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Entering an era of ferment – radical vs. incrementalist strategies in automotive power train development

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Abstract

Incremental improvement of a deeply embedded technology system has been a hallmark of the automotive industry for a very long time. Efforts to develop alternatives have repeatedly failed. This paper analyses paper analyzes how Toyota started to challenge this pattern in the late 1990s, by the architectural innovation embodied in Prius, the first mass-produced hybrid-electric car. This is followed by an account of how key competitors reacted by accelerating their incremental innovation efforts, in an era when concerns over fuel prices and greenhouse gas emissions increased demand for environmentally sound vehicles. The paper builds on records of patenting and performance of actually marketed models to analyze the unfolding technology competition. It also considers the most probable technologies on the market in a 10-12 year timeframe, and further explains how different technology strategies put competing firms in different positions in an era of ferment.

Key words: Technological discontinuity, hybrid-electric vehicle, technology strategy, car manufacturing, architectural innovation

Introduction

Few sectors display such stability as the automotive industry in their selection and long-term incremental improvement of core technologies. Repeatedly researchers have expected this stable pattern to break down and open up for new radical departures, for example in the aftermath of the two oil shocks in the early 1980s (Altshuler 1984), following rising environmental concerns (Nieuwenhuis and Wells 1997), or the Californian zero emissions vehicle (ZEV) mandate (Dyerson & Pilkington 2005). The incremental trajectory of the industry nevertheless prevailed, adding equipment for emissions treatment and efficiency enhancement, but maintaining conventional power-train architectures. In the core activities of the automotive makers, the internal combustion engine has remained largely unchallenged ever since mass production of cars started, almost 100 years ago.

By the late 2000s, however, there are signs that this pattern of stability is changing. There were several reasons for this, including a renewed pressure from upward fuel prices (albeit with a backlash in late 2008), new stringent legislation (in particular the EU mandate to reduce CO₂-emissions for new cars), changed market demands and the maturing of a range of new technologies, as demonstrated in commercially available vehicles. This initiated a technology-based competition within the worldwide automotive industry, based on innovation in the very core of the vehicle, the automotive power train. As noted by Anderson and Tushman (1990) the introduction of new technologies in a mature industry may initiate an “era of ferment”, characterised by increased technological variation and experimentation. Hence strategic decision makers face a genuine uncertainty regarding the prospects and potential of various technologies and the outcome is by no means given.

This paper analyzes incumbent car manufacturers’ strategies in this competition, with a particular focus on hybrid-electric vehicles. Hybridisation is one of several proposed alternatives to improve fuel efficiency and reduce CO₂-emissions. However, by contrast to other options such as

battery-electric and fuel cell vehicles, hybrids have already reached significant production volumes. Therefore, the introduction of hybrid-electric cars constitutes a particularly interesting case of new technology introduction in a mature industry. We compare technology strategies of the hybrid market leader Toyota with strategies relying on accelerated advancements of internal combustion engines and we will also briefly analyze the re-emerging “battery-electric option” in relation to these strategies (Beaume and Midler 2008). The paper does not include bio-fuels such as ethanol or bio-diesel in the analysis, since these alternatives have not initiated any significant innovation in automotive power trains. In countries promoting bio-fuels as full-scale alternatives, this support has even tended to slow the diffusion of fuel-saving technologies (Kågeson 2009).

The paper structure is as follows. Firstly, we present the hybrid-electric vehicle as an architectural innovation in a mature industry, comparing it to other types of innovation. This is followed by a brief section on our research methods and sources of data. The next sections compare different manufacturers’ R&D efforts in hybrid technology as measured by patenting; the market performance of hybrid-electric vehicles and the responses from Toyota’s major competitors. Thereafter we present an in-depth analysis of the development and marketing of the defining hybrid car, the Prius model. Next, the Toyota strategy is put to test in a comparison of Prius III with a refined conventional model from Volkswagen, the no. 2 producer in the world car industry after the demise of the American manufacturers. The following section discusses the technological competition in a more long-term perspective, including battery-electric vehicles, plug-in hybrids and diesel hybrids, and relating these options to the strategies of the leading European and Japanese manufacturers. The concluding section returns to the issue of innovation models in the auto industry and the importance of understanding the complexity of its innovation challenges.

The hybrid-electric vehicle: Architectural innovation in a mature industry

Historical studies of innovation patterns and industrial dynamics in the automotive industry illustrate the industry's predilection for continuous improvement based on process innovation, incremental product innovation and adoption of new component technologies to add new functionality (Abernathy 1978, Abernathy and Clark 1985). There have been numerous attempts to promote alternative technologies for automotive propulsion, e.g. by the Californian government through their emission regulations and ZEV mandates during the 1990s (Dyerson and Pilkington 2005). These efforts failed to materialize in new competitive vehicles, however, mainly because of technological shortcomings and high costs – a particularly daunting obstacle for fuel cell cars. Vehicles with alternative propulsion technologies either failed to proceed beyond an experimental concept stage, or were withdrawn only after a short period on the market.

