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Stockholm Environment Institute, Project Report - 2011

Governance of Innovation for Sustainable Transport

Hybrid-electric Vehicle Technology in Sweden 1990-2010

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Cover Photo: © One Tonne Life/flickr

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EXECUTIVE SUMMARY

This report presents results from the research project GIST-Governance of Innovation for Sustainable Transport, a 3-year research project funded by Formas and conducted in collaboration between IMIT-Institute for Management of Innovation and Technology and SEI-Stockholm Environment Institute.

Using a functional approach to technological innovation systems (TIS) combined with a multi-level framework of technological change, the report describes and analyses the development of hybrid-electric vehicle technology in Sweden 1990-2010. The multilevel framework captures the interplay between the focal innovation system (i.e. the Swedish hybrid-electric vehicle TIS), dynamisms in the global automotive industry and public environmental debates. This description provides a basis for analysing the functionality of a number of essential sub-processes in the technological innovation system, including: knowledge development and diffusion, influence on direction of search, entrepreneurial experimentation, market formation, legitimation and resource mobilisation. The report further discusses how various governance arrangements have influenced these sub-processes during the studied time period.

The study describes several activities the Swedish hybrid-electric vehicle TIS, ranging from public displays of concept vehicles and development of prototypes to field trials and market launches. It further shows how a range of governance arrangements on different levels (local/regional, national, supra-national) has influenced theses activities. The 1990s was characterized by a number of experimentation, testing and demonstration activities. These activities were primarily justified by a need to remedy urban air quality problems. Pending regulation made it urgent for vehicle manufacturers to address these problems. However, by the early 2000s it had become clear that neither battery-electric nor hybrid-electric vehicle technology would not be the preferred option to remedy urban air quality problems. Instead, fuel efficiency and reduced CO_2 emissions emerged as a prime driver for hybridisation. Still, the level of activity in the Swedish hybrid-electric vehicle TIS stagnated by the late 1990s and early 2000s. It was not until the mid 2000s that the motives were sufficiently strong for the Swedish vehicle manufacturers to advance hybrid technology further, engaging in product development directed at commercialization. At this stage, the manufacturers felt strong signals from several sources. Firstly, the sales figures of Toyota's hybrid car Prius on the US market had showed that there was a potential market for hybrid vehicles. Secondly, souring fuel prices made it possible, or at least plausible, to justify hybrid vehicles based on cost rationales.

The analysis shows how national level governance arrangements primarily have addressed the development and diffusion of product-related technological knowledge, and to some extent entrepreneurial experimentation and resource mobilisation. Other sub-processes seem to have been down-played. The analysis further shows how innovation system actors continuously have had to adapt their policies to international trends such as fluctuating oil prices, environmental debates, and crises and dynamism in the global automotive industry. It furthermore shows how it has been necessary for national level governance actors to find international support to be able to affect legitimation processes and influence the direction of search in the innovation system.

1 INTRODUCTION

This report presents part of the results of GIST-Governance of Innovation for Sustainable Transport, a 3-year research project funded by Formas and conducted in collaboration between IMIT-Institute for Management of Innovation and Technology and SEI-Stockholm Environment Institute. The project uses a functional approach to Technological Innovation Systems (TIS) (Carlsson & Stankiewicz, 1991; Hekkert et al. 2007; Bergek *et al.,* 2008) to describe and analyse the development and implementation of more sustainable road transport technologies. It further addresses how such developments can be supported by different kinds of governance arrangements.

1.1 BACKGROUND

The GIST research project combines the TIS approach with a multi-level perspective, which has been outlined as a framework to discuss socio-technical transitions (Rip and Kemp 1998; Geels 2002; Markard & Truffer, 2008). The purpose is to analyse how various governance arrangements (Treib *et al.,* 2007; Newell *et al.,* 2008) affect technological innovation systems.

The TIS approach has been outlined as a means to understand how technological innovations emerge. Traditionally an innovation systems approach focuses on the structural dimension of innovation, defining actors, networks and institutions as of three fundamental components. The TIS approach introduces a process perspective on innovation systems, defining a number of sub-processes which support the development, diffusion and use of new technologies. Assessing the functionality of such sub-processes – which often are denoted "functions" in TIS literature – thus becomes a key issue for policy makers.

Governance has become a very popular term over the last two decades, often replacing 'policy' in contemporary debates about social systems coordination. The conceptual shift from policy to governance has principally occurred to highlight that processes of preparing, deciding on and implementing measures to coordinate and advance societal objectives, increasingly involve – and should involve – stakeholders other than the nation state, such as NGOs, the private sector, and local/regional and international organisations. Governance is also advanced to denote that the rules that shape interactions between actors, as well as the use of different instruments, have changed. Moreover, the coordination necessary to achieve innovation in more sustainable technologies relies on forms of social initiatives that often take place outside traditional policy instruments such as coercive measures and regulation from the state.

A technological innovation system is typically conditioned by a particular mix of governance arrangements, which spans across modes, from standard setting to market signalling and softer approaches such as R&D subsidies. They intervene as part of the context and more specifically infuse political or market signals into the system. Following a TIS approach, the GIST research project considers the challenge for governance being to remedy poor innovation system functionality. This means that different governance arrangements can be implemented to promote a further development of the system, which in turn will support the innovation process. The assumption is then, that governance arrangements of different kinds, such as regulatory standards, market manipulations by the state, and public-private partnerships influence in different ways the functionality of the TIS. We further assume that the influence of governance arrangements on the TIS will vary due to external factors, such as the relation to established technologies, the general political agenda, and the economic situation.

1.2 PURPOSE AND METHODS

This particular report presents a case study on hybrid-electric vehicle technology. Hybrid-electric vehicles has been suggested as one of the most promising routes in a short-to mid term perspective to improve fuel efficiency and reduce CO_2 emissions from road transport (Hekkert *et al.,* 2005; Schäfer *et al.,* 2006). Hybridisation may also pave the way to further electrification of the transport system, which may result in additional reduction of CO_2 emissions.

As an industrial activity, vehicle R&D tends to be concentrated to geographical regions. This is because this industrial activity is based on a systemic knowledge base, comprising both tacit and codified pieces of knowledge (Breschi & Malerba, 1997). Effective coordination under such circumstances relies on territorial proximity. The case study presented here zooms in on such a geographically bounded area, defining the Swedish hybrid-electric vehicle technology innovation system as the unit of analysis.[1]

Situated in a relatively small country with a limited domestic market, the Swedish vehicle industry depends heavily on exports. These exports are also a significant part of the total exports from Sweden. In 2008, exports of the Swedish vehicle industry amounted to 155 billion SEK, which was 13 per cent of the total Swedish exports (BIL Sweden, 2009). Besides the Information and Communication Technology (ICT) sector, the vehicle industry is the largest sector in Sweden in terms of R&D spending (Norgren *et al.,* 2007). The vehicle industry thus constitutes a very important part of the Swedish economy. The Swedish car manufacturers' production volume is small from a global perspective; in 2007 the Swedish car manufacturers' production amounted to 0,6 per cent of the total production world-wide. However, Swedish manufacturers of heavy vehicles (trucks and buses) have a much stronger position on the markets in which they are active. In 2007, the Swedish heavy vehicle manufacturers had a 28 per cent European market share (Faguert *et al.,* 2009).

The time period for the study is 1990-2010. During this 20-year period, different actors in the Swedish hybrid-electric vehicle TIS took several initiatives. The level of activity also varied significantly. Relevant activities range from public displays of concept vehicles and development of prototypes to field trials and market launch of hybrid electric-vehicles. These activities were influenced by a range of governance arrangements (R&D subsidies, market incentives, private-public partnerships, regulation etc.) on different levels (local/regional, national, EU, global). This report describes and analyses the effects of these arrangements. It will thus address the following question: How has governance influenced the Swedish hybrid-electric vehicle technological innovation system 1990-2010?

The empirical study is based on studies of documents and loosely structured open-ended interviews with representatives for key industrial and public actors in the Swedish Hybrid Electric Vehicle TIS. Apart from this, to ensure a strong international component in the TIS analysis (Bergek et al 2008); the report also relies on interviews with representatives for leading international automotive manufacturers, key suppliers and research funding agencies. The interviews were guided by a limited number of broad questions and topics. Mail conversation to clarify the research objectives preceded the interviews. The questions and topics addressed in the individual interviews varied depending on the respondent's background, organization and role in the organization. The stage of the empirical study also influenced the interviews in that later interviews could refer back to information gained in previous interviews and document studies. The studied documents include relevant academic articles, research reports, doctoral theses and public evaluations of state funded R&D and demonstration programs. Reports from financial press, automotive press and press releases from automotive manufacturers have been used as complementary sources of data. Appendix 1 provides details on data sources and methods used in the empirical study as well as an example of an interview guide used.

1.3 HYBRID-ELECTRIC POWER TRAINS

The automotive power train is the vehicular subsystem that generates and delivers motive power to the road surface. It constitutes a dominant part of the vehicle, incorporating some central parts such as engine, ignition system, transmission etc. It also determines some of the most important properties of the vehicle such as speed, acceleration and traction power.

In a traditional car, truck or bus, the internal combustion engine (ICE) is dimensioned according to the maximum power needs of the car during e.g. acceleration. This means that there is an excess capacity in normal driving and this excess capacity results in efficiency losses. However, if you combine the ICE with an electric motor to form a hybrid-electric power train, the engine can be down-sized. As a result, you gain efficiency. Moreover, being assisted by the electric motor, the internal combustion engine is allowed to consistently operate its most efficient range in terms of engine speed (rpm) and torque. The electric motor can also be reversed and used as a generator to recover breaking energy, so called regenerative breaking. Moreover, the hybrid-electric power train minimizes idling losses through automatic shut-down of the ICE, e.g. when waiting for green light at a crossing. Hence, the combination of the virtues of electric machines and internal combustion engines enables significant fuel efficiency gains, especially in driving conditions

1 See Lundvall (1998) for an elaborate discussion and justification of the study of national innovation systems

characterized by repeated starting/stopping and acceleration/ deceleration. Combining electric propulsion with combustion engines may thus result in considerable gains in terms of fuel efficiency, compared to traditional vehicles.[2]

Hybrid-electric automotive power trains can be configured in a number of ways (Chau and Wong, 2002; Ehsani *et al.,* 2005). In a *series hybrid*, the ICE engine drives an electric generator, which is connected to a battery pack via an electronic converter (rectifier). An electric motor propels the vehicle and the electric motor may also be reversed to recover breaking energy. The engine in a series hybrid is thus mechanically separated from the drive wheels and it can operate constantly in its most efficient and low-polluting load range. However some of the efficiency gains are lost through energy losses in the conversions from motive power to electric power and then again back to motive power. In a *parallel hybrid*, the combustion engine is assisted by an electric motor. Hence, both the ICE and the electric motor are mechanically connected to the vehicle transmission. As the most efficient combination of combustion engine and electric propulsion can be selected at any given situation, the main advantage of the parallel hybrid is its fuel efficiency. The power-split hybrid (this configuration is also termed *complex hybrid* or *series-parallel hybrid*) is a combination of the series and the parallel hybrid. It comprises an additional mechanical link compared to the series hybrid and it also comprises an additional generator. The power-split hybrid possesses favorable characteristics of both series and parallel hybrids; but it is also more complicated and expensive.

Figure 1 shows the core sub-systems in a power-split hybrid power train: engine, transmission system (mechanical power split device[3], reduction gear, generator, electric motor), power converter, and energy storage system (battery). A core part of every hybrid power train is also the control system, which is essential to determine which the most efficient mode of operation is and manage the different parts of the hybrid system accordingly. The control system for a hybrid power train is much more complicated than for a traditional internal combustion engine, due to the many different subsystems which must work smoothly together. The mode of operation is determined through algorithms based on parameters such as engine speed, torque, power requirements, and vehicle speed. The control system must also carefully monitor the battery charge level and temperature to secure that the hybrid power train operation does not downgrade the functionality and performance of the battery. Based on these parameters, the control system calculates the most efficient balance between combustion engine propulsion and electric propulsion and thus continuously determines the optimum mode of operation for the hybrid power train.

Another means of hybrid power train classification refers to the extent the vehicle relies on the combustion engine and the electric motor respectively for propulsion. At one end of this spectrum is the traditional vehicle, which only uses a combustion engine, and at the other end of this spectrum is the pure electric vehicle, which only relies on an electric motor for propulsion. All HEVs can be found somewhere in between these two extremes and in general, the potential for fuel efficiency gains becomes higher with a higher degree of hybridization. *Micro hybrids* are essentially conventional vehicles equipped with so called start-stop systems. Somewhat enlarged starter motors in these cars allow for automatic shut-down and start up of the combustion engine to reduce idling losses at e.g. traffic lights. Micro hybrids generally use conventional 12-14V electric systems and they sometimes have limited regenerative breaking capabilities. *Mild hybrids* comprise relatively small electric motors, which primarily assist the combustion engine during acceleration from standing still and at low speeds. To fully capture benefits in terms of regenerative breaking and torque assistance, these hybrids require higher voltage electric systems. In general the voltage level of these systems is up to ca 42V. A *full hybrid* comprises a high voltage electric system (e.g. the third generation of Toyota Prius uses a 201,6V system), and a more powerful electric motor which is integrated in the automotive power train to assist the combustion engine at both lower and higher speeds. The larger electric motor permits the full hybrid to run limited distances in all electric modes, with the ICE shut down. Limited battery capacity, however, put severe restrictions to the driving range. The next step is the *plug-in hybrid,* which comprises a larger battery that may be charged via the electric grid. The electric motor is the prime source of motive power in the plug-in hybrid with the on-board battery capacity delimiting the

2 According to Schäfer et al (2006), the potential gain in fuel efficiency is about 20-30 per cent for cars in combined drive cycles, when compared to cars using traditional internal combustion engine based power trains.

3 A common solution is to use a planetary gear to split the motive power between the engine, the generator and the motor.

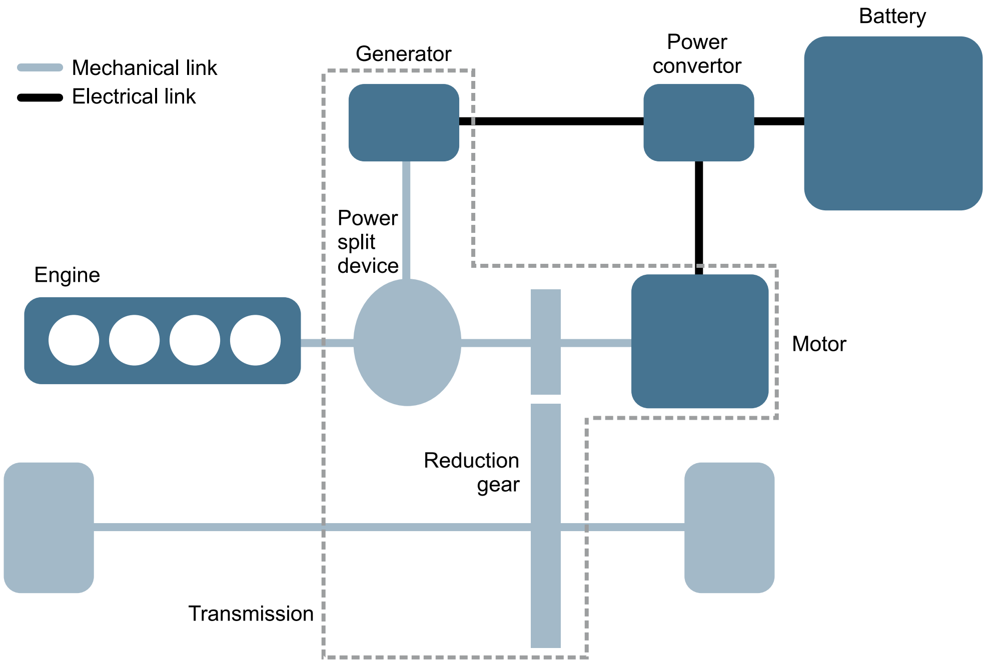

Figure 1: Hybrid power train (power-split hybrid) (Magnusson *et al.*, 2003:11)

all-electric driving range. The internal combustion engine allows battery charging while driving. The hybrid system may also be configured so that the ICE may drive the car directly as the battery runs out of electric power.[4] This enables longer-range drives. Hence, the plug-in hybrid can be viewed as an electric car with an on-board charging device/driving range extender (Håkansson, 2008).[5]

Combustion engines and transmissions are based on entirely different knowledge bases than the knowledge needed for developing subsystems such as high-voltage electrical machines, energy storage systems (batteries), as well as power electronics and energy management systems, which are needed in hybrid-electric power trains. In order to realize the potential gains in terms of fuel efficiency in a hybrid power train, these technologies need to be effectively combined into a coherent and optimized system. The complexity of the system and the large number of possible configurations means that engineers involved in hybrid technology development have to make a lot of choices, matching different systems-level requirements, such as drivability, fuel efficiency, safety, reliability, performance etc. Hence, hybrid-electric vehicle technology is very much about systems integration, combining different sets of engineering knowledge. Additionally, since the hybrid vehicles comprise a lot of additional subsystems compared to conventional vehicles, attaining competitive cost levels is a prime challenge for any manufacturer that engages in the development of hybrid-electric vehicles (Chanaron & Teske, 2007).

The focus of this report is on hybrid-electric vehicle technology, rather than on individual component technologies such as electric machinery technology (motors and generators), battery technology and other energy storage technologies, power electronics, engine and transmission technology etc. However, a certain degree of component-specific knowledge is required to be able to develop a functioning system. Therefore this distinction is not clear-cut. The critical balance between system level knowledge (often denoted "architectural knowledge") and component-specific knowledge is a recurrent theme in automotive manufacturers' technology strategies, which has direct implications for outsourcing decisions and supplier interaction. According to Takeishi (2002) the appropriate balance between architectural knowledge and component-specific knowledge is contingent upon the individual development project. Automotive manufactures therefore have to address this trade-off continuously in their interaction with suppliers. A too high degree

4 The ICE may drive via the rear wheels as the electric motor propels the front wheels or vice versa

5 From a technical standpoint it is possible to make further distinctions, e.g. between a plug-in hybrid based on a series or power-split hybrid configuration with added battery capacity and a plug-in hybrid based on an electric car with an ICE operating as a range extender.

of R&D and production outsourcing may erode the manufacturer's knowledge base, thus delimiting the possibilities to operate as systems integrators (Becker & Zirpoli, 2003). As hybrid-electric power trains partly build upon fields of engineering knowledge, which are relatively new for the automotive industry (e.g. electric machines and battery technology), this adds complexity to supplier interaction and outsourcing decisions.

