners in the Japan and US. This type of policy intervention may also be key to ensuring the long-term sustainability of the automotive industry given pressures to find alternative, environment-friendly technologies and given the current economic climate where automakers find it hard to justify the costs of R&D on alternative technologies (Wells, 2010).

Second, patent records suggest that inventions are more likely to occur between companies embedded in hierarchical organisational structures than between other types of organisation. This is true of both EV and non-EV technologies. Records suggest that innovation networks are not the primary structures for R&D collaboration in the automotive industry, as most collaborations occur via parent or subsidiary companies, or with companies that are part of a strategic alliance or joint venture. This suggests that the risks and uncertainties associated with innovation networks pose significant obstacles for collaboration.

However, and in contrast to bibliometric data, patent records suggest that geography is not a significant barrier for collaboration. Companies have established strong ties with foreign partners where the above conditions are satisfied. This brings us to a third conclusion. Whilst it is widely acknowledged that trust is an important precondition for efficacy in collaborative networks, the findings shown here suggest that trust is realised through different organisational structures in different types of networks. In publication networks it appears to be the case that proximity is the key to strong ties, which may be due to individuals' own social networks and the propensity for individuals within these networks to meet more often and participate in the same collegial communities. In contrast, patenting appears to occur more frequently via organisational hierarchies, which suggests that the risks and uncertainties related to commercialising inventions cannot be offset by networks based on trust and informal ties.

The good news for laggards in the field of electrification is that geography appears not to be a significant obstacle. It is either the case that the knowledge that underpins inventive collaborations in the automotive industry is to a large extent codifiable and thus renders geography unimportant, or that automakers have found ways to overcome the need for proximity when collaborating on new inventions. Further research should focus on the routines associated with hierarchical forms of cross-border organisation in order to examine how knowledge is transferred between foreign partners.

Laggards in the electrification field can adopt two possible strategies. They may benefit from establishing hierarchical agreements with companies in countries such as the US, China and Japan that are at the forefront of vehicle electrification. Alternatively, they may simply purchase components and sub-systems such as batteries and hybridised powertrains from key suppliers as part of a modularisation strategy. However, such an approach has been noted for its risks, as by simply purchasing key technologies 'off the shelf', automakers can lose the architectural competences that are key to competitive advantage (Takeishi, 2002). A precautionary approach would be to ensure that automakers retain and build competences that are relevant to vehicle electrification, which we assume will play a significant role in years to come. This further emphasises the point made above that strategic and targeted academic funding is required to match the needs of automakers in terms of competences and skilled labour given the prevalence of local academy–industry ties.

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