In the public debate the fuel cell programmes of the 1990s received a lot of attention (Hekkert & van den Hoed 2006), but the real action in engine development, particularly in Europe, was related to improvements in diesel technology. Solving the problems of diesel emissions, especially NO_x and particulate matters, were long perceived to be almost impossible. In the 1990s, however, 100 years after its birth, European diesel engines embarked on an impressive improvement trajectory, stimulated by high fuel taxation, advances in component technology, and stepwise tightening of emissions legislation. By incorporating turbo chargers, modern control electronics, new injection systems (common rail injection), and after-treatment systems, diesel engines could improve both performance and convenience and at the same time reduce emissions markedly. As a result, sales increased rapidly. In 2007, diesel engines powered more than 50% of new cars in Western Europe (Berggren, Magnusson and Sushandoyo 2009). European producers such as Peugeot CSA, Volkswagen/Audi and Renault completely dominated this market. Important improvements in gasoline engines and transmissions technology also followed, e.g. direct ignition systems, turbo chargers and compressors, dual clutch transmissions and new types of multi-speed gearboxes. As a result, it is no longer possible to treat automotive power trains as standardized

units. Rather the engine and transmission can be configured in multiple ways, implying different performance, efficiency and cost levels. In North America, sales of diesel engines remained very low, hovering at around 3 % of the car and light truck market, a result both of the historic lack of interest in fuel-efficiency in the US with its tradition of low fuel prices, the relatively high cost of diesel fuel in comparison to gasoline, and previous diesel mistakes by American producers after the oil shocks in the 1970s.

Gasoline engines also remained predominant in Japan. Spurred by the Californian ZEV mandate, as well as their own experience of battery-electric vehicles, Honda and Toyota used the gasoline engine as one of the building blocks when they embarked on a new route of innovation and developed the first series-produced hybrid-electric vehicles during the late 1990s. From a societal or consumer perspective, the introduction of hybrid-electric cars may be considered an incremental step, since they require neither a new fuel infrastructure, nor any significant changes in user behaviour (Hekkert and van den Hoed 2006). However, to be able to develop and produce hybrid-electric vehicles, car manufacturers need to acquire major new knowledge from a number of different technological fields. Moreover, they need to integrate these technologies with their present knowledge base, in an evolutionary reconfiguration process (Geels 2002). This implies difficult challenges for actors in this highly capital-intensive industry. Thus from the perspective of the automotive manufacturers, it is reasonable to consider the introduction of the hybrid-electric vehicle as a technological discontinuity (Anderson and Tushman 1990). However, it is a particular type of discontinuity. It is not the standard case where a new technology, involving a new S-curve, replaces an established technology (Utterback 1996, Foster 1986). Rather it is a case where new technologies and corresponding knowledge bases need to be integrated with still evolving established technologies to result in a superior new system.

Technological innovation in assembled product systems can be categorized as either modular innovation, implying changes in individual components, or as architectural innovation, changing the product configuration and combining components in new ways (Henderson and Clark 1990). In the

automotive industry, the evolution of the diesel engine can be seen as a typical case of modular innovation, involving significant redesign and additions of components (injection systems, turbochargers, exhaust treatments systems), but not changing the basic product architecture. In contrast, the evolution of hybrid-electric vehicles requires technological innovation in both components (e.g. batteries, power electronics and electronic control systems) and in the overall architecture of the power train, to combine the virtues of combustion engines and electric drives. Modular innovation assumes some degree of modularization and standardisation of technical interfaces.

The modern PC is a good example of a modularized product, where components, such as disk drives and CD-drives, are easily interchangeable. Products such as aero engines or gas turbines are contrasting examples, characterised by interdependencies and integral (non-modular) designs. According to Christensen, Verlinden and Westerman (2002), integral designs are favoured in markets where superior functionality and performance are prime means of completion. However, if the level of performance exceeds what customers actually can use, the basis of competition tends to shift towards speed-to-market, convenience and customization. In turn, this will favour standardization of technical interfaces and outsourcing of component design and manufacture. Christensen *et al.* present the automotive industry as an illustration, predicting that competitive forces will favour increasingly modularized designs. This in turn may reduce the added value of systems integration, which is a core activity for automotive manufacturers, and instead favour a limited number of suppliers, who may attain a competitive edge based on functionality and performance at the component level. In contrast to this argument, Takeishi and Fujimoto (2003) maintain that the product architecture of the car is still integral, arguing that the trend of modularization in the automotive industry is only in the “trial and error stage” (p. 273). Hence, systems integration still constitutes a critical activity in automotive development and design. Even though automotive manufacturers do not have to manufacture the complete vehicle in-house, they still need a broad technological knowledge base to be able to absorb new technologies (Cohen and

Levinthal, 1990), as well as to understand interdependencies in the product system and cope with imbalances due to different rates of development in different technologies (Brusoni and Prencipe 2001).

While knowledge management and sourcing clearly are relevant for the introduction of new automotive power train technologies, appropriate product strategies are just as critical. Based on retrospective analyses of four “alternative automobile projects”, including both battery-electric cars and other alternative vehicles concepts, Hård and Knie (2001) argue that new technologies stand a better chance of gaining public acceptance if they are compatible with the daily routines of the users. From a user perspective, today’s hybrid-electric cars are quite similar to traditional cars and do not require significant changes in driving or refuelling behaviours. Hence, in this respect, they stand a better chance of widespread acceptance compared to e.g. battery-electric cars. But car manufacturers still face significant challenges related to the complexity and high cost of hybrid technology (Chanaron and Teske 2007). This is especially true for small cars, which are affected disproportionately by the added costs of hybrid systems, and for diesel hybrids since diesel engines are more expensive than gasoline engines.

For car manufacturers, the challenge is three-fold. Firstly, the cost of the extra components needs to be justified by significant savings on fuel costs. This is only possible when fuel prices are high, which makes sales sensitive to oil price fluctuations. The US market is an illustrative example, with surging hybrid sales from 2005 to mid 2008, when fuel prices were soaring, followed by a steep decline in the second half of the year, when the gasoline price tumbled from \$4 to \$2 a gallon (Gordon & Sperling 2009:18-19, 65). Further, hybrid makers must find the right trade-off in the total power train configuration. If they select simple solutions in the combustion engine system to offset the expenses of the extra electric equipment, costs will be contained but performance will suffer, and the result in terms of fuel efficiency improvement may be marginal in comparison with advanced internal combustion engine power trains. Finally, manufacturers aspiring to offer hybrid-

electric cars in their major markets need to engage in long term efforts to drive down costs of hybrid components, which may necessitate considerable investments in manufacturing capabilities.