1.4 PRODUCT APPLICATIONS

Cars may be divided into different categories depending on their size (mini, compact, medium/midsize, large/full size) or body type (sedan, hatchback, station wagon, Sport Utility Vehicle – SUV, pick-up, van, sports car). Cars and car brands may also be classified according to production volume and price level (low-end/volume car, mid-range car, high-end/luxury car). For various reasons, automotive manufacturers have introduced hybrid technology in several of these car types, including compact cars, mid-size sedans/hatchbacks, luxury cars, vans, SUVs and pick-ups. A prime rationale for introducing hybrid technology in compact cars has been that these cars are mainly used in urban driving conditions, where the potential benefit in terms of fuel efficiency is most significant. The same rationale may be used to justify hybrid technology in e.g. delivery vans. However compact cars are often volume cars, which are sold at relatively low price and with low margins. This makes it difficult for a car manufacturer to justify the higher cost associated with hybrid-electric power trains. Hence several manufacturers have instead preferred to introduce hybrid technology in larger cars such as SUVs. The higher prices and margins of these vehicles make it easier to justify implementation of more advanced and expensive technologies. The same argument can be used for the introduction of hybrid technology in luxury cars. Another rationale for introducing hybrid technology in SUVs is that these cars generally are very heavy and consume a lot of fuel. Therefore there is a large potential to reduce fuel consumption by implementing hybrid-electric vehicle technology.

Another category of vehicles that may benefit from hybrid technology is heavy vehicles such as trucks and buses. In particular this is true for distribution trucks and city buses that operate in urban areas. The potential fuel efficiency gain is generally lower for long-haulage trucks and coaches, which operate over long distances at consistent speed. Because of local air quality and noise problems, city buses have since long constituted a test bed for alternative power train technologies and alternative fuels. Hybrid technology offer possibilities to reduce both noise and harmful emissions such as NO_x and particulate matter (PM). Moreover, it is helpful to reduce large energy losses due to idling and repeated starting and stopping, which is typical for city bus operation. For similar reasons, distribution trucks may also benefit significantly from hybrid propulsion systems. Hybrid technology also opens up possibilities to replace existing auxiliary systems such as servo systems, climate controls and compressors, with more efficient electric systems. Due to the possibility to operate in all-electric modes, hybrid power trains comprising strong electric motors and extensive battery capacity could be particularly beneficial for distribution trucks that deliver goods to indoor terminals. This is because the zero emission-characteristics of such propulsion systems may help improving the indoor air quality.

Apart from these applications, a number of special purpose heavy vehicles may benefit from hybridization, e.g. refuse trucks, wheel loaders and military combat vehicles. Both refuse trucks and wheel loaders tend to operate in extreme start-stop drive cycles, which mean that there is a good potential to improve fuel efficiency through brake energy recovery and electric power assist. Moreover, in most cases refuse trucks operate in residential areas which are sensitive for noise pollution. Hybridization offer possibilities replace the traditional ICE powered hydraulic lifts and compactors with more silent and energy efficient electric equipment. In terms of military vehicles, the main rationales for applying hybrid technology are safety and logistics reasons. In military vehicles, there are compelling reasons to reduce fuel consumptions and thus reduce the need to distribute and store extensive amounts of fuel. However, an even more compelling reason to implement hybrid technology is the mechanical separation between the engine and the drive wheels in a series-hybrid power train. Compared to a traditional power train, this mechanical separation result in more flexibility and more options in vehicle layout and packaging, something that is particularly appreciated in the design of military terrain vehicles (Eriksson, 2007).

In terms of power trains and propulsion technologies, heavy vehicles may appear quite similar to cars, but a closer scrutiny reveals that they are vastly different in several respects. Estimated production and sales volumes are an order of magnitude lower, which means that it is difficult to reach economies of scale and cost reduction is very demanding. In most cases, heavy vehicles operate on a more continuous basis than cars and requirements on reliability, robustness and efficiency are significantly higher. Further a modern heavy vehicle is by itself a complex system with a lot of auxiliary equipment and this means that vehicles require much more advanced system solutions. Unit costs are also much higher and customers are typically professional; hence they pay particular attention to operating costs and life-cycle costs. Therefore purchase behaviours are to a larger extent guided by cost-rationale in the case of heavy vehicles, than in the case of cars. Moreover, as the degree of customization is higher; individual buyers are more intensely involved in the final specification of heavy vehicles than in the case of cars.

1.5 INDUSTRY ACTORS

The established vehicle manufacturers are arguably key actors in the development hybrid-electric vehicle technology. Entry barriers are high in the automotive industry and only the established manufacturers possess the required resources and system integration capabilities to develop and produce hybrid-electric vehicles. However, as noted in section 1.3 Hybrid-electric power trains, these manufacturers also need to acquire knowledge in new fields and the need to co-operate with new suppliers to accomplish this.

The global automotive industry is dominated by a limited number of vehicle manufacturers that operate on a global market. These are large multinational firms generally that take the role of systems integrators, outsourcing a large share of the component R&D and manufacturing to external suppliers. In 2009 four major vehicle manufacturers had R&D and manufacturing operations in Sweden: the two car manufacturers Volvo Cars and Saab Automobile and the two heavy vehicle manufacturers Volvo and Scania. All these manufacturers have announced that they have R&D activities in the area of hybrid-electric vehicles. Together with other European automotive manufacturers, via the joint organisation ACEA – the European Automotive Manufacturers' Association and EUCAR – the European Council for Automotive R&D, the Swedish vehicle manufacturers also take part in joint efforts to promote research initiatives in hybrid technology. This also includes the development and implementation of electric network access and charging infrastructure standards for plug-in hybrids and electric cars. Moreover, the specialised military combat vehicle manufacturer BAE Hägglunds, with R&D and manufacturing capabilities in Örnsköldsvik, is active in hybrid-electric vehicle development.

Apart from these vehicle manufacturers, the Swedish automotive industry also consists of around 1000 suppliers (Faguert *et al.,* 2009). The cooperative organisation "The Swedish Automotive Suppliers (Fordonskomponentgruppen – FKG)" promotes the shared interests of Swedish automotive suppliers. Suppliers to the car manufacturers are organised in different layers or tiers (1st tier, 2nd tier, 3rd tier), an approach which has been pioneered by the Japanese car manufacturers as a way to hierarchically structure a large supplier base. 1st tier suppliers have direct relationships with automotive manufacturers, supplying major sub-systems to their assembly plants. 2nd tier suppliers are generally specialists that supply 1st tier suppliers with components. 3rd tier suppliers are in most cases material manufacturers that operate either as suppliers to 2nd tier component specialists or to 1st tier subsystem suppliers. At each level, suppliers are expected to invest in R&D to develop their own products and further advance their technological expertise (Maxton & Wormald, 2004). However, only a few countries (e.g. USA, Japan and Germany) retain a vehicle industry big enough to support an extensive supplier network. The limited size of the Swedish vehicle industry means that it can only comprise a few leading suppliers, such as SKF (rolling bearings, seals etc.) and Autoliv (automotive safety systems) (Faguert *et al.,* 2009). Figure 2 illustrates the supply chain for cars.

The heavy vehicle supply chain differs somewhat from the car supply chain. Whereas car manufacturers use a network of retailers to reach end users, heavy vehicle manufacturers often sell their vehicles directly to professional customers. In many cases, specialised manufacturers of auxiliary equipment are responsible for final customization before these vehicles are put into operation. In the case of buses, heavy vehicle manufacturers often deliver the chassis and power trains to specialized bus body manufacturers, who customize the body according to specifications from the customer.

Following a round of consolidation in the automotive industry during the 1990s, the two large American

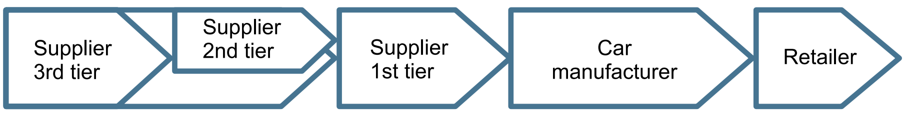

Figure 2: Schematic illustration of car supply chain.

automotive firms GM and Ford acquired Saab Automobile and Volvo Cars respectively. GMs realised their acquisition of Saab Automobile in two steps: in 1989 they acquired 50 per cent of the Saab shares with an option to the remaining shares within a decade. GM subsequently closed the deal in 1998, obtaining full ownership. Ford realised the acquisition of Volvo Cars in 1999. Both GM and Ford maintained development resources in Sweden, but the acquisitions were associated with extensive plans to reduce costs through co-coordinated R&D efforts and shared product platforms. Less than a decade later, however, the American automotive manufacturers suffered significant financial losses and both groups thus announced plans to restructure their operations. As a result, GM declared that they would sell Saab Automobile and Ford declared that they would sell Volvo Cars. These divestment plans were realized in 2010.

By contrast to the car manufacturers, the Swedish heavy vehicle manufacturers have largely remained under Swedish control until 2008, when Volkswagen acquired a controlling stake in Scania. In 2000, after selling off its car division to Ford, Volvo made an attempt to acquire Scania. However the European Union Commission stopped this attempt claiming that it would result in a too dominant market position for them in the Scandinavian countries. Scania's product portfolio is focused on trucks, buses and engines for industrial applications. The company has maintained a careful internationalisation strategy, primarily selling their vehicles in Europe and Latin America. Scania also has some limited sales in Japan, due to a marketing agreement with the Japanese truck manufacturer Hino. However, Scania has consistently avoided entering the North American market, arguing that North American truck buyers want extensive freedom in specifying their own vehicles, using subsystems and components from several different manufacturers. This tradition does not fit with Scania's product strategy, supplying very integrated products. A core part of this strategy is Scania's modular system, which means that they can configure a large number of product variants with a limited number of components. Scania's development resources are primarily concentrated to the headquarters and main manufacturing plant in Södertälje.

Volvo, with R&D headquarters in Gothenburg, has a much more diversified product portfolio including trucks, buses, construction equipment (wheel loaders, haulers, excavators), industrial engines/boat engines (Penta) and aero engines. These products are sold on a worldwide market. In terms of truck production, Volvo is the number 2 global producer after Mercedes. The company produces trucks under four different brands Volvo, Renault, Mack, and UD Trucks (formerly Nissan Diesel). Volvo acquired Renault and Mack in 2000 (after an unsuccessful attempt to acquire Scania) and Nissan Diesel in 2007. A broad product portfolio and presence on a worldwide market means that Volvo is one of the world's largest producers of heavy diesel engines. The different products and brands constitute a basis for a divisional structure, which is complemented by a number of lateral organizational units that co-ordinate activities across different divisions. Together with the divisional structure, these units form a group level matrix organisation.

Out of the lateral organizational units, in particular Volvo Technology and Volvo Powertrain have been involved in hybrid-electric vehicle development. Volvo Technology is the shared organisation for advanced engineering/pre-commercial technology development and Volvo Powertrain is responsible for development and production of engines, gearboxes and drive shafts, which are shared by different products and brands. Moreover, the 3P organisation, which co-ordinates product planning, product range management, product development and purchasing activities for the truck brands are involved in activities related to hybrid-electric vehicle development.

1.6 PUBLIC ACTORS

The technical universities are important public actors in the Swedish hybrid-electric vehicle TIS. Several technical universities are involved in automotive technology R&D in Sweden. This includes Chalmers University of technology in Gothenburg, the Royal Institute of technology (KTH) in Stockholm, as well as the technical universities in Lund, Linköping, Luleå and Uppsala. For example, Chalmers, KTH and Lund University have combustion engine technology research centers. In particular Chalmers in Gothenburg has traditionally had a strong connection to Volvo, whereas KTH in Stockholm has a similarly strong liaison with Scania. Related to hybrid-electric vehicle technology KTH and Lund have strong research traditions in electric machine technology (motors and generators), and Uppsala university, KTH and Chalmers are active in energy storage and battery technology. However, the universities are not only important as research partners. The engineering education is equally important; supplying the automotive manufacturers with engineers with specialization in relevant fields of technology.

Other important public actors include public research funding agencies that financial resources to hybrid-electric vehicle technology R&D. During the 1990s, the Swedish Transport and Communications Research Board (KFB) and the Swedish business development council (Nutek) were the most important funding agencies. In 1998, the Swedish Energy Agency (STEM) was established. R&D funding directed at energy efficient vehicle technology was made part of their mission. Following a restructuring of the research funding system in 2001, the newly established agency VINNOVA (The Swedish Governmental Agency for Innovation Systems) took over the research funding responsibilities of both KFB and Nutek. During the 2000s STEM and VINNOVA thus became the two core governmental research funding agencies in Swedish hybrid-electric vehicle TIS. Other potentially important funding agencies were the foundation for strategic environmental research (Mistra) and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas), the Swedish Environmental Protection Agency and the Swedish Road Administration Authority.

In 1994, the Swedish state and the Swedish vehicle industry (including the supplier organization FKG) set up the umbrella organization PFF (the program council for vehicle research) to coordinate public vehicle research funding. The ambition was to facilitate R&D cooperation between the automotive industry and relevant funding agencies. Between the years 1994 and 2008, a number of research programs were initiated including the Vehicle Research Program (ffp), the Swedish Green Car program 1 and 2, the Emissions Research Program (EMFO) and the Intelligent Vehicle Safety Systems Program (IVSS). Among these programs, the Swedish Green Car program 1 (2000-2007) and 2 (2006-2008) provided financial support for hybrid-electric vehicle R&D. As a follower to PFF, a new private-public partnership called Strategic Vehicle Research and Innovation (FFI) was established in 2009. VINNOVA obtained the role as a coordinating actor. One out of five collaboration programs was devoted to energy and environment and was administrated by STEM. Amongst others, this program provided funding for hybrid vehicle R&D.

2 HYBRID-ELECTRIC VEHICLE DEVELOPMENTS 1990-2010

This chapter describes hybrid-electric vehicle technology developments 1990-2010 in four consecutive time periods. Each of these periods comprises developments on two different levels. Firstly it describes an international governance and industry dynamics level, covering global public debates, and vehicle industry activities, as well as oil price fluctuations, and international policies and regulation affecting hybrid-electric vehicles technology development. Secondly, it describes a Swedish governance and industry level, covering national policies, regulation and industry activities in the area of hybrid-electric vehicle technology. A brief summary concludes each section.

2.1 1990-95: AIR QUALITY ISSUES AND CONCEPT VEHICLES

International governance and industry dynamics

Although several different concept vehicles[6] have been displayed ever since the birth of the automotive industry in the late 19th century, it was not until the 1990s that one could observe any real action in the development of electric and hybrid-electric vehicles. The prime driver for this development was not related to fuel efficiency or greenhouse gas emissions. Instead it was related to urban air-quality problems. Repeated smog alerts in several major cities, called for immediate action. Urban smog caused severe illness, especially among elderly people, children and people with heart and lung diseases. Additionally, there were major problems related to acidification. This called for major reductions of automotive tailpipe emissions. In particular the release of substances such as Sulphur Dioxide (SO_2), Nitrogen Oxides (NO_x), Particulate Matter (PM) and Volatile Organic Compounds (VOC) had to be dramatically cut-down to reduce the risk of serious health effects and of acidification of forests adjacent to major highways.

Among the major cities that suffered most from road traffic related smog problems in the late 1980s and early 1990s was Los Angeles in California. Los Angeles is one of the world's most motorized urban areas, with millions of cars and other vehicles trafficking streets and highways each day. Being situated by the sea in a low basin area surrounded by high mountains, air pollution does not easily blow away in Los Angeles. Hence, the conditions for smog-forming are almost "ideal" here. Therefore, authorities have since long been very active in regulating air emissions in the Los Angeles area. One prominent example is the Californian Zero Emission Vehicle (ZEV) mandate that the Californian Air Resources Board adopted in 1990. The ZEV mandate forced automotive manufacturers active in California to sell a step-wise increased percentage of Zero Emission Vehicles (i.e. battery-electric or fuel cell-electric vehicles). The original mandate required 2 per cent of ZEV sales by 1998. Since California is an important part of the US market, this proposed regulation forced the major car manufacturers that sold cars on the US market to engage in the development of electric vehicles during the 1990s (Pilkington & Dyerson, 2004).

6 A concept vehicle is a kind of prototype that is publically displayed. It is not intended for production or sales and it does not have to be functional or drivable (Backman, 2005).

Swedish governance and industry activities

From a Swedish governance perspective, the Swedish business development council (Nutek) ran a research funding program directed at electric and hybrid-electric propulsion technologies during 1993-96, with an annual budget of 8 MSEK. Both universities and industrial actors could apply for R&D funds from the program. Nutek also initated a public procurement program for the purchase of electric cars. The program involved a consortium with about 40 different actors. These actors were mostly public, such as municipalities, but also a few private companies. The ambition was to jointly purchase between 1200 and 1500 electric cars. However, the program experienced a limited interest from vehicle manufacturers and in the end the consortium only purchased 150 cars (Hedman *et al.,* 2000).

The Nutek programs were coordinated with a broad 120 mSEK national program for research, development and demonstration of electric and hybrid-electric vehicles, initiated by the Swedish Transport and Communications Research Board (KFB) in 1993. Apart from supporting technological R&D and demonstration, the KFB program also comprised an element of social research related to market developments for electric and hybrid electric vehicles and the impact of such vehicles on the society. Several other countries had initiated similar programs during this period, most notably car producing countries such as France and USA, but also countries such as Switzerland that saw possibilities to establish a new industry manufacturing small electric cars. Local governmental initiatives to promote the diffusion of electric cars in the three largest Swedish cities Stockholm, Göteborg and Malmö preceded the KFB program. Co-financing tripled the total resources available for projects within the program. The program ran until 2000 and the program budget covered three areas: (1) Surveys of technology and market development in Europe, North America and Japan (8 per cent). (2) Demonstrations of vehicles in Sweden's major cities and infrastructure development (65 per cent). (3) Pure and applied research regarding the effects of electric and hybrid vehicle technology on Swedish society and technology development of electric and hybrid vehicles, especially in heavy vehicle applications (27 per cent) (Rader-Olsson, 2000).

Among the Swedish manufacturers, Volvo took the most visible initiative during these years, developing a number of hybrid concept vehicles. Nutek co-funded Volvo's hybrid R&D and the government owned Swedish electric utility Vattenfall also sponsored the project. In the Paris auto show 1992, Volvo showed their Environmental Concept Car – ECC publically for the first time. It was displayed in subsequent auto shows and it gained a lot of media attention.