Research Methods

Strategies represent corporate top-management intentions and de facto actions related to what resources to engage and how these resources should be utilized in the market (Collins, Hull, and Hage 1996). While we do not position us in the academic debates as to whether corporate strategies are the results of long range planning activities or if they are continuously evolving as results of responses to emergent contingencies (Mintzberg and McGugh 1985), our prime interest lies in what incumbent car manufacturers actually do. Thus we interpret strategy as a multifaceted concept (Mintzberg, Ahlstrand and Lampel 1998), reflecting choices that have been made and actions that have been taken or proposed. Our perspective is firm-centric and omits the role played by e.g. universities and national laboratories in technological knowledge development. We believe such a perspective is justified, since our analysis particularly focuses on competition in developing, manufacturing and launching innovative products, rather than on pre-competitive technological research activities. In particular, the analysis focuses on critical decisions and actions related to technology and products. The empirical study combines data from interviews, public patent databases, and trade and business journals.

Interviews were used both to get an inside view of how vehicle manufacturers perceive the strategic challenges related to hybrid-electric vehicle development and introduction and how Toyota developed its path-breaking hybrid technology. We interviewed in total 11 technology managers at Toyota Europe, Volvo Cars, Volvo power train (trucks and construction equipment), GM Powertrain and Volkswagen, in addition to previous interviews with project and plant managers at Toyota, Japan. The selected managers all had decision-making positions in their respective companies. They had extensive experience from automotive power train development in general,

and from hybrid-electric vehicle development in particular. The major themes covered in these interviews were how the managers perceived the current and future competition related to climate change challenges, the potential of different technological solutions (in particular hybrid-electric vehicles), the required new skills; and sourcing and partnership strategies. The interview with the Toyota managers focused on their experience from developing and marketing their hybrid car Prius. The interviewed Vice President of R&D at Toyota Europe had previously taken part in the original Prius development project and had also experience from Toyota's efforts in introducing this car. We also make use of an earlier case study of the first and second Prius development projects, which included interviews in Japan with Toyota's chief engineer and two managers at one of the key suppliers (Magnusson and Berggren 2001). To help us better understand trade-offs in the development and production of hybrid-electric cars and to pose "sharper" questions to the car manufacturers, we interviewed a leading Swedish expert in electrical engineering, who has been engaged by several automotive firms as a technical consultant in the development of hybrid-electric vehicles. The appendix presents a list of the conducted interviews.

Patents were used as a measure of R&D efforts in the area of hybrid-electric vehicle technology. With the exception of software development, patents can in most cases be considered a useful indicator of R&D activities (Holmén and Jacobsson 2000). To facilitate a comparison between the two largest markets for automobiles, USA and Europe, we used two different patent databases: the US Patent and Trademark Office USPTO and the European Patent Office EPO. We limited the search to patents granted between 1990 and 2007. Firstly we searched all patents related to hybrid technology. In the USPTO case, we focused on patents that comprised the words "hybrid" (abstract) and "vehicle" (all fields). In the EPO case, we used "hybrid vehicle" as the search term. By so doing, the search engine showed all patent documentations that include those two words. In the second step, we scrutinized the abstracts and eliminated irrelevant patents and checked the text describing the background of the invention (particularly the paragraphs "Field of the Invention" in USPTO patents and "Technical Field" in EPO patents) to ensure relevancy.

Patent data must be used with caution given the differences in propensity to patent across companies. This is particularly true for established technological fields, such as diesel, where the European technology leaders have been reluctant to patent compared to the Japanese and American firms. Further, patents cannot be used as indicators for capabilities in product development and industrialization (Pilkington, Dyerson and Tissier 2002). The development of complex products like automobiles relies on an ability to integrate diverse knowledge and components into effectively functioning technological systems, i.e. on integration capability. To capture this aspect of the innovation process we use data on product releases and sales, gathered from corporate web sites and automotive trade journals, especially the Detroit-based weekly Automotive News, which provides very detailed weekly production and sales data. In the section discussing the most recent development, such as the re-emergence of the electric vehicle option, the account is mainly based on reports in the trade press. The benefit of these sources is that they provide information also on very recent trends which was particularly important in our study. However, this type of media tends to be susceptible to corporate PR-efforts, not clearly distinguishing between visions and actual commitments. We have tried to increase the validity by selecting reports on specific marketing and launch plans, for example when and where Toyota or Mercedes plan to introduce electric vehicles. These plans may be changed of course, especially in the current deep crisis in the industry, but still we believe the information is relevant and Toyota, in particular, is known for being very careful when they promise to launch a new vehicle.

Inventive activities in hybrid power train development – the patent picture

Toyota pioneered hybrid technology patenting in the US in the early 1990s, but except for these initial years, Toyota has not taken a leading position. Nevertheless, their consistency is remarkable. Ford was also an early patentee, but with a much more instable performance. In the early 2000, Honda outperformed Toyota in an effort to catch up with the market leader, but its

performance has been falling. GM started late but was very active in the last period of 2006–2007, a testimony of its late awakening and accelerated efforts to develop competitive technologies for the next round of hybrid evolution. Figure 1 shows US patenting activities of incumbent automotive manufacturers in the field of hybrid-electric vehicles 1990–2007 and figure 2 illustrates the patenting activities in Europe.