Volvo's development and display of the series hybrid concept car ECC can be seen as a response to the increasingly stringent Californian emission regulations (Fogelberg, 2000). In a report on their Environmental Concept Car, Volvo stated that this vehicle complies with CARB's Ultra Low Emission Vehicle requirements. But they also argued that, because of the extremely low emissions and because of the possibility to drive in an all-electric mode for shorter distances, vehicles comprising this kind of power train should be accepted as Zero Emission Vehicles (Volvo, 1992). Volvo's preference for hybrid technology at this stage can be explained by a product portfolio comprising relatively large and heavy cars. Due to the limited energy density of the batteries, Volvo's cars did not fit very well with battery-electric propulsion. By contrast to battery-electric vehicle technology, hybrid-electric vehicle technology also seemed plausible for heavy vehicles. The American market was the largest national market for Volvo and Californian car sales constitutes an important part of this market. California is also considered as a "trend-setting market", and presence in California is important to sense and probe future trends.

ECC was based on Volvo's 850-platform, but the Volvo engineers replaced the internal combustion engine and gearbox by a series plug-in hybrid power train. The exterior design of Volvo ECC was also quite different from a standard 850. Instead of combining a traditional internal combustion engine with an electric propulsion system, Volvo used a small gas turbine (microturbine) that drove a high-speed generator to charge a package of Ni-Cd batteries. The high-speed generator technology had originally been developed by researchers at the Royal Institute of Technology (KTH) in Stockholm. ECC was essentially a battery-electric car with an on-board generator to extend its driving range. Relying on a continuous combustion process at moderate temperatures, the microturbine was favorable due to its low emissions of NO_x, VOC and particulate matter. United Turbine, a subsidiary to the aero engine manufacturer Volvo Aero, developed the turbine package. ABB Hybrid Systems supplied the electrical machinery and power electronics, including the innovative high-speed generator. Volvo subsequently developed and implemented an up-scaled version of the microturbine-based series hybrid power train in a concept truck and a concept bus, which they presented 1995-96.

Summary

Local air quality problems forced automotive manufacturers to pay attention to tailpipe emissions. While the preferred means to address this problem was to improve combustion processes and add emission treatment equipment such as catalytic converters, the electric vehicle was also introduced as a plausible zero emission alternative. In particular, the Californian ZEV regulation promoted this alternative. In this respect Volvo considered hybrid-electric propulsion as a possibility to address the main deficiency of the battery electric vehicle – the limited driving range. However at this stage, these initiatives were delimited to concept vehicles, neither intended for volume production nor for commercial markets.

2.2 1995-2000: KYOTO, PRIUS AND DEMONSTRATIONS

International governance and industry dynamics

In California, strong lobby groups representing the major car manufacturers and the oil industry market defeated the ZEV mandate, pressing the CARB regulators to withdraw their strict demands for zero-emitting (electric) vehicles (Pilkington & Dyerson, 2004). While they still imposed emission requirements, the car manufactures could reach these by incrementally improving the internal combustion engine and adding emission treatment equipment (Fogelberg, 2000). The late 1990s also saw an emerging global political debate on climate change, global warming and the negative consequences of greenhouse gas emissions. In particular, the attention was directed to CO_2 emissions from the use of fossil fuels to generate heat and electric power, for running industrial processes and for transportation purposes. The debate culminated with the Kyoto conference and the signing of the Kyoto protocol in December 1997. The Kyoto protocol was the first global agreement where different countries committed to individual, legally binding targets to limit or reduce their greenhouse gas emissions. For industrialized countries, the reductions added up to a total cut of at least 5 per cent from 1990 levels during the period 2008-2012. The commitment of EU was to reduce six greenhouse gases by 8 per cent, from the 1990-level, by 2008-2012. For the transport sector, EU approved a goal in 1995 that average CO_2 emissions of new cars should be maximum 120 g/km by 2005. The goal was later postponed until 2012. In 1998, the European car manufacturers agreed with EU that average CO_2 emissions of their cars would be maximum 140 g/km by 2008 (Kågesson, 2007).

During this time period the automotive industry also witnessed the advent of the first mass-produced hybrid-electric car, Toyota Prius. The Prius 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. Toyota's initial plan with this concept study 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 concluded that they could not accomplish this with a traditional power train. Toyota had previous experiences from battery-electric vehicles, developing and producing their compact SUV RAV4 in an electric version (Pilkington and Dyerson 2004). In this case, however, they considered it important that the car should use the existing fuel infrastructure; Prius was to be perceived by customers as a conventional car. At this stage, Toyota's division for advanced engineering had recently presented as a rudimentary hybrid-electric power train and the team thus settled for this technology (Magnusson & 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. Toyota Prius subsequently entered the market in December 1997, well timed with the Kyoto conference. The car is based on a full hybrid power train with a complex hybrid configuration. It used a planetary gear as a mechanical "power split device", connecting the internal combustion engine with an electric motor and a separate generator that charges the NiMH-battery package. During the first two years after market introduction, the compact size Prius was exclusively sold on the Japanese market, a sign of Toyota's cautious market introduction strategy, wanting to verify the technology before initiating large scale production and export sales.

Swedish governance and industry activities

In Sweden, the KFB program proceeded with its support for electric and hybrid-electric vehicle demonstration. The lion's share of the support went to demonstration programs in four major Swedish cities: Stockholm, Gothenburg, Malmö and Uppsala (Rader-Olsson, 2000). In total, 279 vehicles were part of the demonstrations. 20 of these were scooters (one model), 104 were passenger cars (five different models), 128 were delivery vans (four different models), two were distribution trucks (one model), two were refuse trucks (one model) and 23 were buses (five different models).

Battery electric vehicles completely dominated the demonstration programs; only 15 of the 279 demonstrated vehicles (and none of the passenger cars) were hybrids (Hedman *et al.,* 2000). At this stage, neither Toyota nor Honda had introduced hybrid cars on the European market and none of the demonstrated passenger cars were developed and/or manufactured by Swedish manufacturers. In their evaluation report KFB notes that "The Swedish car manufacturers have not been able or willing to offer any electric/hybrid vehicles" (Hedman *et al.,* 2000: 17). According to the report, this limited interest may be explained by three factors. Firstly, the Swedish car manufacturers experienced financial problems during this period. Secondly, since the Swedish manufacturers are small players in the global automotive industry, they had very limited resources for R&D and demonstrations. Thirdly, being controlled by large American manufacturers, the Swedish car manufacturers had limited control over strategic R&D. In particular, this applies to SAAB, as GM had acquired 50 per cent of SAAB Automobile already in 1989.

Following their display of ECC in 1992, Volvo developed four different series-hybrid prototypes, comprising internal combustion engines instead of micro turbines. However, Volvo's management stopped this development after producing a limited number of test vehicles in 1998 (Pohl, 2010). Moreover, Volvo displayed a converted S40 with a new hybrid concept at the Geneva Motor Show in 1999. This concept vehicle, called "Desiree" was equipped with a full power-split hybrid similar to Toyota's hybrid system, and it comprised a lager battery package that could be charged via the electric grid. Following their acquisition of Volvo Cars, however, Ford's top management decided to concentrate the group's efforts in full hybrid development to their technology centre in USA. During this period, Volvo also developed a mild hybrid concept vehicle, which they displayed in a converted S40 at the World Expo 2000 in Seville, only to terminate the development shortly thereafter.[7] Following these decisions, Volvo Cars' subsequent effort in hybrid technology was significantly reduced.

By contrast to the cars, hybrids dominated the heavy vehicle demonstrations in the KFB program. This development was supported by the implementation of so called "environmental zones" in the inner-city regions of the three largest Swedish cities Stockholm Gothenburg and Malmö. These zones were associated with special regulations and restrictions for heavy goods vehicles and buses to reduce emissions of harmful substances to the air. By 2002 such environmental zones had been implemented in 16 of the largest cities in Europe (Trendsetter, 2002).

In total 27 heavy vehicles were demonstrated in the KFB program and of these, 15 were hybrids: two distribution trucks and 13 buses (4 different models) (Rader-Olsson, 2000). So, hybrid technology R&D and demonstration still attained a substantial part of the KFB program's financial resources. In fact Volvo Buses was the second largest beneficiary of the program, attaining support for the development, manufacturing and demonstration of hybrid buses (Hedman *et al.,* 2000). Malmö Gatukontor was the largest beneficiary and other large beneficiaries were local governmental organisations in major Swedish cities such as Göteborg Stad Trafikkontoret, Skånetrafiken/Region Skåne and Miljöförvaltningen Stockholm.

In terms of ownership structure and market position, the situation for the Swedish heavy vehicle manufacturers was different from the car manufacturers. Both Volvo and Scania strengthened their positions as major players in the heavy vehicle industry and they were also much more active in the program. Volvo enjoyed support from the KFB program for development and field tests of their microturbine-based series hybrid concept in buses in two BL 10L City buses, which the municipal city bus operator Göteborgs Spårvägar operated in regular traffic in 1999-2000 (Rader-Olsson, 2000). Volvo had initiated the development of these vehicles in 1996. Low emissions of NO_x and PM (10 per cent of the prevailing Euro 2 requirements) were primary targets and the project had an ambition to share as many components as possible with Volvo's standard vehicles. Apart from Volvo Technology, ABB Hybrid Systems, Volvo Aero, Tudor AB (Swedish manufacturer of lead-acid batteries), Turbec AB (spin-off company focusing on stationary microturbine applications), Volvo Trucks and Säffle Karroseri AB (manufacturer of bus bodies) took part in the project (Andersson & Björler, 2000). However, as the buses equipped with the new power train technology were not as reliable as conventional buses the interest from Göteborg Spårvägar declined. Moreover, Volvo learned that it was difficult to show any gains in fuel efficiency compared to traditional internal combustion engine powered vehicles. Therefore they decided to spin off their venture in microturbine technology completely to Turbec AB in Malmö, with the aim of developing and commercialising this technology for stationary applications (small-scale distributed combined heat and power generation). Thus, the microturbine-based series power train concept, which Volvo originally presented in their environmental concept car ECC in 1992, never reached a commercial production stage. Only the exterior design of ECC survived. The heritage of this design was clearly distinguishable in Volvo's subsequent car models.

Volvo also ran field trials with a series-hybrid power train using a conventional ICE as an internal source of motive power. Two FL6 distribution trucks equipped with this power train were leased to and operated by TGM, a distribution company in Gothenburg. Since TGM made many inner city deliveries to underground cargo terminals, they particularly appreciated the ability to drive in an all-electric, zero emission modes.

Scania enjoyed indirect support from the KFB program via SL – Storstockholms Lokaltrafik, which is the municipal city bus operator in Stockholm. Scania's subsidiary the Danish Automobile Manufacturer – DAB in Silkeborg, a manufacturer of bus bodies and chassis, manufactured and delivered six buses to be used by SL. SL had been involved in tests of hybrid-electric buses already during the 1980s. The Scania-DAB bus was based on a series hybrid configuration with a small internal combustion engine (a SAAB 2.3 l turbo engine converted to run on ethanol). Atlas Copco supplied power electronics to the bus. A major objective for this project was to investigate and optimise the system control and management strategies for the bus hybrid power train (Blückert *et al.,* 2000).

7 Volvo had tested this configuration already during the late 1980s in a converted model 740.

Summary

During this period, global warming and climate change entered the political debate. Whereas the interest for battery-electric cars was reduced, the first hybrid cars entered the market. However sales were still very limited. Volvo was active in hybrid R&D, developing prototypes and conducting field tests but as large American manufacturers acquired the Swedish car manufacturers, they lost authority over strategic R&D decisions. On the other hand the Swedish heavy vehicle manufacturers Volvo AB and Scania still maintained control over R&D.

2.3 2000-2005: NEW CONFIGURATIONS AND RAISED FUEL PRICES

International governance and industry dynamics

On the global scene, the US refusal to ratify the Kyoto protocol stalled the process to convert the agreements into forceful governance mechanisms directed at relevant sectors such as the automotive industry. In addition, powerful car manufacturers had fought back the Californian ZEV regulation, forcing regulators to withdraw the proposed strict regulation on ZEV sales. With relatively stable oil prices, the automotive industry thus had limited incentives to invest in innovative but uncertain alternative power train technologies.

Still Toyota pursued their introduction of Prius and they were soon accompanied by Honda in the development and market introduction of hybrid-electric cars. Honda began to develop a simpler mild/parallel hybrid, shortly after Prius. In fact, since Toyota limited their initial hybrid sales to the domestic market, Honda was the first manufacturer to enter the American market, introducing their Insight about one year in advance of Toyota's introduction of Prius. With an aluminium body, a futuristic aerodynamic design and extensive use of lightweight materials, Hondas 2-seated hatchback offered superior fuel economy. Honda soon followed up this introduction with hybrid versions of their compact Civic and midsize sedan Accord. With its emphasis on acceleration and speed rather than fuel efficiency, the Honda Accord hybrid was different than Honda Civic and Toyota Prius, targeting a sporty high-end segment of the car market.

The American manufacturers' reactions to Toyota's and Honda's introduction of hybrid cars on the American market were mixed. William Ford, chairman of Ford Motor Company, declared in January 2000 that hybrids would account for 20 per cent of car sales in 2010 (Sperling, 2000). Patenting records also show that whereas Ford met the two Japanese contenders' introduction of hybrid cars with intensified R&D, GM was more sceptical initially. The third of the big three American manufacturers, Chrysler, hardly showed any activity at all (Figure 3).

Patenting records in Europe (EPO database) indicate that European car manufacturers were even more sceptical than the Americans (Figure 4).[8] Due to significantly higher fuel taxation, European car manufacturers had been exposed to high fuel prices on their home markets for several years. But instead of embracing hybrid technology, they seemed to focus on a corresponding, but technologically more conservative race, introducing more advanced and fuel efficient diesel engines. Being forced by stringent emissions legislation, these efforts were complemented by intense R&D efforts to reduce NO_x and PM emissions, e.g. by introducing particulate filters.

The heavy vehicle industry was even more exposed to demands to reduced diesel engine emissions. The stepwise raised demands on low NO_x and PM emissions in European (Euro) and American (EPA) regulation emerged as the major driver for R&D in the heavy vehicle industry. A lot of effort was put on developing and implementing a number of advanced exhaust gas treatment technologies (particulate filters, EGR – Exhaust Gas Recirculation, SCR – Selective Catalytic Reduction, etc.).

Initially the hybrid car sales on the American market were very limited. Annual sales during the years 2000-2003 were less than 40,000 cars. However in 2004 crude oil prices started to soar and this had a direct effect on the American fuel prices. This coincided with Toyota's release of the second generation of their hybrid car Prius, with a midsize body and more distinct design than its predecessor. The new Prius hatchback quickly turned into a symbol of the modern environmental car in the US (UBS 2007) and Toyota alone sold 88,000 hybrid cars on the US market in 2004. None of their competitors came close; neither Honda with their Insight, Civic and Accord hybrids, nor Ford which introduced a hybrid version of their Escape SUV in 2004.

Swedish governance and industry activities

During this period, all major car manufacturers had fuel cell R&D programs running and there was a firm belief that if the internal combustion engine eventually

8 While Nissan-Renault is present among the top 5, 85% of the group's patents were filed by Nissan (Japan) and only 15% by Renault (Europe).

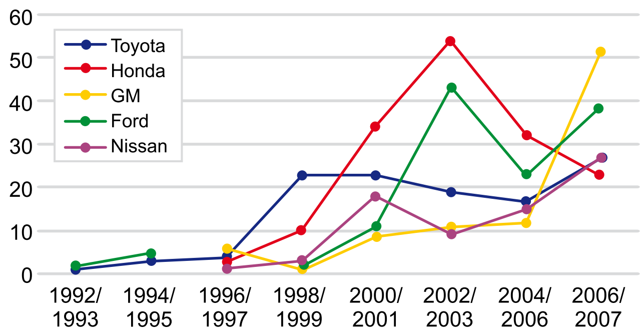

Figure 3: R&D activities in hybrid vehicle technology measured by US patenting – the 5 most active firms. Search includes patents that comprise the words "hybrid" (abstract) and "vehicle" (all fields) (Magnusson & Berggren, 2011)

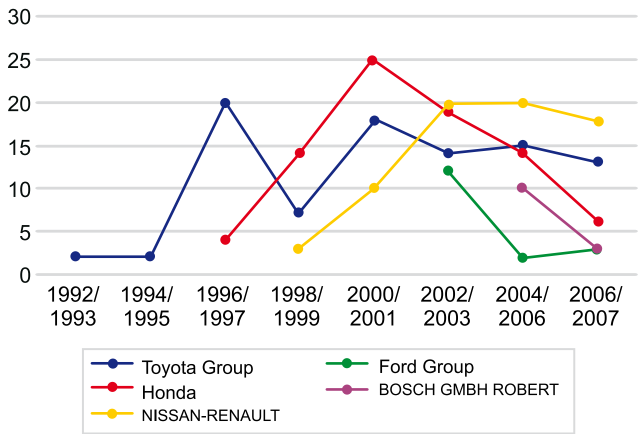

Figure 4: R&D activities in hybrid vehicle technology measured by EPO patenting – the 5 most active firms. Search includes all patents containing the words "hybrid" and "vehicle" (Magnusson & Berggren, 2011)

was to be replaced as a prime source of motive power in cars, it would be replaced by hydrogen fuel cell propulsion systems, not hybrids (or battery electric cars). The evaluation report for the Swedish KFB program underlines this, noting that:

> *Fuel cell technology has made such progress that many think that it could be commercially available even before 2005. If so, this technology will probably have several advantages over battery-electric cars. The implication of this is that the battery-electric car has lost its momentum. Some professionals consider the battery-electric car as a side-track and one can note a certain discouragement among the enthusiasts.*
>
> (Hedman et al 2000:17-18, author's translation).

The significance ascribed to fuel cell technology in the industry's visions of the future at this point in time can be illustrated by Volvo's decision to sell Volvo Cars. The argument posed was that the development and commercialisation of fuel cell technology would require extensive investments. Being a relatively small manufacturer, Volvo just could not bear these investments themselves. Hence, Volvo managers meant that access to resources for fuel cell R&D was one of the prime reasons for them to close the deal and sell off Volvo Cars to Ford in 1999.

The Swedish KFB program on electric and hybrid-electric vehicles engaged Professor Daniel Sperling from Institute of Transportation Studies at UC Davies, California, to conduct a retrospective review of the program and its outcomes. This served as a valuable input to the program evaluation. Professor Sperling concluded that, in hindsight, it seems as the program could have focused more strongly on hybrid technology and he also noted that the program probably had small short-term effects on the automotive industry. However, he could envision possible long term effects, especially in the field of hybrid technology:

> *While the impact has been minimal – so far – it is plausible that KFB's efforts might someday lead to something big. It may be that KFB's support for hybrid trucks and buses has helped Scania and Volvo maintain and even strengthen their interests in hybrid technology.*
>
> (Sperling, 2000:52)

One of the prime conclusions from the program evaluation was that future programs should be designed and executed in close consultation and collaboration with the automotive industry. This was also emphasized in the Green car program, which commenced in 2000. The aim of this initiative was to develop more environmentally benign vehicle technology through directed R&D efforts. The new technology developed should be possible to integrate in future products and thereby provide improved environmental performance and improved competitiveness. The program was based on a joint agreement between the Swedish state and the Swedish automotive manufacturers Volvo Trucks, Volvo Car, Scania CV and Saab Automobile. The contract stipulated that also Swedish suppliers should have access to research funding through the program. The Swedish Governmental Agency for Innovation Systems administrated the initiative under the program board for automotive research (PFF) umbrella. The budget for the program was in total 1 816 mkr, whereof 545 mkr from the state. 45 mkr of these 545 mkr was dedicated to fuel cell and hybrid technology.[9] The program ran until 2007 (Faguert *et al.,* 2007).

In the heavy vehicle sector, Volvo Powertrain initiated the development of a full parallel hybrid, in which they combined a traditional diesel engine with an electric motor. Volvo argued that while the series hybrid may offer benefits in a very limited number of applications (e.g. city bus operation with frequent start-stop), the parallel hybrid was the most versatile solution, offering a lower unit cost and superior fuel efficiency in a broad range of applications. They implemented this power train concept in prototype trucks, running field tests and demonstrations for selected customers.

Scania's Danish subsidiary DAB started developing a series-hybrid concept bus in 2004 as a highly autonomous venture (Overgaard & Folkesson, 2007). In the beginning the project team was small, with a broad responsibility to develop the concept, developing competence, and also convincing other Scania people/divisions about the project. They selected a series-hybrid power train configuration with a diesel engine and super capacitors to serve as an electric power buffer with good capacity to absorb energy from regenerative braking. Compared to parallel or complex hybrid configurations, engineers have a greater freedom designing the layout of the chassis and body of a series hybrid bus. This is because the series hybrid does not require a mechanical link between the internal combustion engine and the drive axle. Scania's engineers benefitted from this, integrating the power train into a separate module, allowing for a fully-flat low floor design of the passenger module.

The refuse and recycling company Renova took another noteworthy initiative in 2002 (Boss, 2005). When a refuse truck stops to collect wastes, the combustion engine is kept running. This is because the power is needed to lift the waste into the truck and to compact it. Consequently, the truck idles for a considerable amount of time when the workers collect refuse bins, emitting pollutants without doing any work. The collection is often also considered noisy by people in the vicinity. Together with Volvo, Norba (lifting and compacting equipment manufacturer) and ETP (electric equipment retailer), Renova therefore started to develop a refuse truck with all-electric loading and compactor equipment. The vehicle was equipped with sufficient battery capacity for the loading and compacting, allowing the engine to be automatically shut down as the vehicle was stopped. By using this vehicle Renova could reduce air emissions and noise pollution in the vicinity of the collection site. By 2004 Renova operated 15 such gas-electric hybrid refuse trucks in the central parts of Gothenburg. Ten of these were included in a project that received subsidies from the European Union fund LIFE.

Summary

On the international scene, this period was characterized by increased R&D efforts in the hybrid technology field, with several car manufacturers showing activity. Following raised fuel prices, hybrid sales also took off on the US market by the end of the period. While the activities among the Swedish vehicle manufacturers appear less official during this period, some R&D activities were still maintained, partly supported by the state funded R&D programs.

9 According to a program evaluation report, about 2/3 of these funds (i.e. about 30 MSEK) were spent on hybrid R&D and 1/3 of the funds were spent on fuel cell R&D (Persson *et al.,* 2003).

2.4 2005-2010: IPCC, MARKET AMBITIONS AND FINANCIAL CRISIS

International governance and industry dynamics

The international debate on global warming and the serious effects of increased percentages of greenhouse gases in the atmosphere revived and escalated during this period. Several interrelated factors facilitated this development. Among these were the hurricane Katrina that hit New Orleans in August 2005, causing death and destruction, and serving as an alarm clock for the American debate. In the aftermath of this came the initiatives of the former US presidential candidate Al Gore, who filled movie theatres around the world with the film version of his slide show "An inconvenient truth". Another influential event was the Stern Review on the Economics of Climate Change. The British government originally ordered this scientific review, assigning the task to the British economist Nicholas Stern. Released in 2006, the Stern Review convincingly argued for the economic sense in a strong policy for CO_2-reduction (Stern, 2006). This drew extra attention to the work of the Intergovernmental Panel on Climate Change – IPCC, which had been initiated by the United Nations already in the 1990s. IPCC released its fourth assessment report in 2007, a report that further underlined the scale of the Global Warming problem and pointed at the urgency to initiate action to mitigate climate change.

At this stage it was clear that the European policy relying on long-term goals and voluntary agreements on maximum CO_2 emissions from new cars had not been effective. In 2007, the European Commission therefore initiated a more forceful policy. They proposed a directive stipulating that new cars in average should emit a maximum of 130 gram CO_2 per km by 2012 according to EU's test cycle (Kågesson, 2007). The directive would follow a similar structure as the US CAFE standards (Corporate Average Fuel Economy), which had been first enacted by the American Congress already in 1973 (Sperling & Gordon, 2009). According to the CAFE standards, the average fuel efficiency of cars sold by each manufacturer on the US market was controlled and fines were imposed on those that did not reach stipulated limits. The European Commission also signaled ambitions to strengthen the CO_2 emission requirements to maximum 95 g/km by 2020. Referring to interviews with representatives from car manufacturers, Kågesson (2007) noted that hybrid technology (full hybrids and plug-in hybrids) would be the most promising technology alternatives to reach the required CO_2 emission reductions. By the late 2000s, several European countries also implemented governmental subsidies and tax reductions to support the purchase of cars with low CO_2 emissions.

The oil price continued to climb, reaching all time high in early 2008, with a price level approaching $140 a barrel. Being faced by stiff competition from fuel-efficient diesel cars, European hybrid sales were however still limited. With less than 50,000 cars sold in 2006, hybrid-electric vehicles did not even reach 0,2 per cent of the market. Being supported by first-tier suppliers with relevant capabilities and optimistic projections, several European manufacturers also equipped their diesels with micro-hybrid (start-stop) systems pushing down fuel consumption further and making them competitive with gasoline fuelled full hybrids in terms of fuel efficiency.[10]

The soaring fuel prices made American car buyers turn attention to fuel efficiency in general and to hybrid cars in particular. 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). While Toyota Prius completely dominated the hybrid segment, the sales growth attracted several new entries. On the auto show in Detroit in January 2008, all major car manufacturers displayed hybrid models, either as ready to launch or in more conceptual stage. Amongst others, this included GM, introducing hybrid versions of existing pick-ups, SUVs and mid-size sedans and Nissan introducing a hybrid version of their mid-size Altima model. Figure 5 displays hybrid car sales on the US market 2001-2009.

The Japanese heavy vehicle manufacturers followed suit, and several Japanese firms, from Nissan Diesel to Mitsubishi and Hino, launched light-duty trucks equipped with hybrid power trains. American heavy vehicle manufacturers, such as Paccar and International also announced hybrid plans. So did European manufacturers. Mercedes-Benz, for example, demonstrated the Axor BlueTech hybrid medium truck in the 2008 IAA International Commercial Vehicles show in Hanover, announcing customer trials during 2009.

10 Whereas only 54,000 cars were equipped with this system in 2007 (of these 53,350 were sold in Europe), 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.

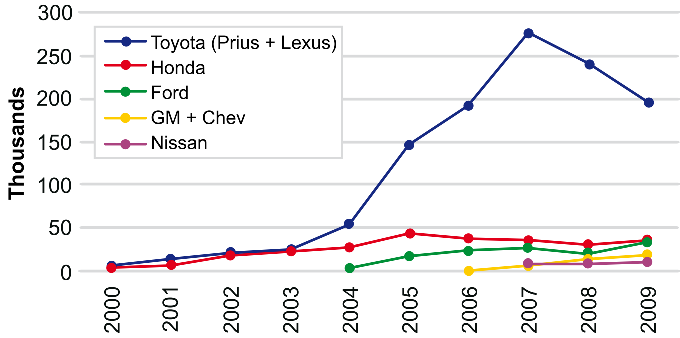

Figure 5: Number of hybrid cars sold on the US market 2001-2009

In an effort to take the lead in hybrid car development, GM presented plans to produce and sell plug-in hybrids by 2010, only to be followed by Toyota announcing plans to be faster to the market than GM. Toyota also introduced several hybrid versions of existing cars, amongst others a couple of Lexus models[11], and a hybrid version of the midsize Camry, the top selling car on the American market. Ford followed up the introduction of the Escape SUV, introducing two additional SUVs with Mazda and Mercury brands. Haunted by financial problems, however, they were unable to keep up the pace and it took until 2009 before they released their next hybrid model, a hybrid version of the midsize sedan Ford Fusion.

Following poor initial sales, Honda went in an opposite direction, discontinuing production of their Insight and Accord hybrids 2006-07, and restricting their offerings to hybrid versions of Civic. A few years later though, Honda revived their dedicated hybrid brand introducing the new Insight in 2009. In terms of size, body type and styling, this car was quite similar to Toyota Prius, and it was offered at a lower price.

Honda's re-introduction of Insight with a new styling and package attracted a lot of attention to hybrids, especially on the domestic market. Supported by governmental subsidies for so called "Next generation vehicles"[12], it became the top selling car (all categories) in Japan during the month that it was introduced, only to be surpassed by the 3rd generation of Prius that Toyota introduced shortly thereafter. At this moment, financial crisis had seriously struck the car market. According to business press, US car sales dropped 18 per cent from 2007 to 2008 (Krebs and Visinic, 2009) and this rate of sales reduction continued all through 2009. In late 2008, following the collapse of their most profitable segments and a general downturn in the domestic market, the American car manufacturers 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 American manufacturers finally had started investing in hybrids, oil prices were falling sharply, which reduced consumer interest in alternatives to conventional vehicles.

The financial crisis also affected vehicle sales on the European and Japanese markets significantly. To stimulate car sales and thus save the car manufacturers from bankruptcy, governments in several European countries as well as in Japan implemented extensive financial support programs, so called scrappage programs. These programs provided financial support for people who scrapped their old cars in order to buy new ones with lower CO_2 emissions.[13] Several countries also implemented separate subsidy programs for the purchase of cars with low CO_2 emissions. The European investment bank and several national banks also offered extensive state secured loans to ensure that the vehicle manufacturers would pass the immediate crisis.[14]

Following the financial crisis GM and Ford announced plans to sell off their Swedish subsidiaries in an attempt to rescue their domestic operations. In 2010, after several rounds of buyers and bids, GM announced that that Dutch Spyker Cars would take

11 Lexus is Toyota's premium brand.

12 Hybrids, electric cars, fuel cell cars and clean diesels were classified as "Next generation vehicles" according to the Japanese definition.

13 In total 17 European countries implemented such programs. Notable exceptions were Poland, the Czech Republic and Sweden. Different countries imposed different requirements on CO_2 emission levels.

14 According to the head of the car section at the European commission, the sum of these loans was approximately 34-36 billion Euro.

over Saab Automobile's operations and the Chinese car manufacturer Geely acquired Volvo Cars from Ford.

Swedish governance and industry activities

In 2005 the Swedish government started implementing regulation (2004:1364) to stimulate market development and diffusion of hybrid cars and other "environmental cars" through public procurement. The regulation stipulated that at least 50 per cent of new cars purchased or leased by public authorities should be cars using electric or hybrid-electric propulsion or alternative fuels such as ethanol or gases other than liquefied petroleum gas (LPG). They also assigned the Swedish Road Administration authority to further elaborate a definition of environmental cars.

The emerging hype on hybrids was also reflected in Swedish Automotive R&D policy. An extension of the Green car program was announced an in 2006. This extension had a much heavier focus on hybrid technology than the original program. The aim of Green car 2 was to support the Swedish development of more environmentally benign vehicle technology, with the ambition to promote long-term growth and competitiveness for the Swedish vehicle industry. The program stipulated that it is possible to speed up the transition to environmentally sustainable road traffic system through the development of vehicles and vehicle components with better environmental performance. An agreement was signed between the Swedish state and the Swedish automotive manufacturers Volvo Trucks, Volvo Cars, Scania and Saab Automobile in 2006. The budget for the program was in total 804 MSEK, whereof 282 MSEK from the state. The program included research in combustion engines and hybrid power trains, as well as alternative fuel vehicles and measures for improved energy efficiency (e.g. weight reduction and auxiliary equipment). The distribution between different kinds of technologies was not stipulated in advance, but in the end 105 MSEK of the 282 MSEK state funds was awarded to hybrid-related projects.

The new definition of "environmental cars" that the Swedish Road Administration put forward in 2006 focused on emissions rather than power train technologies, stipulating a CO_2 emission limit of 120 g/km for environmental cars using gasoline or diesel fuels. Implemented in 2007, the new definition was complemented by a governmental subsidy of 10 000 SEK that came with the purchase of a new environmental car, as well as advantageous company car taxation terms and free parking in several cities. The 10 000 SEK governmental subsidy ceased in July 2009, being replaced by a tax reduction scheme for "environmental cars".

In 2007, the Swedish Energy Agency STEM initiated a particular program for hybrid vehicle research. The program would also include projects on fuel cell vehicles, energy efficient conventional vehicles and lightweight/aerodynamic vehicle designs. However it was preceded by an evaluation of STEM's transport research funding that suggested a greater emphasis hybrid vehicle R&D funding. Therefore focus was set on hybrid vehicle technology. Between 2007-02-14 and 2008-02-11, the program decided on funding 72 different projects. In total these projects have budgets on 1134 MSEK, whereof 343 are funded by the Swedish Energy Agency. The program supported both university and industry projects. It filled out a funding gap between the Green car 2 program, which ceased in 2008, and the a new private-public partnership called Strategic Vehicle Research and Innovation (FFI) that was established in 2009.

Another step was taken in 2007 through the establishment of the Swedish Hybrid Vehicle Center (SHC), a Center of Excellence financed by the Swedish Energy Agency (STEM) with Swedish universities and industrial companies as partners (SHC, 2007). Chalmers University of Technology in Gothenburg was selected as host. The stated mission was to be a strategic knowledge and competence base for education, research and development within hybrid electric vehicle technology, and to form a framework for cooperation between industry and academia. Focus of the research was on a systems perspective, emphasizing on integration of and interaction between components and subsystems, but work was to be divided into three thematic areas: System studies and tools, Electrical machines and drives, Energy storage. The initiative was meant to be a 10-year commitment by the partners, with a first phase extending over a 4-year period. Initially, the SHC partners were: the Swedish Energy Agency, AB Volvo, Scania CV AB, Saab Automobile AB/GM Powertrain Sweden AB, Volvo Car Corporation AB, BAE Systems Hägglunds AB, Chalmers University of Technology, Royal Institute of Technology (KTH), and Lund University (LTH). The program statement stated an ambition to involve additional members at a later stage to cover important areas such as the electric power industry and infrastructure. The ambition was also to gradually involve suppliers.

The increased level of R&D support for hybrid technology appears well in line with a few important initiatives by the Swedish heavy vehicle manufacturers.

In 2006, Volvo's CEO Leif Johansson publically announced that they would develop their parallel hybrid power train concept further, aiming for market introduction of a hybrid truck in late 2009. Moreover, Volvo shortly signalled forthcoming introductions of a hybrid bus and a hybrid wheel loader. The Volvo engineers opted for a full hybrid configuration in which they integrated the electric motor/generator within the diesel engine and an automatic gearbox. The battery would be based on Li-ion technology. They called the hybrid package I-SAM (Integrated Starter, Alternator, Motor). Volvo expected that it could reduce fuel consumption by up to 20 per cent in refuse truck applications, 15-20 per cent in distribution truck applications and up to 30 per cent in inner-city bus applications.

During an interview, a group manager at Volvo Powertrain explained that the decision to develop a hybrid truck differed very much from standard practice at Volvo. Normally, a development project would be initiated as a result of explicit demands from customers or regulation. However, in this case there were no such demands. Instead the demands came from the company top management. According to a senior manager, this caused turbulence in the organisation. The reason for this was that medium level product managers, who normally would order a development project, found it difficult to justify the development project based on the estimated demand.

Field trials with selected customers were an important part of Volvo's development. In 2008 the refuse and recycling companies Renova and Ragn-Sells started operating Volvo hybrid trucks. In December 2008 Volvo announced that they would deliver four refuse trucks with hybrid power trains to Veolia Propreté, one of the world's largest companies in refuse handling, commencing operations in France and England during the subsequent autumn. In April 2009 Volvo initiated field tests of hybrid city buses in collaboration with Göteborgs spårvägar and in June 2009, they announced that six Volvo double deck hybrid buses had been delivered to Arriva London for field trials in inner-city London. The project got support from Transport of London. Volvo postponed their plans to introduce the hybrid truck to the market by 2009, though they maintained their plans to make the hybrid bus commercially available by April 2010. In 2010, Volvo initiated series production and sales on a commercial basis, receiving orders for about 200 hybrid buses during this year (Volvo, 2010).

In 2007, Scania displayed their series-hybrid concept bus at the UITP Mobility & City Transport Exhibition in Helsinki. They also transferred the series-hybrid bus development to their main R&D facility in Södertälje, aiming for market introduction by 2012. Around 2007 Scania also initiated a less public development of a parallel hybrid truck. In competition with other heavy vehicle manufacturers Scania aimed at supplying hybrid buses to be used during the London Olympics in 2012. Scania initiated field trials of 6 series-hybrid bus prototypes in 2009. This was done in collaboration with SL, the regional public transport company in Stockholm. Scania announced that the tests would run for at least one year. Following the effects of the financial crisis 2008-2009, the plans to introduce the series-hybrid bus to the market by 2012 were however put on hold.

Being seriously affected by the market downturn, their own heavy losses and their American owners' precarious financial situation, the Swedish car manufacturers were not as active in the development of full hybrids as their heavy vehicle counterparts. Still, Saab Automobile reports to have been running a number of field tests of various hybrid power train configurations in converted standard cars. In 2006, they also publically displayed a converted 9-3 using a power-split hybrid configuration, a result of collaborative R&D and prototyping efforts with electric machine experts at Lund University. Saab subsequently also showed a concept car using the 2-mode parallel hybrid transmission developed by GM. They also announced that they were working on plug-in hybrid technology in collaboration with Volvo Cars.