INSERT FIGURE 1 and 2.

The graphs show that Toyota started patenting hybrid vehicle technology earlier than any other vehicle manufacturer, except for Ford in the US. In addition, they also tell us that the vehicle manufactures patented in both USA and Europe, regardless of their countries of origin. In the case of Renault-Nissan, both Nissan (Japan) and Renault (France) contributed to its European patents, but Nissan's 60 patents dwarfed the efforts at Renault (only 11 patents). Remarkably, other European manufacturers are virtually non-existent, with the exception of one of the major European component suppliers, German Bosch GmbH. Also in the field of diesel technology there has been a significant patenting activity since the early 1990s. But in spite of their leading market positions, the European makers rank third also here, after the Japanese and American makers, which seem to suggest a different propensity to patent among European firms.

From inventions to products – market performance of hybrids

The first hybrid-electric car to enter the market was the compact size Toyota Prius, a full hybrid that uses a complex hybrid configuration with a planetary gear as a mechanical “power split device”, connecting the internal combustion engine with an electric motor and a separate generator. During the first two years after market introduction, Prius was exclusively sold on the Japanese market and when Prius was introduced in the US in 2000, it was an upgraded version of the original

car. US sales were initially slow, but following the market launch of the re-designed and upgraded Prius II in 2003, sales increased as fuel prices and environmental concerns started to take off. Honda began to develop a simpler mild/parallel hybrid shortly after Prius but introduced its first hybrid on the American market one year before Toyota introduced Prius. With an aluminium body, a futuristic aerodynamic design and extensive use of lightweight materials, Hondas 2-seated hatchback Insight offered superior fuel economy. It was followed by hybrid versions of the Civic and Accord models. Sales were poor, however, and Honda later discontinued production of both Insight and the Accord Hybrid, restricting their offerings to hybrid versions of Civic.

By contrast, the new Prius quickly turned into a symbol of the modern environmental car in the US (UBS 2007). In 2004 Toyota sold 88,000 hybrid cars in the US market and quadrupled sales to 350,000 three years later. The majority of these were Prius. In June 2007, Toyota announced they had sold 1 million hybrids globally since the initial market introduction and that 757,600 of those were Prius (Press release June 7 2007). The same year Toyota Prius sales briefly surpassed Ford Explorer, America's top-selling SUV for more than a decade (Simon 2008). Figure 3 outlines hybrid car sales on the U.S. market 2000-2007.

INSERT FIGURE 3

The American competitors first reacted to the introduction of hybrids with disinterest, and their early R&D activities in the field were not followed by actual product launches. However, when gasoline prices started to soar in 2004–2005, SUV sales declined and hybrid sales gained market shares. The Americans ramped up their technological activities, and started to introduce their own hybrid cars. On the auto show in Detroit in January 2008, hybrid technology occupied a pride of place, with all manufacturers offering hybrid models, either as ready to launch or in more conceptual stage. However, in late 2008, following the collapse of their most profitable segments

and a general downturn in the domestic market, the American firms found themselves in a disastrous financial situation, fighting for government subsidies to survive. In return politicians demanded more environmentally friendly cars, but now when the US makers finally had started investing in hybrids and other fuel-saving technologies, gas prices were falling precipitously, which drastically reduced consumer interest in alternatives to conventional vehicles.

In contrast to the developments on the American market, European hybrid sales were languishing. With less than 50,000 cars sold in 2006, hybrid-electric vehicles did not even reach 0,2% of the market. Toyota and Honda dominate hybrid sales in Europe, but selling only 36470 (Toyota) and 3410 (Honda) in 2006, neither of their hybrid cars have been successful in Europe so far. The contrast to the success of hybrids in the US is striking. There may be several reasons to the differing sales performances of hybrids. However, comparing US and European market characteristics, we can distinguish three contrasting factors, which are likely to have affected sales. The first relates to the volatility of fuel costs. Although European prices still are higher than American, fuel prices in Europe have increased on a continuous basis and remained high for decades. By contrast, US fuel prices increased drastically during a short period in time, 2004–2008 (first half), urging car buyers to search for alternatives. Secondly, the diesel car is a strong contender on the European market, presenting a readily available and considerably lower-priced alternative for consumers interested in fuel cost savings. Thirdly, while a distinct and growing niche of environmentally concerned buyers embraced the hybrid car Toyota Prius on the US market (Sperling and Gordon 2009); such a market niche did not arise in Europe, or at least it did not adopt the hybrid car as its defining artefact.

Notwithstanding the poor hybrid sales in Europe, European manufacturers have stepped up their efforts in this technology field. Daimler-Benz plans to launch a gasoline hybrid of its S-class using lithium-ion batteries in 2009, followed by a diesel version in 2010 (Kable 2008); VW is investing in the development of a plug-in hybrid version of Golf, FIAT is planning to test hybrid diesels for its small commercial vehicles, etc. Leading European suppliers, such as Bosch,

Continental and Siemens VDO are also entering in order to develop the integrated solutions needed to build hybrids. One reported example of such a solution by a component maker is the gearbox integrated with an electric motor developed by ZF Friedrichshafen in 2007 (Chanarron and Teske 2007).

The chief trust of the European makers, however, is not architectural innovation as symbolized by the hybrid power-train, but a strategy which may be labelled “accelerated incrementalism”, characterized by increased efforts to improve the performance of the established internal combustion engine. This is complemented with various forms of “micro hybridisation”, such as start-stop functionality and the technologies BMW offers under the “Efficient Dynamics”-umbrella, which include some brake energy regeneration and electrical instead of belt-driven support systems (Chanaron and Teske 2007). During 2008 the German makers, Volkswagen, Audi and Mercedes-Benz also made strong efforts to launch “clean diesels” in the US. These efforts were supported by reports forecasting long-term growth for diesel cars on the American market (UBS 2007), but with falling fuel prices and a general market downturn, these forecasts too have become highly uncertain.

In spite of this turbulence, the Japanese hybrid pioneers seem determined to increase their investments in the area of hybrid-electric vehicles. Toyota has launched several new hybrid models, and announced plans for annual sales of 1 million vehicles by 2010 (press release May 15 2008). Honda only sold 55,000 hybrids globally in 2007, 1.5 percent of their total sales, but they have publically announced a target to increase this percentage to 10% by 2010 (press release Dec 19 2007).

The development and market launch of Toyota Prius

At this point, we will take a step back to follow Toyota’s strategy for the original development and launch of the Prius model. The development started in the early 1990s as a concept study with a

vision to create a “car for the 21st century”. Based on projections of future oil shortages and rising fuel prices, Toyota’s top management identified fuel efficiency as a prime criterion. However, the initial plan was *not* to develop a hybrid-electric car. Nevertheless, as the top management ordered a significant leap in terms of fuel efficiency, the development team led by chief engineer Takeshi Uchiyamada concluded that they could not accomplish this with a traditional power train. Toyota had previous experiences from battery-electric vehicles, developing and producing their RAV4 model in an electric version (Pilkington and Dyerson 2004). In this case, however, it was considered important that the car should use the existing fuel infrastructure; Prius was to be perceived by customers as a conventional car. The team thus settled for a hybrid-electric power train, a solution which at that stage in time recently had been presented as an “elemental technology” by Toyota’s division for advanced engineering (Magnusson and Berggren 2001). In 1995, Toyota’s top management decided that the project should proceed from a conceptual stage to a fully-fledged product development project, aiming for market introduction. The decision to develop and introduce a hybrid-electric car meant that Toyota departed from a tradition of caution, only using reliable and thoroughly tested technologies in product development projects (Liker 2004). Still, the project received top priority from Toyota’s senior management as it was allowed to use a very substantial portion of Toyota’s prototyping and testing resources. Moreover, executive vice president Akihiro Wada directly supervised the progress.

For the crucial battery system development Toyota selected the same supplier as for electric vehicle batteries, Panasonic; but as the battery is a very integrated part of the hybrid power train, the collaboration had to be more intimate. Toyota therefore formed a joint venture with Panasonic and located a significant number of vehicle engineers at Panasonic during the development project. At a later stage, Toyota acquired a controlling interest in this joint venture. As described by Ro, Liker and Fixson (2007), Toyota stands out among car manufacturers, insisting on having detailed knowledge in every core technology. The virtue of having key competencies in-house was also emphasised in our interview with Toyota Europe’s Executive Vice President of R&D:

We don't believe in black box design, where suppliers have all design responsibility and design insight. We want to know all the details of new important technologies. With black box design, the OEM cannot do anything if there is a problem. To develop hybrid systems is about integration. Then you need to have detailed knowledge of key components. After we have acquired this detailed knowledge it is possible to subcontract production. (interview 7 November 2006)

While Toyota's initial decision to develop and launch a hybrid car may appear unusually bold, this was compensated by a carefully planned market launch. Initial production volumes were kept low and sales restricted to the domestic market. This meant that Toyota's prime competitor in the hybrid race, Honda, could launch its Insight as the very first hybrid in the US. But this was a price that Toyota executives were prepared to pay to ensure that the company's quality reputation would not be jeopardized. Toyota Europe's Executive Vice President of R&D elaborates on their cautious introduction strategy:

When we launched Prius I in 1997 several people started asking us when we would launch the car in the US. But Prius was a newborn baby. A newborn baby, you want to keep her in sight during the first years. So the first 2 years we kept Prius in Japan, supported by a 24h/day and 365 days/year rescue organization with engineers from the development project. Every time there was a problem, engineers were sent from this organization to investigate the problem. (interview 7 November 2006)

The first generation Prius was a test period where hybrid technology was considered one among several options to improve fuel efficiency, including improved internal combustion engines, alternative fuels, battery-electric vehicles and fuel cell vehicles. Hence, Toyota initially adopted a "probe and learn strategy" (Lynn *et al* 1996) carefully investigating the characteristics and potential of the new technology. Initial sales in the US were low, but Toyota's confidence in the new

technology nevertheless grew. When Prius II with a more distinct design than its predecessor was launched, there had been an important shift of perspectives within Toyota. Rather than being seen as one of several technological options, hybrid technology was now perceived as a knowledge platform, a generic technology to be utilized in various power train configurations. For example, electric motors, batteries and electric regenerative brakes developed for hybrid-electric cars can also be used in fuel cell or battery-electric vehicles.

A key element in the Toyota strategy is to build deep knowledge both in new technological fields and in critical component manufacturing, for example of electrical motors, where Toyota has become a significant mass producer. These decisions are related both to technical problem solving to ensure performance and functionality and to cost considerations. Many components in the hybrid power train have originally been developed for low-volume applications, and have previously not been exposed to the process innovation required to reach competitive prices in the automotive industry. To optimize performance *and* cost Toyota therefore deemed it necessary to have first-hand knowledge also of production processes. The basic reason – and big difference to the development of personal computers for example – is that a fuel efficient cost-competitive hybrid car must optimize on all its components and cannot carry any excess capacity in power, energy storage, control systems, etc. Optimization on a systems level assumes that the systems integrator takes an active role during the development process and, as noted by Brusoni and Prencipe (2001), this means that the integrators need to possess technological knowledge beyond what they manufacture in-house. Extending this argument, Toyota's strategy in hybrid-electric vehicle development indicates that when the required knowledge base changes, it is not sufficient to develop new technical insights at the R&D level. To gain access to the required knowledge in manufacturing and cost structure, it may also be necessary to in-source component manufacturing.