Following the acquisition by Ford, hybrid R&D at Volvo Cars had been reduced. However, following Ford's market introduction of the Escape hybrid discussions were initiated in 2004 at Volvo Cars to develop and introduce a Volvo hybrid car and in 2006, Ford's executive management decided to locate a European hybrid R&D centre at Volvo Cars in Gothenburg, with intentions to develop and launch a Volvo hybrid car. Volvo engineers also made an attempt to fit the Ford Escape power-split hybrid to a Volvo platform. However, the idea to develop a Volvo hybrid car for the market was not realised. Still, in 2007 Volvo Cars presented a plug-in hybrid concept called ReCharge. At this stage however, as a result of corporate financial crises and consecutive plans to sell off Volvo Cars, Ford's executive management withdrew Volvo's hybrid technology R&D funds.

Volvo Cars redirected their product strategy towards fuel efficiency by the end of the 2000s period, releasing several car models with fuel-efficient diesel engines under the new "Drive" brand in 2008-09. Three of the

Drive car models (C30, S40 and V50) were equipped with micro-hybrid systems. This pushed down their CO_2 emissions below 105 g/km, something that, amongst others, qualified these cars for significant governmental subsidies in Belgium (15 per cent discount of the purchase price). At the beginning of 2010, the Drive models constituted 30 per cent of Volvo Car's total sales on the European market. In 2009, Volvo Cars also announced ambitions to start producing a plug-in hybrid with a diesel engine by 2012. However, they also noted that it would be difficult to sell any plug-in hybrids without significant subsidies since the added cost for batteries and electric propulsion systems would be prohibitive. Volvo undertook the development in a joint venture with the Swedish electric utility and network operator Vattenfall, initiating field trials with three converted V70 models in 2009.

Summary

This was a period of significantly raised activity among the Swedish vehicle manufacturers. The demand for hybrid cars soared on the American market due to raised fuel prices, public debates on global warming and an expanding market segment of environmentally concerned car buyers. Volvo made a move to become a leader in hybrid technology in the heavy vehicle segment and Volvo Cars responded to demands on reduced fuel consumption, introducing fuel efficient engine alternatives equipped with micro hybrid systems. Also Scania geared up their efforts in hybrid R&D. But by the end of the period the financial crisis struck the automotive manufacturers hard, resulting in significant industrial turbulence.

3 SWEDISH HYBRID TIS FUNCTIONALITY 1990-2010

This chapter assesses how the functionality of the Swedish hybrid-electric vehicle technological innovation system evolved 1990-2010, using six critical sub-processes (Hekkert *et al.,* 2007; Bergek *et al.,* 2008; Hillman *et al.,* 2011):

1. **Knowledge development and diffusion**: The generation of breadth and depth of the knowledge base of the TIS, and the diffusion and combination of knowledge, taking into account different types of knowledge (e.g. scientific, applied, patents) from different sources.

2. **Influence on direction of search**: The existence of incentives and/or pressures for actors to enter the TIS, and to direct their activities towards certain parts within the TIS (e.g. technologies, applications, or markets).

3. **Entrepreneurial experimentation**: The probing into new technologies and applications, unfolding a social learning process reducing uncertainty.

4. **Market formation**: The timing, size and type of markets that have actually formed.

5. **Legitimation**: The social acceptance and compliance with relevant institutions: the new technology and its proponents need to be considered appropriate and desirable by relevant actors in different parts of the TIS to acquire political strength.

6. **Resource mobilization**: The mobilization of competence/human capital through education in specific scientific and technological fields as well as in entrepreneurship, management and finance, financial capital (seed and venture capital, diversifying firms, etc.).

The chapter further analyses how governance arrangements on different levels (i.e. local, regional, national, international) have affected the functionality of the innovation system during this time period. To investigate how governance may affect TIS functionality, the analysis relies on means-to-ends separation of governance from functions. Whereas TIS functionality is the dependent variable, the specific mix of governance arrangements is the independent variable. The chapter is divided in sections according to the six sub-processes, as outlined above.

Each section contains three parts: The first part contains description and motivation of the indicators used to assess functionality (Appendix 2 presents a compilation of the selected TIS-functionality indicators). The second part assesses TIS-functionality (Appendix 3 presents a summary of whole assessment) and the third part analyses the effect of various governance arrangements on the TIS-functionality.

Appendix 4 presents a compilation of governance arrangements that have been mentioned in the empirical studies and Appendix 5 presents a coding of these arrangements. The coding follows a scheme which is based on a framework presented in Hillman et al (2011). It includes a classification of the identified governance arrangements according to the following dimensions:

- Which spatial level it is implemented on (Local, National/state, EU/federal or Global).

- The degree of involvement from private actors/industry (low/little, moderate or high involvement).

- The primary mechanism involved: *Regulative* (operating through coercion and hierarchical control, setting absolute limits), *Market* (modifying the economic incentives of market actors), *Cognitive* (developing consensual knowledge around a problem and its suggested solutions) or *Normative* (developing values and beliefs about 'what is good for the society').

- If the arrangement is aimed at the demand side ('market pull'), or the supply side ('technology push') of the innovation system.

- If the arrangement is directed to automotive technology in general, specifically to hybrid-electric vehicle technology or to particular hybrid technology subsystems.

- Which TIS sub-processes the governance arrangement address (i.e. Knowledge development and diffusion, Influence on direction of search, Entrepreneurial experimentation, Market formation, Legitimation, Resource mobilization).

3.1 KNOWLEDGE DEVELOPMENT AND DIFFUSION

Functionality indicators

Knowledge development and diffusion is about generation of breadth and depth of the knowledge base, and the diffusion and combination of knowledge, taking into account different types of knowledge from different sources. As discussed in the introductory section, the hybrid power train comprises several interacting sub-systems and components, which build upon a number of disparate fields of engineering knowledge. Requirements in terms of drivability, performance, fuel efficiency, safety, reliability and, not the least, cost put heavy restrictions onto the development. Hybrid-electric vehicle R&D is thus very much about systems integration. Vehicle manufacturers' abilities to operate as systems integrators hinge on a critical balance between system level architectural knowledge and component-specific knowledge (Takeichi, 2002). A well functioning hybrid electric vehicle TIS has to support R&D activities in order to develop this product-related technological knowledge.

Moreover, cost reduction in the vehicle industry to a large extent depends upon production volumes. This is because increased production volumes result in organizational learning and economies of scale. Both individual vehicle manufacturers' and suppliers' in-house operations and complete industrial supply chains become more effective through these learning processes. Technological and organizational knowledge related to production is therefore an essential part of the required knowledge base in a well-functioning hybrid-electric vehicle TIS.

Another relevant instance of knowledge is related to the interface between the vehicle and the market. Clark & Fujimoto (1991) describes this in terms of external product integrity, i.e. the fit between the function, structure and semantics of the vehicle and the customer's objectives, values, production system, lifestyle, use pattern, and self identity. 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 vehicles technologies stand a better chance of gaining public acceptance if they are compatible with the daily routines of the users. However early experiences of the introduction of hybrid-electric cars on the American market indicate that this may not be sufficient. To attract attention and justify a premium price it appears as these products also need to stand out; not different in terms of user behaviour but clearly distinguishable in package and style (Magnusson & Berggren, 2011). While these observations refer to the introduction of hybrid-electric cars on the American market, different rules will most likely apply to different geographical markets (such as Europe) and in different product applications (such as heavy vehicles).

Consequently one may discern three aspects of knowledge which are essential for a well functioning hybrid-electric vehicle TIS. The first is product-related technological knowledge (component and architectural knowledge) emanating from R&D activities. Patents can in many cases be considered a useful indicator of R&D activities (Holmén and Jacobsson 2000). However it cannot be used as a sole indicator of product-related technological knowledge and comparisons are difficult as different firms have different patenting strategies.[15] Patenting propensity also differ across industries.[16] Hence the assessment will complement patent data with information on reported R&D activities as well as demonstrations of functioning products through prototypes and field tests. The second aspect of relevant knowledge is technological and organizational knowledge related to production. To indicate this, the assessment will use vehicles available for purchase and accumulated production volumes as indicators. The third aspect is knowledge related to the interface between the vehicle and the market. Executed field trials with users and actual sales will be used as indicators of this aspect of knowledge.

Functionality assessment

The functionality assessment thus starts by assessing product related technological knowledge development, as measured by patents, prototypes and field trials. Patenting records indicate that no specific car manufacturer had a particular lead in hybrid R&D until the mid 1990s (Figures 3 and 4 on p 14). At this stage, Toyota and shortly thereafter Honda started patenting much more actively. This coincides with the start of these manufacturers' development efforts aiming for market introduction by the late 1990s. Just like other

15 The graphs in Figures 3 and 4 on p 14 illustrate this. While Toyota can be considered as an undisputed leader in hybrid vehicle technology, Toyota has only occasionally been a leader in terms of patenting.

16 Patenting is more prevalent in the car industry than in the heavy vehicle industry. This means that it is not useful to compare the patenting of car manufacturers and heavy vehicle manufacturers. The limited number of patents in the heavy vehicle industry also delimits the viability of using patents as an indicator of R&D activity in this industry sector.

European car manufacturers, the Swedish vehicle manufacturers are largely absent in these records, signaling a relatively low degree of R&D activity by comparison to their Japanese contenders. This holds true also during the 2000s when the large American manufacturers Ford and GM (a few years later) started patenting more aggressively. Some Volvo activities can be discerned, but by comparison to their owner Ford, Volvo Cars' hybrid R&D appears marginal. According to the American database USPTO, Volvo Cars took four hybrid vehicle patents 1990-2008 (all of these were filed after 1999). This can be compared to 156 patents by Ford during the same period. Patenting records thus illustrate Ford's decision to centralize the group's hybrid technology R&D efforts after their acquisition of Volvo Cars. From a Swedish perspective it is also worth noting that Saab Automobile does not appear at all in these patenting records.

On the international scene, Toyota and Honda took the lead during the early 2000s, pioneering the market introduction of hybrid cars. The significantly raised sales figures for Prius on the US market 2004-2008 served to reinforce Toyota's lead. Several additional car manufacturers introduced hybrid cars during the late 2000s, but by the end of the decade no other car manufacturer came even close to Toyota in terms of accumulated production volumes. Honda appeared to have consolidated their position as an obvious runner-up in the hybrid segment. American and European car manufacturers (including the Swedish ones) were left behind. Their reluctance to enter the market prohibited learning from production and marketing of hybrid cars (see further 3.4 Market formation).

Being supported by first-tier suppliers such as Bosch and Valeo, European manufacturers instead emerged as front runners in the implementation of micro-hybrid systems during the late 2000s. Volvo Cars was by no means first to enter the market as they introduced micro-hybrid systems in three of their Drive models 2008-09. Still, with this fuel efficient product line they appeared well in line with their European competitors and with a positive response from the market (see 3.4 Market formation) sales and production volumes rose steeply since the market introduction. In this case, Volvo Cars benefitted from the extensive experience of first-tier supplier Bosch, both in terms of product and production related knowledge.

The Swedish heavy vehicle manufacturers were active during the late 1990s, as well as in the late 2000s, running several field tests and demonstrations of hybrid buses and trucks. These tests represent significant milestones for the Swedish hybrid-electric vehicle TIS in terms of development and diffusion of both product-related technological knowledge and knowledge related to the product-market interface. Amongst others, experiences from the tests in the late 1990s made Volvo finally abandon their micro turbine based hybrid in favor of ICE-based configurations (see further 3.3 Entrepreneurial experimentations). During interviews, respondents from Scania also emphasized the importance of field tests for their knowledge development, both in terms of technological possibilities and limitations, and in terms of learning how users perceive the new technology.

The heavy vehicle industry differs from the car industry in that no particular manufacturer emerged as an obvious leader in hybrid R&D and production. While a few Japanese manufacturers introduced products in the light-duty segment, several manufacturers (including the Swedish ones) aspired to take leading positions in the heavier segments. Judging from their official plans to introduce hybrid buses and trucks, Volvo appeared to be well positioned in the international competition. With a product portfolio more focused on long-haulage trucks, hybrid technology may not seem as urgent for Scania, something that may explain a more restrictive strategy. This may also explain their focused R&D efforts developing a dedicated series hybrid power train for inner-city bus applications.

Consequently, information on reported R&D activities as well as demonstrations of functioning products through prototypes and field tests show that a certain level of product related technological knowledge has been created and sustained within the Swedish hybrid-electric TIS 1990-2010. The varying intensity of reported R&D activities and demonstrations of functioning products naturally affected the level of knowledge generated in the system. In particular, one may discern a decline during the early 2000s and a recovery during the mid and late 2000s. Moreover, the heavy vehicle manufacturers' decisions to initiate product development aiming for market introduction during the late 2000s, and the consecutive field trials with customers also initiated some production and market related knowledge generation in this sector. Still, by the end of 2010, apart from Volvo Cars' Drive micro hybrids, no significant volumes had been produced. This severely restricted the generation of production and market related knowledge in the Swedish hybrid-electric TIS.

Influence of governance

Several sources underline the importance of the state funded R&D and demonstration programs for knowledge development and diffusion of hybrid vehicle technology in Sweden. During an interview a senior manager at Volvo explained that the financial support from the KFB electric and hybrid-electric vehicle demonstration program was a prerequisite to justify Volvo's hybrid heavy vehicle field trials in the late 1990s. He recalls that it was possible attain internal funding that would cover about half of the required budget. The other half had to come from external sources. Otherwise Volvo's senior management would not have passed the project.

A general evaluation of the effects of state funded R&D programs directed at the Swedish automotive industry since the early 1990s provide additional support for the positive effects of these R&D programs (Faguert *et al.,* 2009). The report specifically points at positive effects in a few areas, and hybrid-electric vehicle technology is one of these. According to the report, state funded R&D support was decisive for Volvo's ability to maintain hybrid technology knowledge when Ford acquired Volvo's car division in the late 1990s (Faguert *et al.,* 2009:140, author's translation):

> *One case in which ffp was of great importance was the hybrid efforts at Volvo Technology, comprising about 10-15 people. In this case, ffp projects in combination with EU-projects constituted a means to retain the hybrid competence within Volvo Technology and keep it from being part of the sales of Volvo Cars in 1999 until the Green Car program started in 2001.*

Referring to the Green Car programs during the early and mid 2000s, a technology manager at Volvo Cars claimed that dedicated governmental funding in many cases was a prerequisite to justify long term development efforts directed at fuel efficiency. At this stage (i.e. early and mid 2000s) it seemed as if demands on fuel efficiency were not sufficiently explicit, at least not in the customer segments that Volvo Cars aimed for. Under such circumstances, the only way of justifying R&D efforts addressing fuel efficiency was to have dedicated funding from external sources (see further 3.5 Legitimation).

The establishment of the Swedish Hybrid Center in 2007, supported by STEM, signals another step in the ambition in technological knowledge development, connecting academic researchers within relevant fields of knowledge to the vehicle manufacturers. While it is difficult at this stage to assess any results of this effort, this initiative may illustrate an insight that a deeper component-specific knowledge is necessary to build a sufficient level of integrative knowledge. This knowledge is required to move from a stage of limited field trials to the development of vehicles intended for sales on a commercial basis. The Swedish vehicle manufacturers did not possess sufficient resources to develop this knowledge individually all by themselves. Collaboration between vehicle manufacturers and academic research was put forward as a means to overcome this problem (see further 3.6 Resource mobilization).

Consequently it seems as if state funded R&D and demonstration programs filled a role to develop and maintain a certain level of knowledge in the Swedish hybrid-electric vehicle TIS. In particular, these programs have been valuable to mobilize engineering resources (see section 3.6 Resource mobilization) during periods when the automotive manufacturers experienced relatively weak motives to invest in hybrid R&D and when it was difficult for them to justify such efforts internally. Hence, these programs occasionally served to compensate for a low legitimacy in the innovation system (see section 3.5 Legitimation). However, this only applies to certain aspects of knowledge development and diffusion. The state funded R&D and demonstration programs have been important to support pre-commercial technology development. They have also supported field trials with users, particularly in the case of heavy vehicles. This has helped vehicle manufacturers developing product-related technological knowledge. It has also helped heavy vehicle manufacturers to understand user requirements and behaviors, i.e. knowledge related to the product-market interface. Altogether, this has reduced their take-off distance for initiation of product development projects directed at commercialization. However, while the KFB program during the 1990s dedicated a share of the total budget to social science research, addressing issues such as market developments for electric and hybrid-electric vehicles and the role of such vehicles in the society, R&D funding programs during the 2000s have been largely techno-centric.

3.2 INFLUENCE ON DIRECTION OF SEARCH

Functionality indicators

Influence on direction of search is about incentives and/or pressures for actors to enter the TIS, and to direct their activities towards certain parts within the TIS (e.g. technologies, applications, or markets). The automotive industry is very public, attracting a lot of interest from media. Each year vehicle manufacturers worldwide present their visions about the future. These are often materialized in concept vehicles which are displayed auto shows. The display of a concept vehicle at an auto show constitutes a weak indicator of knowledge development.[17] However, it is useful as an indicator of a vehicle manufacturer's long-term direction in terms of technology and product strategy. In some cases concept vehicles are associated with production plans, signalling an imminent market launch. In other cases car manufacturers merely use concepts vehicles as means to probe the future, to show their position vis-à-vis competitors and to test how customers and other market actors react to new ideas before having to invest heavily in testing, industrialization and production capabilities (Backman, 2005).[18] Therefore, it is necessary to include the vehicle manufacturers' public announcements, such as official project plans and specific targets (e.g. plans for market launch and production volumes) in the set of indicators.

Functionality assessment

Responding to raised demands on low emission vehicles, Volvo's display of their Environmental Concept Car ECC in 1992 represents an early milestone in terms of Influence on direction of search. By comparison to a traditional ICE-based power train, the microturbine based series-hybrid offered clear advantages in terms of reduced emissions of Nitric Oxides (NO_x), Particulate Matter (PM) and Hydrocarbons (HC). These substances are directly related to urban air quality problems, which was a very important issue for vehicle manufacturers during the early 1990s. The positive reactions that Volvo got encouraged them to engage in further development of the microturbine based series-hybrid, developing heavy concept vehicles (a truck and a bus) based on similar technological concepts in the mid 1990s, and also to proceed to a stage of field trials. However, it is important to note that these vehicles never were intended for production. By the late 1990s, Volvo abandoned the microturbine based series-hybrid. As noted in the previous section (3.1.2 Functionality assessment), this decision can partly be explained by lessons gained from field trials. However, the weakened Californian ZEV-regulation as well as incremental improvements of traditional engine technologies and emission reductions through wide-spread implementation of catalytic converters (Fogelberg, 2000; Bauner, 2007) also contributed. Considering these changes, a radical shift to alternative power train technologies for the purpose of reducing NO_x, PM and HC emissions, appeared less plausible during the late 1990s. Instead, CO_2 emissions and fuel efficiency started to emerge as the prime motive for hybrid-electric vehicle technology, turning the focus from series-hybrids to parallel or power-split hybrid configurations.

As indicated by patenting numbers (Figures 3 and 4, page 14) Toyota's market launch of the hybrid car in Prius in 1997 resulted in a lot of R&D activities among competitors in the area of hybrid vehicle technology. Volvo Cars displayed a hybrid concept car in 1999, comprising a similar hybrid configuration as Toyota Prius, i.e. a power-split hybrid. Due to Ford's acquisition of Volvo Cars in 1999 and Volvo's subsequent attempt to acquire Scania, this was a period of great turbulence for the Swedish vehicle industry. Moreover, with a relatively stable fuel price, customers were not expected to be prepared to pay for expensive fuel saving hybrid technologies. By consequence, incentives to further advance hybrid technology towards commercialization were limited and the functionality in terms of Influence on direction of search in the Swedish hybrid-electric vehicle TIS appear relatively weak during the early 2000s (see further 3.5 Legitimation).

This period was broken in the mid 2000s, as crude oil prices started to soar. In particular this affected the hitherto relatively low US fuel prices. Heated public debates on global warming and CO_2 emissions served to reinforce the drive for fuel efficiency and 2004-2007 there was a five-fold increase of Toyota Prius sales on the American market. In 2006 Volvo's CEO announced intentions launch a hybrid truck three years later and he also announced that Volvo intended to launch buses and wheel loaders based on a similar power train configuration. During interviews, Volvo managers directly referred to Toyota as their role model in this endeavor, claiming an ambition to become a corresponding hybrid technology leader in the heavy

17 Both academic and industrial respondents confirm this view. During an interview a senior manager stated that any manufacturer can present a concept car for display at an auto show. Even if the manufacturer does not possess the necessary knowledge for this, the manufacturer can easily engage an engineering consultancy firms to develop such a car. Moreover, a professor in electric machinery explained that there is a huge step from running bench tests to running field test on actual vehicles; the demands are much more complex and unpredictable in the field.

18 Sometimes, the display of concept vehicles can have unintended effects. A famous example is the battery-electric concept car "Impact", which GM displayed in 1990, a car that they later would launch under the model name EV1. The display of Impact is claimed to have inspired CARB regulators to pass the ZEV mandate, forcing GM to start producing electric vehicles. GM produced about 2000 units if EV1 1996-1999, making the car available for lease. GM was later criticized for their half-hearted launch and marketing, as well as the subsequent discontinued production and withdrawal of EV1 from the streets.

vehicle segment. Volvo's announcement also seems to have affected Scania. During an interview, a senior manager at Scania expressed his admiration for the bold statement from Volvo's CEO. Moreover, Scania followed suit displaying their series-hybrid concept at the UITP Mobility & City Transport Exhibition in 2007 and they subsequently transferred this hybrid development project to their R&D centre in Södertälje, announcing market introduction by 2012.

While financial crisis and reduced fuel prices during the late 2000s reduced the pace of development, the long term direction and aim for significantly increased fuel efficiency appeared set for the heavy vehicle industry. This also applies to the car industry. Saab Automobiles display of hybrid concept vehicles in the late 2000s, as well as Volvo Cars' display of the plug-in hybrid concept ReCharge in 2007 can be interpreted as signs of aspiration to take part in the race towards increased fuel efficiency. Volvo Cars' introduction of the Drive model range in 2009, comprising three models equipped with microhybrid systems as well as their announcement that they aim for production of plug-in hybrids by 2012 (albeit with a reservations that a commercialisation will rely on subsidies) also indicate long term direction in terms of hybrid technology, aiming for leaps in fuel efficiency and reduced CO_2 emissions.

Influence of governance

The Californian ZEV mandate obviously promoted electrification and – especially in the case of Volvo – the development of hybrid-electric vehicles. Volvo considered the microturbine based series-hybrid as a promising means to reduce emissions of local pollutants and fulfil the proposed ZEV regulation during the 1990s. However this law-enforced market did not materialise. Instead fuel efficiency emerged as the main driver for hybrid-electric vehicle technology. Toyota introduced their Prius in the late 1990s and the global scene saw an emerging debate on CO_2 emissions and global warming. However, during this period, the vehicle manufacturers had relatively weak incentives to pursue this development. Fuel prices were low and the voluntary agreements between the EU commission and European car manufacturers on average CO_2 emissions were not forceful enough to promote further commercialization.

It was not until the mid 2000s that the motives were sufficiently strong for the Swedish vehicle manufacturers to advance hybrid technology further, engaging in product development directed at commercialization. At this stage, the manufacturers felt strong signals from several sources. Firstly, the sales figures of Toyota Prius on the US market showed that there actually was a market for hybrid vehicles. Secondly, souring fuel prices made it possible, or at least plausible, to justify hybrid vehicles based on cost rationales. Thirdly, a specific governance arrangement that Scania managers repeatedly have referred to during interviews is a contest between bus manufacturers to deliver fuel efficient and low polluting transport solutions to the London Olympics. According to these managers, this was a prime reason why Scania decided to aim for market launch of their series hybrid bus by 2012.

In addition to this, the more forceful policy on transport related CO_2 emissions adopted by the EU commission in 2007 comprised clear limits on average emissions from new cars as well as plans for stepwise reduction of these limits. This presented strong signals to the European car manufacturers, providing clear targets to aim for. Subsidies and tax reductions associated with CO_2 emission threshold levels in individual EU-countries were highly influential as well. For example, the 15 per cent governmental subsidy for the purchase of cars with CO_2 emissions below 105 g/km in Belgium provided an obvious target for the engineers at Volvo Cars in the development of the smallest Drive models and thus had an important influence on the decision to implement micro-hybrid technology in these models.

3.3 ENTREPRENEURIAL EXPERIMENTATION

Functionality indicators

Experimentation and probing into different technologies and applications is necessary to reduce uncertainty and facilitate learning in a technological innovation system (Bergek *et al.,* 2008). For the assessment of entrepreneurial experimentation in the Swedish hybrid-electric vehicle TIS the report relies on two main indicators. The first indicator relates to the variety in technological configurations under development. As noted in the introductory section, a number of different hybrid power train configurations exist, each with its individual characteristic. Different technological options also exist on component and sub-system levels.

The second indicator of entrepreneurial experimentation refers to the number of different product applications in which Swedish vehicle manufacturers have implemented hybrid-electric power trains. As noted in section 1.1 Hybrid-electric power trains, hybridisation in general tend to offer particular benefits in driving conditions characterized by repeated starting/stopping and acceleration/deceleration. Moreover, different hybrid configurations offer different benefits, which make them particularly useful in different product applications. In terms of potential product applications for hybrid-electric vehicle technology, a rough categorisation can be made into cars and heavy vehicles. However, each of these categories comprises a number of different vehicle types and the scheme of categorisation differs between heavy vehicles and cars. Different heavy vehicles are generally categorised according to the application or intended range of utility. Examples of such categories are long-haulage trucks, distribution trucks, inner-city buses and coaches. A number of special purpose heavy vehicles exist as well, i.e. vehicles such as refuse trucks that operate in narrow applications. The categorization of heavy vehicles according to application or intended range of utility means that it is easier to identify product applications for heavy vehicles than for cars, in which hybrid-electric vehicle technology (or individual hybrid configurations) appear most beneficial. Cars tend to be more versatile in its utility. The same car is often used both for short- and long-range transport and it is designed to carry both passengers and cargo. Instead of categorising cars according to the application or intended range of utility different cars are therefore often categorised according to the body size or body type (see section 1.2 Product applications).

Functionality assessment

The entrepreneurial experimentation differs between the Swedish vehicle manufacturers. In terms of the variety of hybrid configurations under development, Volvo's activities seem to have peaked during the late 1990s. Encouraged by positive feedback from their display of the microturbine based series-hybrid concept car ECC during the early 1990s, they extended this concept to two other applications, a concept truck and a concept bus. Volvo also took the microturbine series-hybrid one step further, testing it in an inner-city bus application in regular operation. Concurrently, they conducted field tests with an ICE-based series-hybrid distribution truck. Volvo's car division was also very active during the late 1990s. They developed and tested several different ICE-based hybrids, including five versions of a series-hybrid as well as a mild hybrid configuration. In 1999 they also displayed a concept car with a power-split hybrid (Pohl, 2010).

The variety in terms of technological configurations at Volvo decreased during the early 2000s. This was to a large extent because of Ford's acquisition of Volvo Cars and their subsequent decision to concentrate the group's hybrid R&D efforts to USA. During this period, the R&D efforts also started to converge towards an ICE-based parallel full hybrid configuration, which Volvo primarily tested and demonstrated in a distribution truck application. Their Construction Equipment division also conducted pre-commercial R&D, testing an ICE-based parallel hybrid configuration in a wheel loader application. Moreover, initiated by Renova's efforts and interest, refuse trucks emerged as a viable application for hybrid-electric vehicle technology.

The decision to initiate product development directed at commercialization further enhanced the convergence in terms of hybrid configurations at Volvo. A common platform strategy would mean that all relevant product divisions could share the same technology. This was deemed necessary to reach sufficiently high production volumes, which was crucial to justify the investment. To realize this, Volvo managers selected the most versatile hybrid configuration and positioned the development project at Volvo Powertrain, an organizational unit that operates across the product divisions. The hybrid platform strategy addressed several product applications such as trucks, buses, construction equipment (wheel loaders) and Penta (industrial engines/boat engines). In the Penta application, the hybrid power train was primarily intended as an integrated auxiliary/back-up electric power unit, comprising both engine and power generator. Hence, while the degree of entrepreneurial experimentation was reduced in terms of technological variety, it increased in terms of variety in product applications.

In 2004, Ford released a hybrid version of their Escape SUV on the American market. It was equipped with a full power-split hybrid. At this stage had Ford intentions to expand their hybrid model range and introduce hybrid technology on the European market. Following these intentions, Ford's management acknowledged the virtue of having R&D capabilities close to the market and reconsidered their decision to concentrate the group's hybrid technology R&D to USA. Thus the Ford management assigned Volvo Cars' Torslanda plant as their European hybrid technology center. However Ford ran into severe financial problems by the mid 2000s, which slowed down the plans to expand the hybrid model range. As Ford announced plans to sell of Volvo Cars by the late 2000s they also withdrew the hybrid R&D funds. However Volvo Cars still maintained activity in the hybrid technology field, developing and initiating field tests of a plug-in hybrid car with a diesel engine. Moreover they expanded the range of hybrid technology, developing and launching three car models equipped with micro hybrid systems.

Scania conducted some R&D on hybrid trucks, especially during the mid and late 2000s, using a parallel hybrid configuration. However Scania has particularly focused their hybrid R&D on bus applications. This is natural since the heavy truck models Scania manufactures primarily are intended for long-haulage applications. According to Overgaard & Folkesson (2007) Scania has tested and demonstrated around 30 buses since the 1980s with different hybrid power trains. This includes buses equipped with both parallel hybrid and series hybrid configurations. Scania has often build these buses in collaboration with the Danish body manufacturer DAB, a company that Scania owned 1995-2002. Their focus on bus applications explains why they have maintained a prime interest for the series-hybrid configuration even though the automotive industry in general has turned its main focus towards parallel or power-split hybrids.

Influence of governance

Analysing the influence of governance on entrepreneurial experimentation will result in similar results as the analysis of the influence of governance on Knowledge development and diffusion, which is outlined in section 3.1. State funded R&D and demonstration programs have made it possible for the Swedish vehicle manufacturers to test various hybrid configurations in a number of different product applications.

A retrospective evaluation report of the Swedish KFB program for research, development and demonstration of electric and hybrid-electric vehicles 1993-2000 argue that the program could have had a stronger focus on hybrid technology for heavy vehicles, rather than the present focus on electric cars (Hedman *et al.,* 2000). Due to the American ownership of the Swedish car manufacturers it would probably have been easier to influence the degree of activity at the heavy vehicle manufacturers than at the car manufacturers. However, it is still questionable to what extent the heavy vehicle manufacturers would have been able to justify a further expansion of their R&D, testing and demonstration activities at this stage. Such decisions are still determined through strategic considerations (see 3.5 Legitimation). An important lesson from the KFB program was that such a program has to involve the vehicle industry more actively, engaging the car manufacturers in a dialogue both in the planning and execution of the program. These lessons were transferred to the subsequent Green Car programs, which was based on a public-private partnerships involving the Swedish state and the Swedish vehicle manufacturers.

While the Californian ZEV-mandate, the implementation of environmental zones and the generally strong focus on local air emissions during the early 1990s particularly encouraged the development of electric cars, the turned focus towards fuel efficiency and CO_2 emissions in the late 1990s and 2000s resulted in a larger variety in terms of hybrid configurations. This includes series, parallel and power-split hybrids as well as micro, mild, full and plug-in hybrids. An important note, however, is that in terms of product applications recent market-based incentives, such as subsidies, tax reductions and regulation on CO_2 emissions have primarily been directed at cars rather than heavy vehicles. So these governance mechanisms have not been very effective to increase variety in product applications. However, heavy vehicles are more exposed to local regulations, such as environmental zones that restrict operation of diesel-engine powered vehicles in inner city areas order to improve air-quality and reduce noise. Such regulations have indeed encouraged experimentation of hybrid technologies (and other alternative power train technologies and fuels) in heavy vehicle applications such as distribution trucks, inner-city buses and refuse trucks.

3.4 MARKET FORMATION

Functionality indicators

New technologies are often relatively crude and perform badly according to an established set of performance parameters. This means that they are rarely competitive on regular markets, which are dominated by existing technologies. These technologies have been subject to years of continuous improvement and adjustment to fit the exact needs and requirements of users. Additionally, these products have been standardised and production processes have been developed and fine-tuned, resulting in reduced manufacturing costs. Therefore so called “nursing markets” are often necessary to support an early diffusion of the new technology onto the market. Nursing markets constitute protected spaces, which allow for testing, experimentation, demonstration, adaptation, and further improvement (Kemp *et al.,* 1998). Such markets can also provide a prosperous interaction between manufacturers and so called ”lead-users” (Von Hippel, 1988), i.e. professional users who tend to push technology development by defining requirements on new technology, by evaluating new product designs and by taking initiatives in the development of new product concepts and ideas.

The next step in a TIS market formation is the emergence of bridging markets (Andersson & Jacobsson, 2000). Such markets allow for production volumes to increase and may thus provide a prerequisite for the opening of a mass market for the new technology. Bridging markets are niches or segments of the market, such as particular customer groups, geographical areas or domains of application. In these segments, the particular merits of the new technology are of great value, while the deficiencies are acceptable. Hence such bridging markets provide a necessary basis for volume increases that support production learning and incremental innovation. In turn, this will enable improvements of the price/performance ratio of the new technology, eventually making it competitive with established technologies on mass markets.

The assessment of the market formation will thus focus on the stage of market development, including the availability of nursing markets, as well as bridging markets that may open up a mass market for hybrid vehicle technology. In the assessment of market formation, it is important to make a distinction between the market for hybrid cars and the market for heavy hybrid vehicles. As noted in the introductory section (1.2 Product applications), buying behaviors differ markedly between cars and heavy vehicles. These two markets have also reached different stages in terms of market development.

Functionality assessment

In the hybrid car market, Toyotas careful entry with limited sales on the domestic market in the late 1990s can be interpreted as an attempt to address a local nursing market. The limited sales reduced the level of risk and the geographical proximity made it easier for Toyota's organization to respond to signals from the field and to correct potential problems with the new technology. Lessons gained from the field were fed back to product development, resulting in the release of an upgraded and improved Prius two years later, a vehicle intended for export markets. From a Swedish perspective, such nursing markets for hybrid cars did not emerge during the late 1990s. According to Hedman et al (2000) this was essentially because no hybrid vehicles were available on the Swedish market at this stage.

The subsequent development of the hybrid car sales in the US during the 2000s can be interpreted as a bridging market for hybrid vehicle technology. After a period of relatively modest sales in the early 2000s, hybrid sales took off remarkably during the late 2000s, propelled by soaring fuel prices and a heated global warming debate. Sperling & Gordon (2009:171) explain how the hybrid car's particular merits in terms of its symbolic value, made an emerging segment of American car buyers embrace the new technology in spite of its relatively high cost:

> *Hybrids collectively, but mostly the Prius, were the first commercially available cars that were thought of as "environmental" vehicles. Hybrids elevated high fuel economy from a trait of small cheap econo-boxes into high technology, smart engineering, and high quality. And it all had to do with symbolism. (...) Owning a hybrid, at least for the early buyers of hybrids, is about the symbolism of "doing the right thing", even if the individual contribution is infinitesimally small. Hybrid ownership is about participating in something larger than the individual – a collective effort to clean up and preserve the natural environment so that it can continue to provide for and be enjoyed by others, including future generations. Hybrids convey to their owners and the world that these are people who care about the planet and other people and are willing to make changes in their own lives to serve a greater good.*

In terms of expressing these values, the second generation Toyota Prius was superior among the cars available on the US market. Compared to the hybrid versions of Honda's standard models Civic and Accord, the dedicated hybrid brand made it easier to distinguish a Toyota Prius. This was important for hybrid owners who wanted to make a statement and convey a message with their car purchase. The distinct body design of second generation Prius reinforced this feature. Moreover, the Prius mid-size body could attract a broader market segment than Honda's peculiar two-seated Insight model, which "had little appeal for mainstream customers" Sperling & Gordon (2009:169). The release of several hybrid versions of standard car models from a number of car manufacturers (not the least Toyota) by the late 2000s indicate that the vehicle manufacturers may have foreseen that hybrid vehicle technology was about to take the step from the bridging market to the mass market. But even though several other hybrid car models and manufacturers were available on the market, Toyota Prius still dominated the hybrid car market by the end of 2009. This indicates that hybrid vehicle technology had not yet taken the step from a stage of bridging market to a mass market stage.

While both Toyota and Honda introduced hybrid cars in Europe in the early 2000s, sales on the European market were more limited. By contrast, Europe has been the prime target market for micro hybrid technology. Volkswagen implemented a start-stop system already during the 1990s in a version of their Golf model called "Ecomatic" and in the most fuel efficient versions of the micro car Lupo and Audi A2. However, the market reception was cold at this stage. Volkswagen therefore decided to cease the production after a few years. The market failure was explained by the discomfort that car drivers felt when the engine automatically shut off at red lights. However, by the late 2000s the technology experienced a revival. Several major European car manufacturers implemented micro-hybrid systems to supplement their most fuel efficient engine alternatives, reducing fuel consumption even further. First-tier suppliers Bosch and Valeo expect a rapid market growth for these systems, more rapid than for full hybrids. Hence, after its re-entry in the late 2000s, micro-hybrid technology has moved rapidly towards a stage of mass market.