The only major car manufacturer to challenge Toyota has been Honda. Honda selected a simpler hybrid power train configuration, reducing the task of integration and lowering the cost, and invested considerably less in developing in-house production capabilities. There are also significant

differences in product market strategy between the two hybrid pioneers. Whereas the original Prius was similar to a traditional compact sized car, the original Honda Insight had a very special design and a more narrow range of utility. None of these models reached any larger sales volumes. Honda proceeded by introducing hybrid versions of standard models Civic and Accord, with limited success. By contrast, Toyota introduced a second generation of Prius, and sales started to soar. While there may be several explanations to this course of events, Toyota's consistent adherence to their hybrid brand Prius is striking. With Prius II, Toyota pinpointed a niche of environmentally concerned motorists on the US market, where customers were prepared to pay extra to own a car with a particular (green) profile. With these observations in mind we may return to Hård and Knie's (2001) statement that products based on new technologies need to be compatible with the daily routines of its users. As indicated by the experiences of introducing hybrid-electric cars, this may not be sufficient. To attract attention and justify a premium price it appears as if products based on new technology also need to stand out; not different in terms of user behaviour but clearly distinguishable in package and style.

According to critics among competitors, Prius was a loss-making product several years after launch. But by exposing it to a real market test, selling the vehicle to regular private customers, the company was able to build invaluable knowledge of the car's performance, problems and potential, which it could never have developed inside R&D. After a period of rapidly increased sales on the US market, the strategy is now to expand hybrid production and sales through a broader variation of the product portfolio. To what extent Toyota will be more successful than Honda in selling hybrid versions of their standard car models will probably be closely related to the offered price; Camry consumers will hardly be prepared to pay the premium price accepted by Prius buyers.

Does HEV technology pay off? A comparison of actual performance

In 2009, based on 12 years of market experience of gasoline-fuelled hybrid-electric vehicles, Toyota launched Prius III. This redesigned model contained a list of new features, as well as a more powerful engine and a stronger motor. The mileage according to the EPA cycle increased from 48/45 city/highway to 50/49 mpg city/highway (equivalent to 4.3–4.4 l/100 km), an improvement of approximately 6 % compared to Prius II (Jackson 2009b). At the same time, Toyota presented a redesigned RX, their best selling Lexus model, with the hybrid version RXh offering an improved fuel economy of about 7 % (Jackson 2009a). In early 2009, Honda launched its much-awaited new Insight model, designed to compete on costs with Toyota, with a US list price \$2,000 cheaper than Prius (Soble 2009). Honda targeted sales of at least 200,000 cars/year of this new model, but the lower price came with considerably lower fuel efficiency than Prius.

For innovation researchers, advanced technologies command an interest as such and they may appeal to specific niches of affluent buyers. But for success in mainstream markets, cost and actual performance are decisive. Therefore it is instructive to compare Prius III with the performance of the main models of its European competitor VW. In 2008, Volkswagen launched the sixth generation of its best-selling Golf-models, which in terms of vehicle size are similar to Prius III. The new Golf generation is offered with a broad program of diesel and gasoline engines and advanced auxiliary systems such as dual-clutch transmission and multi-speed gearboxes. According to company figures, this will reduce fuel consumption and CO₂-emissions with 11%–16% compared to the previous Golf generation. In 2009 VW will launch a “Blue Motion” of the new Golf, incorporating start-stop and other fuel-saving measures, which will reduce fuel consumption to 3.8 l/100 km, clearly below Prius III. Since diesel fuel is more carbon-rich than gasoline, a diesel car emits roughly 10% more CO₂ than a gasoline car with the same fuel consumption. Thus, the emissions of Prius III and a Blue Motion Golf will be roughly similar, in spite of the higher fuel efficiency of the Golf.

A key question then is why Prius III, six years after the launch of Prius II, only improved its mileage by 6%, to be outperformed in terms of fuel-efficiency by a key competitor? One reason may be that Toyota targets Prius to the US market where diesel competitors have no real presence. Another reason may be the tradeoffs in the total power-train configuration. Since hybrid power-trains are inherently more expensive due to the added electrical motor and energy storage systems, Toyota has opted for a simpler gasoline engine, avoiding the costs of direct ignition, turbo chargers and compressors, which are part of the VW concept. This however dilutes the advantage of the hybrid system as a whole.

Since the “architectural breakthrough development” of Prius I in the mid 1990s, Toyota has returned to its established mode of incremental innovation, gradually refining each new Prius model. Being challenged by Toyota, however, the competitors have increased the pace of incremental and modular refinements of internal combustion engine power-trains. The improvements in fuel efficiency scored by the new VW engine program demonstrate the continuing potential of this trajectory. Increased power density is aggressively used by VW to downsize its engines, which is translated into further fuel savings. At the same time, micro-hybridisation in the form of start/stop to eliminate idling is rapidly becoming cost-competitive on the European market. Whereas only 54,000 cars were equipped with this system in 2007 (of these 53,350 were sold in Europe), component specialists Valeo and Bosch expect this number to increase to 2.8 million in 2010, whereof 2,5 million in Europe! By contrast, this fuel-saving equipment is not expected to debut in the US before 2011 (Weernink 2008). A key driver of this European uptake is the legislation on CO₂-emissions. French Peugeot has announced it will make the system a standard option in 2010–2012 and VW is moving in the same direction. Stop-start systems improve the efficiency of conventional power trains by 8–15 % in city driving, where hybrids are most competitive. Further, they build on the established trajectory of modular innovation in the European car industry, and take advantage of the independent component suppliers to achieve economies of scale rapidly.