The market for heavy hybrid vehicles is more diverse than the hybrid car market. Particularly in the US, there is a limited market segment for hybrid buses, mainly driven by local regulations that restrict operation of traditional diesel engine powered buses in areas which are particularly sensitive to air pollution and noise. This market is served by specialised firms that equip buses or bus chassis with hybrid power trains. Moreover, a market for light-duty trucks has recently begun to emerge in Japan, primarily served by Japanese manufacturers such as Toyota-owned Hino. The Swedish heavy vehicle manufacturers, however, have not been active in this segment.

The Swedish heavy vehicle manufactures have repeatedly benefitted from field trials in collaboration with local customers. Volvo has benefitted from collaboration with the distribution company TGM in the field trials of their series hybrid truck in the late 1990s and the refuse and recycling companies Renova and Ragn-Sells in the case of the parallel hybrid in the late 2000s. Renova also took the role of a lead user, promoting the development of hybrid-electric vehicle technology during the early 2000s by initiating development and testing of refuse trucks with electric auxiliary equipment. Two of the most important customers forming local nursing markets for the Swedish heavy vehicle manufacturers have been the municipal bus operators SL (Stockholm) and Göteborg Spårvägar. Close collaborations between Scania and SL and between Volvo and Göteborg Spårvägar have been instrumental to test the field performance of the hybrid technology and feed user experiences from the new technology back to R&D.

The Swedish heavy vehicle manufactures' decisions to initiate product development aiming for market launch indicate a belief that bridging markets will emerge and that hybrid technology eventually will take the step to a mass market. In this effort, Volvo has also proceeded beyond restricted collaboration with local partners, delivering field trial vehicles to customers in e.g. Great Britain and France. During the second half of the 2000s, however, the market for heavy hybrid vehicles was still in a nursing stage and the financial crisis meant that the imminent market development for hybrid technology was associated with question marks, at least on the short-term.

Influence of governance

Apart from supporting knowledge development, the Swedish KFB program for research, development and demonstration of electric and hybrid-electric vehicles 1993-2000 had an objective of influencing market development. However during its initial years, the program experienced severe problems in obtaining cars. The program directors had overestimated the vehicle manufacturers' capabilities as well as their actual interest in supplying cars. According to an evaluation report (Hedman *et al.,* 2000), this particularly relates to the capabilities and interest of the Swedish manufacturers. Saab Automobile ceased their activities in electric and hybrid cars as they were acquired by GM and Volvo developed hybrid-electric cars during the 1990s, but this project was near closure in 1996/97.[19] By consequence, the program had to purchase vehicles from large international manufacturers (primarily the French manufacturers Renault and PSA).

The KFB program and the parallel public procurement program orchestrated by Nutek provided financial funds and technical support for municipalities and other local market actors to purchase battery-electric and hybrid cars. The idea was to push the development forward by creating a demand for these cars. These coalitions of buyers were supposed to be strong enough to enforce challenging product requirements onto the car manufacturers. Hence, the KFB program and the parallel Nutek program aimed at creating bridging markets for electric and hybrid electric vehicles. However, the evaluation report states that the program in the end had a small impact on market development. It also concludes that in future programs, the vehicle distribution network (i.e. the car retailers) have to be involved to ensure availability of vehicles, as well as spare parts, service and maintenance (Hedman *et al.,* 2000). In the end these actors were not sufficiently powerful. Furthermore, it appears that the vehicle manufacturers and other actors in the vehicle supply chain were not prepared to serve a bridging market for hybrid-electric cars at this stage.

Even though the heavy vehicle part of the KFB program was significantly smaller than the car part, this part of the program probably had a greater impact on technological development. It provided a basis for a

19 Most likely, this refers to Volvo's activities in series hybrid cars, which according to Volvo managers was terminated in 1998 (Pohl, 2010).

constructive interplay between vehicle manufacturers and users. However the collaboration was occasionally hampered by diverging expectations. In 1999 Göteborg Spårvägar purchased two microturbine based series hybrid buses from Volvo for operation in regular traffic. In an interview, a Volvo manager argued that the decision to operate the buses in regular traffic at this stage was premature. The operation meant that the buses were directly compared with traditional buses and the new technology was thus exposed to too high demands in terms of reliability and availability. There was not a sufficient acceptance for the downtime, which was significantly higher for the hybrid buses than for traditional buses. Hence, also in this case, the diverging expectations can be interpreted as caused by differing perceptions about the stage of market development and the maturity of the technology.

The voluntary agreements between the EU and the European car industry on CO_2 emissions did not have any substantial effect on the market development for hybrid vehicle technology. By contrast, the stricter EU-regulation proposed by the late 2000s, combined with tax incentives and subsidies at certain CO_2 emission threshold levels had a much stronger effect. These were implemented in several EU countries during the late 2000s. Apart from providing a direction for R&D activities (see 3.2 Influence on direction of search), these emission thresholds have provided the industry with valuable instruments for product proliferation. Figures such as 120g/km or 105g/km, associated with tax incentives or subsidies, have simplified market communication, providing a useful tool for the car manufacturers in the promotion of their most fuel efficient car models.

3.5 LEGITIMATION

Functionality indicators

Legitimation is about social acceptance and compliance. The new technology and its proponents need to be considered appropriate and desirable by relevant actors in the innovation system to acquire political strength. While a number of different actors are involved in the Swedish hybrid-electric vehicle TIS, the vehicle manufacturers and key subsystem suppliers are arguably key actors. In order to advance further, hybrid technology therefore has to be considered appropriate and desirable within these organisations.

The global automotive industry is marked by production overcapacity and shrinking margins. Most manufacturers balance on the edge of survival. By consequence, failed ventures in innovative R&D could have severe consequences and potentially even jeopardize the complete business. Hybrid development projects thus have to present strong motives to attain organizational support. The assessment of TIS-functionality according to the legitimation function will thus focus on the strengths of the motives to conduct hybrid R&D and the ability to justify investments related to hybrid technology. In particular the assessment will focus on the ability to justify the step from a stage of concept or prototype development to the development of vehicles intended for production and sales on a commercial basis. This is because the level of the investment (and thus the risk level) associated with a commercial venture is by an order of magnitude higher.[20]

As noted in the introduction section (1.3 The Swedish automotive industry), the limited size of the Swedish automotive industry means that it cannot support a complete supplier network. Nevertheless, Toyota's way of organising hybrid vehicle R&D and manufacturing indicates that proximity between vehicle manufacturers and suppliers of key subsystems is advantageous.[21] Therefore the existence of committed suppliers of key subsystems to the hybrid system is also a useful

20 According to a rough cost estimate made by a senior manager at Volvo Cars, a budget of approximately 5-25 MSEK is sufficient to develop a full hybrid concept car, and a budget of 25-50 MSEK is sufficient to develop a drivable prototype which can be used for field trials. By contrast, the cost of developing full hybrid technology that can be launched on the market is about 1000-1500 MSEK (this estimate corresponds to an estimate made by another manager at Volvo Cars in a separate interview). The cost of implementing a micro hybrid system is significantly lower – about 80-100 MSEK. According to an experienced project manager at Volvo Trucks, there is a similar difference between a prototype stage and a commercial stage in the case of heavy vehicles. Worth noting is that the estimate only refers to the cost of power train development. It does not include necessary investments in production development and tools; nor does it include the cost of promotion and marketing. Furthermore, if a car manufacturer decides to launch a separate hybrid car model (as Toyota did with their Prius), that would require an additional investment of approximately 5000 MSEK for developing the car plus 5000 MSEK for new tools. Moreover, because of high initial production costs and price pressure on the market, a car manufacturer introducing a hybrid car may have to accept significant initial losses after market launch.

21 Toyota's sourcing strategy for hybrid power train key components is characterized by a high degree of vertical integration, relying on internal suppliers for both electric machines and battery systems (Magnusson & Berggren, 2011).

indicator of legitimation in the Swedish hybrid vehicle technology innovation system.

Functionality assessment

As noted in section 3.2 Influence on direction of search, the prime motives to conduct hybrid technology R&D changed substantially during the time period 1990-2010. While the focus during the 1990s primarily was set on local air pollutants, it gradually turned towards fuel efficiency and CO_2-emisisons. However neither local emissions nor the emerging global warming debate during the late 1990s provided sufficient motives for the Swedish vehicle manufacturers to engage further than development of concept vehicles and prototypes. Still during the early 2000s, motives for commercial product development appeared relatively weak. There are at least three reasons for this. These reasons are both related to external landscape factors and to organizational routines and mindsets.

Firstly, within these organizations a number of different project proposals compete to achieve internal R&D funding. In most cases development projects that address explicit customer demands win this internal competition and achieve funding. If customers clearly state that they are prepared to pay for certain attributes, the perceived risk of engaging in such a development project is low. During the early 2000s, customers did not pose any explicit demands of the potential benefits associated with hybrid vehicle technology and therefore these project proposals attained limited organizational support. Secondly, the additional cost associated with the purchase of a hybrid vehicle can be justified by reduced fuel expenses while using the vehicle. However the fuel price was relatively stable during this period and it was difficult to justify the purchase of hybrid vehicles based on such cost/benefit estimates. Thirdly, as investments in product development were assessed on a product level it was difficult to justify the additional cost associated with hybrid technology development. The product based calculation model simply did not fit with long-term hybrid technology investments. To justify these investments, a longer time frame was required and the calculation had to assume a sharing of learning costs between several products and product generations. The fact that an unusual top-down decision eventually (in 2006) was needed at Volvo to initiate the development of heavy hybrid vehicles for commercial production and sales show that existing decision making routines within the organization were insufficient for such a bold decision.

During the late 2000, several heavy vehicle manufacturers presented hybrid concept vehicles and announced plans to launch such vehicles on the market. At this stage, a number of converging factors served to reinforce the legitimacy of hybrid technology, making the decision to initiate product development directed at commercialization more viable. The crude oil price had started to climb dramatically and this altered the cost/benefit estimates. It was still difficult to justify the purchase of a heavy hybrid vehicle based on the current fuel price. However, at this stage it was possible (and appeared reasonable) to base estimates on projections of a long-term trend of significantly raised fuel prices. Under such circumstances reduced fuel costs would make it rational for customers to prefer the more expensive heavy hybrid vehicles to traditional ICE powered vehicles. Hybrid technology could thus be justified based on cost rationales. Moreover, the intense debate on global warming and the emerging global consciousness on the sense in and necessity of drastically reduced CO_2 emissions provided additional arguments in favor of fuel saving technologies. The sales figures of Toyota Prius on the US market also showed that it was possible to make business out of hybrid vehicle technology. Thus it was tempting for heavy vehicle manufacturers to repeat Toyota's success in the heavy vehicle segment. The focus on fuel efficiency, global warming and CO_2 emissions became particularly strong by the end of the time period. However, at this stage the industry was also seriously affected by financial crises and a severe downturn of the market.

Due to a generally lower mileage it may have been even more difficult to justify hybrid technology using rational cost/benefit estimates in the case of cars. However, car buyers found other arguments to adopt hybrid technology, especially on the US market. According to Turrentine & Kurani (2007) there is a lot of symbolic value associated with fuel efficiency in general and with the purchase of a hybrid car in particular. In interviews with American hybrid car owners they found that their car purchases rarely were based on any rational economic calculations. Instead "buyers of HEVs talked about making a commitment" and "for several hybrid buyers the idea of commitment included setting an example, being a pioneer" (p. 1221). Hence it is important for these buyers that it actually shows that they are driving a hybrid car (see further section 3.5 Market formation).

Several market launches of new hybrid car models from Japanese and American manufacturers show that hybrid technology gained legitimacy in the car industry during the mid 2000s. Still the European manufacturers (including the Swedish ones) appeared hesitant to introduce full hybrids, preferring the less radical (and less expensive) option of complementing traditional power trains with micro-hybrid systems. There may be several reasons for this, but comparing US and European market characteristics, one can distinguish three particular factors, which may have affected the European manufacturers' product strategies. The first relates to the volatility of fuel costs. Although European prices still were higher than American, fuel prices in Europe have increased on a relatively continuous basis. By contrast, US fuel prices increased dramatically during a short period in time, 2004–2008 (first half). This urged car buyers to search for alternatives. Secondly, the diesel car is a strong competitor on the European market, presenting a readily available and lower-priced option for consumers interested in fuel efficiency. European car manufacturers also responded to customer demands on fuel efficiency by introducing their most fuel efficient models (typically propelled by small direct-injection diesel engines complemented with micro-hybrid systems to further reduce fuel consumption) under special brands.[22] Thirdly, while a distinct and growing niche of environmentally concerned car buyers embraced the hybrid car Toyota Prius on the US market; such a distinct and significantly growing niche of environmentally concerned car buyers did not arise in Europe or at least it did not adopt Toyota Prius as its defining artefact.

As for suppliers of key hybrid subsystems, the large Swedish-Swiss electric equipment manufacturer ABB was deeply involved in hybrid-electric vehicle R&D during the 1990s, developing electrical machines and power electronics for Volvo's concept, prototype and demonstration vehicles. For this reason ABB formed a particular division dedicated to hybrid vehicle technology, ABB Hybrid Systems, in the mid 1990s. Sweden also still had a vivid battery industry during the 1990s, with the battery supplier Tudor occasionally taking part in Volvo's hybrid projects. However, by the turn of the century none of these two suppliers remained in the Swedish hybrid vehicle TIS. In the case of Tudor, the prime reason was that the large American battery manufacturer Exide acquired Tudor in the mid 1990s. In 1999 they closed down Tudor's Swedish R&D and manufacturing operations. In the case of ABB, their senior management decided to terminate the company's efforts in hybrid vehicle technology in 2000. This decision was taken in connection with the severe corporate financial crisis that ABB suffered in the late 1990s. As a result ABB initiated a through restructuring, selling off a number of business areas and focusing on their core businesses in electric power transmission and distribution, as well as industrial automation. At this stage ABB had invested some 80-100 MSEK in hybrid-electric vehicle technology over a period of 10 years (Eriksson, 2007:381). Volvo Cars had recently terminated the series hybrid development efforts that ABB had been part of. Moreover, BMW had recently (in 1999) terminated an electric vehicle development project for which ABB had supplied electric drive systems. There were thus serious doubts on the future business potential of electric and hybrid-electric vehicle technology. Moreover, ABB managers realised that the high manufacturing volumes and low profit margins in the automotive industry did not correspond very well with their traditional line of business. The vehicle manufacturers demanded a detailed insight and a high degree of control into their suppliers' operations and the ABB managers were not prepared to accept such a business proposal. Hence they took a strategic decision that automotive technology should not be part of their business and that they should not serve as a supplier to the vehicle industry in the future.

Influence of governance

R&D investments in the vehicle industry tend to need justification in terms of explicit or perceived market requirements. Strict regulation could be used for this purpose. The law enforced requirements related to local air pollutants and demands on zero and low emission vehicles during the 1990s were sufficient to justify the development of hybrid concept vehicles and prototypes. However, the requirements were weakened and traditional ICE-powered vehicles became cleaner by the end of the 1990s. In the end the regulatory requirements did not provide sufficient motives for the Swedish vehicle manufacturers to engage further in hybrid R&D.

Volvo Cars' redirection of the product strategy towards fuel efficiency in the late 2000s can be ascribed to a sudden insight that fuel efficiency had become an important competitive parameter on the market. These customer requirements on fuel efficiency were supported by governance arrangements in terms of CO_2 declarations and threshold levels that enabled benchmarks between different car models. At this stage Volvo Cars lagged behind several of their European competitors. Product development was urgent to catch up with the competitors' lead. The quick development and introduction of the new fuel efficient Drive model range, with micro-hybrid systems in three of these models, was an important part of Volvo's strategy to catch up.

22 Volvo Drive, VW Blue Motion, BMW Efficient Dynamics etc.

For the heavy vehicle manufacturers, soaring oil prices during the mid 2000s instead provided decisive motives to engage further and initiate R&D directed at commercialization. By extrapolating these trends it was now possible to justify commercialization of fuel saving technologies. Governmental subsidies could help stimulate such demand further. However a project manager at Volvo Powertrain underlined that a strategic decision to introduce a hybrid vehicle on the market cannot rely on governmental support. It is important that the development project is commercially feasible without subsidies. In some cases, governmental subsidies can even be counterproductive in terms of legitimation. An interview respondent with long experience from R&D on electric machines and with positions both within industry and academia projected that ABB eventually would reconsider their decision and reenter as a supplier of electric machines to hybrid electric vehicles. In particular the heavy vehicle industry should be interesting for ABB since the size of the electric machines in these applications correspond relatively well with the traction machines that ABB currently produce. What is more, heavy vehicle production volumes are much lower than car production volumes. However a prerequisite for such a strategic reentry is that the vehicle manufacturers show that they are serious about hybrid technology. One way of showing this is to make comprehensive investments in the new technology. According to the manager, the seriousness of the vehicle manufacturers' efforts in hybrid vehicle technology can be questioned as long as a significant portion of their R&D is funded through governmental R&D subsidies.

3.6 RESOURCE MOBILIZATION

Functionality indicators

A vehicle consists of thousands of components. In order to be approved for production, each component has to fulfil detailed requirements. Furthermore, the complete vehicle has to be validated to ensure strict system level requirements in terms of safety, manufacturability, reliability, durability, cost, drivability, comfort, serviceability etc. Vehicle development projects thus comprise very elaborate validation activities. By consequence, such projects are extremely engineering intensive endeavours, requiring thousands of engineering hours.

As noted in the introductory section (1.1 Hybrid-electric power trains), the hybrid-electric power train builds upon integration of different fields of engineering knowledge. Some of these fields are very familiar to the vehicle industry. Vehicle manufacturers have since long built a competitive edge based on expertise in areas such as mechanical engineering and internal combustion engines. However the vehicle manufacturers are less familiar with other fields of engineering knowledge, such as electric propulsion systems and battery technology.

The assessment of the resource mobilization function of the Swedish hybrid-electric vehicle TIS will focus on the number of available engineers with competence in relevant fields, in relation to the experienced need as expressed by key actors in the system. The functionality assessment will also incorporate a discussion on how the Swedish vehicle manufacturers have addressed the problem of mobilizing the necessary engineering resources for their hybrid-electric vehicle development efforts.