From the short to the longer term: What alternatives?

From this brief overview it seems reasonable to argue that both the Japanese approach – further improvements and expansion of gasoline-electric hybrid platforms – and that of their European competitors – continued refinement of combustion engine power trains complemented with hybrid offerings in niche markets for premium cars – will suffice to meet the challenges of fuel prices and emission standards in 6–8 years (two car development cycles). But in a somewhat longer perspective, when European CO₂-emission standards are tightened to a level in the range of 80–100 g/km, and fuel prices have increased further, new twists of the current innovation trajectories will be required.

For the established hybrid makers, a further electrification in the form of plug-in hybrids is a possible step. In an effort to make a leapfrog in technology development GM presented such an ambition at the Detroit motor show in January 2008, only to be followed by Toyota announcing a plan to be faster to the market than GM. Plug-in hybrids offer a considerable extension of electric drive compared to a conventional hybrid. Nevertheless, this comes with a significant cost penalty, since the car has to be equipped with a full-size electric motor in addition to the combustion engine, and a much larger and more expensive battery system. Sticking to its carefully controlled market strategy when announcing its response to the GM plug-in hybrid, Toyota emphasized that the initial sales of the new vehicles would be “in the hundreds”, and did not disclose when or if they planned to mass-produce plug-ins for retail customers (Reed 2008). Plug-in hybrids are favoured in the US by various incentives and mandates, for example in the latest revision of the Californian ZEV rule, which requires automakers to produce 58,000 plug-in vehicles between 2012 and 2014 (Gordon & Sperling 2009:189). This will certainly help introduction and the creation of niche markets. But to succeed in main markets, car manufacturers will have to reduce expected costs significantly, which

will require several development cycles of 3–4 years each after the first launch. In the meantime, other alternatives may be more attractive.

One of these could be the new generations of battery-electrics. Electric vehicles have suffered several false starts. However, a flurry of announcements from major vehicle makers in 2008–09, suggests there is now a chance of a real (albeit cautious) take-off: Mitsubishi started fleet-testing of its small iMiEV already in 2007 in Japan. Nissan has announced battery-electric cars for limited leasing in Japan and the US in 2010. Somewhat reluctantly, Toyota has announced plans to offer a very small electric vehicle on a small-scale basis on the US market in 2012 (Greimel 2008, Kranz 2009a). BMW is launching a 2-year lease program in the US for electric Minis (Kurylko 2008), while Mercedes plans to start producing electric Smart ForTwo cars in late 2009 to be launched in selected cities in both Europe and the US (Kranz 2009b). All taken together, there seems to be real possibility for the long expected battery-electric vehicle market to develop in the 2010–2020 period. The major difference to previous false starts is the advances in technology, in particular the progress of lithium-ion batteries, because of its mass use in mobile phones, laptops and hand-tools. Another difference is a change in customer demand, where several actors now perceive a real potential in a specific sub-segment, affluent customers with an interest of a second or third car for “green” urban commuting.

New business models also support the development plans (Beaume & Midler 2008). In contrast to previous periods when battery-electric vehicles were reluctant exercises forced by regulation, major makers now present these as commercial projects, which take advantage of government incentives in the introduction phase, but are calculated to be competitive after further development and cost-reduction. This process may take a long time, however. Honda has rejected to take part, predicting that electric cars will account for less than 1 percent of the market in developed markets even by 2015. They may be overly pessimistic, but indeed the high cost of battery packs, the limited range, and the inconvenience of long charging times will restrict the market appeal of battery-electric vehicles for a considerable time. Along these lines, analysts such as Bonnaure

(2009) stresses that the market for all-electric vehicles should be confined to small urban models, and only then if the performance and lifespan of the new batteries turn out to match the claims made for them and if the authorities support the initiative.

With manufacturing of motors and batteries within the group, Toyota will enjoy an early scale advantage compared to other manufacturers without these in-house capabilities. This underlines the strategic dilemma facing Toyota's main competitors, concerning how much of the new technologies they need to develop and manufacture in-house. Referring to an on-going, internal Volkswagen discussion on whether to invest in building battery technology capabilities or not, the Director of Group Research at Volkswagen explained the challenge of accessing knowledge of detailed cost figures, when a company is dependent on sourcing from external suppliers:

We have worked two years with suppliers and we see that beyond a certain level these suppliers won't give us detailed information on things like the value chain for the raw materials for battery, what are the cost prognoses, what chances do you have to reduce production cost, etc. These are key questions that companies won't tell us, because this is proprietary knowledge, competitive knowledge. But we need to know this to make the right decision internally. So it seems to be the only way to get answers to these questions is to build up your own competence. (Interview 4 July 2008)

Still, battery-electric cars are much simpler as technological systems than hybrids, without the need for the sophisticated optimisation systems required in full hybrids. A battery-electric car is much more of a modular system. This means that vehicle makers will benefit from investments in advanced battery manufacturing at component specialists. After a few more development cycles, electric cars might become competitive with hybrid-electric cars, and take away some of their customers, but only in a dedicated market segment: city cars for limited urban driving. For the main markets, battery-electric vehicles will not possess the desired functionality. The same goes for fuel cells cars, where the cost hurdle is an order of magnitude larger, not to mention the need for major public investments.

Life cycle assessments of 10 different power trains, from an “evolving baseline” vehicle (gasoline fuelled combustion engine) to fully a fledged hydrogen fuel cell vehicle, suggest that hybrid power-trains with diesel engines and electric technologies is the most promising alternative in a 25-year timeframe, taking both costs and environmental performance into account (Schäfer, Heywood, and Weiss 2006). A somewhat different comparison, which did not include energy used in the vehicle production cycle, arrived at a similar conclusion but with a long-term potential for fuel cell vehicles based on hydrogen from natural gas (Hekkert *et al* 2005). Taken together, these studies underline the importance of hybrid technology also in a longer time perspective. Development of diesel hybrids has been going for considerable time at Toyota, PSA and Volkswagen but, as usual, the obstacle is cost. Gasoline hybrids are more expensive than conventional power trains, and diesels are more expensive than gasoline engines. Moreover, they tend to become even more expensive because of tightening standards on noxious emissions (PM and NO_x). Thus, no manufacturer has seen a business case in introducing diesel hybrids in today’s market conditions. However, if technology development continues, fuel prices increase further and regulation on CO₂-emissions tightens, this configuration will become highly competitive both in urban and cruising driving conditions.

This brings us back a key question. How do current technology strategies of the major Japanese and European firms, in particular Toyota and VW, prepare them for the competition up to 2020, where hybrid-electric vehicles, battery-electrics and especially diesel hybrids can be expected to play important roles? With its massive market and production experience, systems engineering capabilities and deep industrial resources, Toyota may seem to be in a very strong position, assuming that hybrid technologies maintain their character of being deeply integrated architectures, where intimate component knowledge is essential for optimizing the entire system. If, however, hybrid-electric power-trains develop in a modular direction in the coming 10 years, VW could be in a position of combining its own deep knowledge in combustion technologies with modular innovations at mass-producing component specialists, in a similar way as start-stop systems have

become an independently produced component. This reliance on external suppliers finds parallels in the way car manufacturers have managed the development of battery-electric vehicles so far, where suppliers have taken a leading role in developing and introducing new technologies (Pilkington and Dyerson 2004). Already German component supplier Bosch AG has announced hybrid power train technology as a new core competence and their patenting records also indicate a certain level of technological knowledge in the field.

Conclusions

The position of incumbent car manufacturers as systems integrators, combining extensive architectural knowledge with component-specific knowledge in core technologies has remained unchallenged during several decades, and so has their innovation trajectory of incremental fine-tuning of combustion engine power trains. However, this pattern has been challenged both by new social and environmental pressure and by an unexpected architectural innovation at one of the industry's most pronounced incrementalists. Hybrid-electric vehicles build on a different set of technologies than traditional vehicles. Electrical engineering, energy storage, power electronics and electronic control systems are just as critical as mechanical engineering and combustion engine technology. The need to integrate diverse bases of engineering knowledge to produce a coherent and optimized system presents car manufacturers with a dilemma. Either they may try to expand their role as a systems integrator, building up considerable knowledge and industrial resources in new fields. Or they may source significant parts of power train development from outside specialists and thereby outsource critical parts of the integration process. The result of these decisions may be a new industry structure where the locus of innovation in core technologies has shifted away from the established car manufacturers. This holds true also if hybrid systems develop in a modular direction, which means that innovation at component levels will be of decisive importance.

Toyota's introduction of hybrid-electric vehicles initially received widespread scepticism in the industry. But patenting records also show that it was soon met by intensified R&D activities, particularly among the American manufacturers, whereas European producers increased their efforts to refine established power trains and related transmission systems. The commitment at Toyota to give hybrids a real market presence thus contributed to expanded innovation activities both of an incremental and more radical type. Whereas the "accelerated incrementalism" of the European producers has been successful so far, the US manufacturers who tried to compete head-on with Toyota had remarkable difficulties to catch up in this hybrid race even before the extraordinary crisis of late 2008 when vehicle sales dropped considerably. This illustrates another crucial lesson in a capital intensive mass-producing sector like the automotive industry: investments in R&D are never enough. The critical leap is to proceed from concepts and prototypes to industrialization: to design attractive products around the new technologies, build networks of competent suppliers, ramp-up production in cost-effective ways, set prices that permit sales and establish a reliable service network. All of this means that the power of the incremental innovation trajectory will remain strong in this industry, but also that instances of architectural innovation, as the one symbolized by Prius I, will be important for meeting future challenges.

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Appendix: Interviews

Company	Name	Position	Date
Toyota Europe	Kazuhiko Miyadera	Executive Vice President, R&D	7 November 2006
	Colin Hensley	General Manager R&D External Affairs & Communication	7 November 2006
Volvo Cars	Magnus Willner	Manager Product Planning	23 February 2007
	Sten Sjöström	Manager Product Planning	23 February 2007
GM Powertrain Europe	Kjell AC Bergström	Vice President Product Engineering	4 May 2007
	Tommy Bjorkqvist	Manager Advanced Engineering	4 May 2007
Volkswagen	Jürgen Leohold	Executive Director Group Research	4 July 2008
Volvo Powertrain	Niclas Thulin	Project Manager Hybrid Development	16 April 2007
	Filip Alm	Patent Engineer	4 May 2007
	Henrik Svenningstorp	Team Leader Hybrid Development	20 April 2009
Volvo Construction Equipment	Lennart Zander	Manager Driveline Development	15 May 2008
Swedish Hybrid Vehicle Centre	Mats Alaküla	Professor and Expert in Electric Machines and Drives	11 February 2008

Figure 1

Figure 2

Source: JDPower-LMC Market (Reuter), Hybridcar: for the sales in 2007

Figure 3