Functionality assessment

In general, the hybrid vehicle concept, prototype and demonstration projects during the 1990s and could be conducted by small dedicated teams of engineers. Therefore the need for engineering resources was relatively limited in the Swedish hybrid-electric vehicle TIS until the mid 2000s. At this stage the need for engineering resources escalated during a short period of time. This was primarily due to Volvo's decision to initiate the development of heavy hybrid vehicles in 2006 aiming for market introduction three years later, as well as Scania's decision to transfer their hybrid bus development to Södertälje, initiating extensive field tests and aiming for market introduction by 2012. Moreover, at this stage, Ford decided to locate their European hybrid R&D at Volvo Cars. All these vehicle manufacturers competed for similar engineering resources and by comparison to the previous concept, prototype and demonstration projects, the engineering input required for the development of vehicles aiming for market introduction was an by order of magnitude higher. Hundreds of engineering specialists were required in order to validate the vehicle for production. To fulfil their immediate need for engineering resources with relevant competencies, the vehicle manufacturers had to devise a number of different approaches, such as external and internal recruitment as well as engaging consultants. A group manager at Volvo Powertrain explained that it was particularly difficult to find engineers who had knowledge within the "new" fields (e.g. electric machinery, energy storage, and power electronics) in addition to experience from vehicle development and production. Although subsystems such as batteries and electric drives are sourced from external suppliers, this combination of engineering knowledge and industrial experience was required to provide the suppliers with accurate specifications in terms of product quality, terms delivery, product support etc. Moreover, it was required to be able integrate the hybrid power train as a system.

During the time period 1990-2010, the Swedish vehicle manufacturers used a number of long-term strategies to acquire relevant engineering knowledge in support of their hybrid-electric vehicle developments. These strategies range from internal R&D to collaboration with external parties such as suppliers, consultants and academic researchers.

Due to a significantly increased use of electronics and electrical components, vehicle manufacturers continually recruited electrical engineers during this time period. According to a manager at Volvo Cars, the number of engineers with electric and electronics specialisation at Volvo Cars increased from about 50 in 1980 to about 1000 in the mid 2000s (Eriksson, 2007:373). However it is important to note that the vast majority of these engineers are active in the development of electronics and electrical components for auxiliary systems (fans, pumps, windshield wipers, rear view mirrors and chairs with motor assisted adjustment etc.), rather than in the development of electric motors and generators for vehicle propulsion.

As noted in the previous section (3.5 Legitimation), the input from ABB was critical for Volvo's hybrid-electric vehicle development activities during the 1990s. ABB engineers took active part in Volvo's development and demonstration projects, providing necessary expertise in electric propulsion systems. In terms of energy storage and battery technologies, Volvo lacked such a collaboration partner. Instead Volvo established a team within their central advanced engineering division, Volvo Technology, which was devoted to energy storage and battery technologies. They furthermore engaged engineers from this team to evaluate battery performance and manage contacts with international battery suppliers in their hybrid-electric vehicle development and demonstration projects.

The lack of key hybrid subsystem suppliers can be considered as a weakness of the Swedish hybrid-electric vehicle TIS. During an interview, a professor active in the Swedish hybrid centre freely admitted that their long term R&D would have benefitted greatly from the participation of such specialised suppliers. However, it is important to note that although geographical proximity may be beneficial during explorative pre-commercial R&D activities, vehicle manufacturers select suppliers on commercial grounds rather than proximity. In order to be considered, suppliers must have product development capabilities, approved quality, reliable deliveries, global presence and sufficient financial strength to survive and support the products (Eriksson, 2007). Hence, having a national supplier base is not a prerequisite for the development, production and sales of hybrid-electric vehicles. During the 2000s, both Volvo and Scania therefore collaborated with international partners for the supply of electric machinery and energy storage subsystems to their heavy hybrid vehicles.[23]

Another example of collaboration with international suppliers is Volvo Cars' implementation of a micro hybrid system supplied by Bosch in three of their Drive models during the late 2000s. The micro hybrid system does not alter the vehicle power train architecture the same way as a full hybrid configuration does. Whereas a full hybrid entails a completely new architecture, the micro hybrid is more of a modular extension of a traditional ICE based automotive power train. Therefore the need for close collaboration to achieve integration was lower in this case. However Volvo Cars still needed to acquire extra engineering resources, engaging international engineering consultants to understand how they could integrate the micro hybrid system with the power train in order to benefit the most from the new technology.

The Swedish hybrid-electric vehicle TIS has repeatedly benefitted from collaboration between industry and academic researchers. One notable example is the development of the microturbine propelled high-speed generator at KTH, a concept that ABB developed further and Volvo implemented in their environmental concept vehicles during the 1990s. Another example is how Saab Automobile engaged researchers from Lund University to support their hybrid concept and prototype developments during the early 2000s. A third example is how Volvo Powertrain employed a

23 Volvo selected Kollmorgen for the supply of electric drives and Magna-Steyr for the supply of battery systems. Kollmorgen is an experienced producer of electric drives, but a relatively new entrant as a supplier of such systems to the vehicle industry. Magna-Steyr is an established 1st tier supplier to the vehicle industry which in this case will operate as a battery subsystem integrator, having discretion to source battery system components from different 2nd tier suppliers. Scania selected Voith for the supply of electric drives and Maxwell as a supplier of super capacitors. Voith is an established supplier of transmission systems for buses and the firm also has previous experience from supplying electric machines for industrial applications such as paper machines. However, both Voith and Maxwell are relatively new entrants as suppliers of electric drives and super capacitors respectively to the vehicle industry.

professor in electric machine technology as an expert consultant to support their parallel hybrid development project during the late 2000s. A fourth example is how Scania sent employees to follow PhD studies and take doctoral degrees in order to strengthen their internal engineering capabilities in areas such as electric machines. These are merely a few examples. Over the studied time period it seems as if there has been a frequent collaboration between industry and academia.

Influence of governance

As noted in section 3.1 Knowledge development and diffusion, subsidies from Swedish governmental programs have filled an important role to support R&D in the Swedish hybrid vehicle TIS. In particular, these external funds made it possible for automotive managers to justify hybrid R&D activities when it was difficult to obtain internal funding. Thus it was possible to retain engineering resources within the Swedish hybrid-electric vehicle TIS during periods characterized low legitimacy for the technology (see 3.5 Legitimation).

While the governmental programs during the 1990s were primarily focused on R&D and demonstrations, provision of engineering resources with relevant competence became a more pronounced mission of the programs during the mid and late 2000s. The Green Car program funded PhD level courses in hybrid vehicle technology that engineers from the vehicle manufacturers could follow and the Swedish Hybrid Vehicle Centre was very much focused on engineering competence development, employing several PhD students in that conduct research in technology areas such as control systems, electrical engineering and electrochemistry. However there is a lag in education and it seems as if was difficult to fulfill the drastically increased need for engineering resources in the Swedish hybrid vehicle TIS during the late 1990s.

As noted in the functionality assessment, there have been several examples of industry-university collaborations in the area of hybrid vehicle technology (and related subsystem/component technologies) during the last 20 years. However it would appear as if these collaborations primarily were relatively uncoordinated until the mid 2000s. At this stage, the establishment of the Hybrid vehicle centre meant that it became more institutionalized. With its emphasis on horizontal projects involving different vehicle manufacturers it also opened up an arena for more effective resource utilization by sharing engineering resources directed at long-term and pre-competitive R&D between different manufacturers.

The lack of key subsystem suppliers in the Swedish hybrid vehicle TIS during the 2000s meant that there were no national partners available for joint hybrid technology R&D. Particularly in the area of battery technology, international manufacturers (primarily from Japan, South Korea and US) appeared to have established an impregnable lead. This deficiency of the innovation system may have delimited the possibilities for mutual long term knowledge development, both in terms of product- and production related knowledge (see 3.1 Knowledge development and diffusion). In remedy, Sweden retained university-based vehicular battery technology research supported by public R&D funding. The prime motive for this was that it is important to maintain advanced battery technology knowledge in the Swedish hybrid-electric vehicle TIS to be able to serve the vehicle manufacturers with competent engineers. For the vehicle manufacturers, access to such engineering resources has been essential to be able to specify battery systems requirements and act as a professional buyer. Still, for the supply of batteries for their heavy hybrid vehicles, Volvo preferred to give Magna-Steyr an intermediate role, functioning as a battery systems integrator between Volvo and the battery suppliers. Consequently, although the support for battery technology R&D at Swedish universities may facilitate development of product related battery knowledge, the extent to which it can facilitate sufficient development of production related knowledge in the Swedish hybrid-electric vehicle TIS seems questionable.

4 DISCUSSION AND CONCLUSIONS

4.1 INFLUENCE OF INTERNATIONAL GOVERNANCE

The assessment of the Swedish hybrid-electric vehicle TIS outlined in the previous chapter shows how the functionality varied significantly between 1990 and 2010. The 1990s was characterized by a number of experimentation, testing and demonstration activities. These activities were primarily justified by a need to remedy urban air quality problems. Governance arrangements in terms of pending regulation made it urgent for vehicle manufacturers to address these problems. The Californian ZEV mandate probably is the most well-known example of governance arrangements in this direction. Worth noting is that among alternative propulsion technologies, battery-electric vehicles appeared as the favored alternative by regulators at this stage (early 1990s) and several large car manufacturers responded by developing, producing and selling battery-electric cars in limited numbers. The Swedish vehicle manufacturer Volvo's focus on hybrid technology as a response to the Californian ZEV mandate was different in this respect.

However, by the early 2000s it had become clear that neither battery-electric nor hybrid-electric vehicle technology would be the preferred option to remedy urban air quality problems. At this stage, the strict Californian ZEV regulation had been softened. Moreover, incremental progress of the internal combustion engine and emission treatment technologies such as catalytic converters had significantly reduced vehicular emissions of local air pollutants. Emission regulation both in US, Europe and Japan continued to enforce technological progress, but this had a limited effect on hybrid technology development. Instead further improvements seemed plausible by adding more advanced emission controls to internal combustion engines (e.g. particulate filters, and systems for selective catalytic reduction and exhaust gas recirculation in the case of diesel engines).

Although there was an emerging debate on global warming in the late 1990s, with the Kyoto conference in late 1997 as a significant milestone, this did not have any major effect on the Swedish hybrid-electric vehicle TIS, at least not at this stage. Emerging activities among the Japanese competitors were not sufficient to justify any significant responses from the Swedish manufacturers. Moreover, the restructuring of ownership during this period, with GM acquiring full control of Saab Automobile, Ford acquiring Volvo Cars in and Volvo's subsequent attempt to acquire Scania, reduced the Swedish manufacturers' activities in hybrid-electric vehicle technology. The level of activity in the Swedish hybrid-electric vehicle TIS thus seems to have decreased during the early 2000s.

By the mid and late 2000s the level of activity increased significantly. The heavy vehicle manufacturers Volvo and Scania initiated efforts directed at commercialization of hybrid-electric trucks and buses. Volvo Cars developed a fuel-efficient product-line that included cars equipped with micro-hybrid systems and they announced field trials of plug-in hybrids. Saab Automobile developed hybrid prototypes, conducted field trails and displayed hybrid concept cars. Several converging landscape and industry dynamics factors promoted this increased level of activity. At this stage, the global warming debate gained momentum, the oil price had started to soar and Toyota had shown that there could be a potential business in producing hybrid-electric vehicles. The EU commission, signalling a more forceful policy directed at reduced CO_2 emissions from vehicles, served to further strengthen the motives for developing and launching hybrid-electric vehicles during this period and this was amplified by national subsidies for cars with low CO_2 emissions in several European countries, as well as in Japan. Still the financial crisis and collapsing markets in the late 2000s put the vehicle manufacturers in a very difficult situation.

4.2 INFLUENCE OF SWEDISH GOVERNANCE

On a Swedish level, two notable governance arrangements were the KFB program for development and demonstration of electric and hybrid vehicles during the 1990s and the Green Car programs that offered R&D subsidies for (among others) hybrid-electric vehicle technology during the 2000s. These two programs were both commissioned by the Swedish government. Still these programs are very different in terms of the instruments and mechanisms they deployed and the functions of the TIS that they addressed. With its involvement of local public authorities and focus on demonstrations, the KFB program of the 1990s was very public. It addressed a broad set of issues; supporting both technology oriented R&D and social science research (market surveys and studies on the impact of the technology on the society). Hence

Knowledge development and diffusion in a broad sense was a primary concern. However, the KFB program also addressed Market formation. In fact, one of the program goals was to support the introduction and demonstration of electric and hybrid vehicles. In particular, the program (as well as the parallel Nutek public procurement program) was designed to stimulate market demand through empowerment of potential customers. By supporting potential customers, an early market for electric and hybrid vehicles was supposed to emerge, a market that would be attractive for vehicle manufacturers to enter. However, in the end this "demand pull" arrangement was deemed ineffective. In retrospect, actors in the program appear to have been overly optimistic about how mature the technology was. Moreover they overestimated their possibilities to influence and in the end the program failed to engage the car manufacturers. By contrast, the heavy vehicle manufacturers received more direct support and according to the evaluation report, these parts of the program were also more successful (Hedman *et al.,* 2000).

The Green Car programs during the 2000s addressed a more exclusive set of actors than the preceding KFB program. These public-private partnerships primarily involved the manufacturers themselves, as well as researchers at technical universities within relevant fields of technology. The Green Car programs were designed to fit explicit needs as expressed by the Swedish vehicle manufacturers and thus these programs also became less public than the preceding KFB program. Moreover, they became more narrowly oriented, first and foremost focusing the development and diffusion of product related knowledge, and to some extent Resource mobilization through education of engineers. The design of the Green Car programs can be seen as a reaction to observed shortcomings of the KFB program in terms of weak involvement from the vehicle industry. Letting the vehicle manufacturers orchestrate the programs was a means to ensure a strong industrial participation. An evaluation of the first Green Car program also maintains that the program was successful in facilitating R&D projects and interaction between different vehicle manufacturers, and it was also successful in establishing networks between industry and academia in relevant fields of technology (Faguert *et al.,* 2007).

However, a well-functioning technological innovation system has to support several sub-processes of innovation. From a TIS-perspective, it is therefore possible to question the narrow focus on the development of product related technological knowledge. Technology development is merely one part of it; technological innovation has to be considered in a broader context. Interview respondents also acclaim that development of hybrid-electric vehicles in the Swedish TIS often has been slowed down by deficient organizations rather than by technological shortcomings. This refers both to the vehicle manufacturers' internal processes for assessing and understanding market developments and needs, as a basis for strategic decisions on product development, as well as processes for acquiring new knowledge and establishing efficient production networks involving new suppliers.[24] In the early 2000s, leading Japanese hybrid car manufacturers had already started climbing the learning curve rapidly in terms of production and market related knowledge. The steeply increased sales during the mid 2000s further reinforced this and additional manufacturers entered the market. In terms of hybrid car production, Toyota appeared to have a clear lead by the late 2000s, with Honda as an obvious runner-up. Other car manufacturers (including the Swedish ones) were left behind. In the heavy vehicle sector, the Swedish manufacturers were better positioned, much due to the fact that no global manufacturer so far had attained the position as an international leader in hybrid vehicle technology.[25] Volvo had announced ambitions to become such a leader, but by the end of 2009 their release of a hybrid truck on the market had been postponed. Still, they maintained their ambitions, introducing a hybrid bus to the market in 2010.

However, still after 20 years of R&D in the Swedish hybrid-electric vehicle TIS, no Swedish hybrid car was available on the market and no significant volumes of heavy hybrid vehicles had been produced. As noted in section 3.1 Knowledge development and diffusion, the reluctance to enter the market severely restricted the possibilities to generate production and market related knowledge. However, in terms of Swedish governance arrangements, little was done to explicitly address these issues during the 2000s. As illustrated by the discussion in section 3.5 Legitimation, governance arrangements in terms of R&D subsidies may even have had detrimental effects on the legitimacy for hybrid vehicle technology in that it sent signals to potential new entrants that the technology had not yet proved its commercial viability.

24 Doctoral dissertations presented by Williander (2006) and Eriksson (2007) also support this observation.

25 Japanese Hino may be denoted as a leader in hybrid truck development, production and sales, but only in the light-duty truck segment primarily serving the domestic market.

Having this stated, it is important to note that it appears very difficult to influence global vehicle manufacturers by implementing governance arrangements on a national level. Experiences from the KFB program (as well as the parallel Nutek public procurement program) illustrate that this may be particularly true for relatively small nations like Sweden with a very limited domestic market. The case study shows how the Swedish hybrid-electric vehicle TIS was very much influenced by industrial dynamics, international competition and global trends such as the oil price, the financial situation and international debates on emissions from road transport (both in terms of NO_x, PM and CO_2). The case further shows that strong signals were required to legitimate hybrid R&D and particularly strong signals from several sources were required for the manufacturers to initiate product development aiming for market introduction. To be able to take these decisions, the vehicle manufacturers had to justify them internally in their respective organizations. Hence they needed to be confident that a market for these vehicles would develop and that this market would be large enough to justify the required investment. With a limited domestic market, the search for such signals will primarily be pursued on the international market.

4.3 IMPLICATIONS FOR GOVERNANCE

A general conclusion from the discussion above is that the possibility to influence the Swedish hybrid-electric vehicle TIS through national level governance arrangements has been very limited. International governance appears much more fruitful in this respect. An often referred example is the Californian ZEV-mandate during the 1990s. As the ZEV-mandate was imposed on a US state level, it may be false to label this arrangement "international". Moreover, the Californian ZEV mandate may seem to contradict a general conclusion that it is difficult to influence vehicle manufacturers through national level governance. However some important notes have to be made on this. Firstly, the Californian market is much larger than the Swedish one, something that by itself implies greater possibilities to influence. Secondly, the Californian regulators attracted global support from several actors during the 1990s. In fact, the KFB program and the Nutek public procurement program in Sweden, as well as similar programs in other countries, can be interpreted as such supporting initiatives. The implementation of emission free environmental zones in major European cities also pulled in this direction. Still, the Californian regulators did not manage to maintain the momentum and in the end they were not successful in their pursuit for a widespread diffusion of zero-emitting vehicles. Instead the internal combustion engine prevailed, being subject to step-wise reduction of emissions, as stipulated by European, Japanese and U.S. regulatory requirements. This may illustrate how deep-rooted the internal combustion engine is in the vehicle industry and how large the step is from a stage of prototypes, limited field trials and nursing markets to a stage of production and sales on a commercial basis serving a mass market. However, this may also illustrate that much can actually be accomplished through incremental improvements based on the well-established internal combustion engine, at least as long as explicit long-term requirements on such improvements exist.

Another influential international governance arrangement is the new and stricter EU policy on vehicular CO_2 emissions that was announced by the late 2000s. Since such a policy will only be realized if it attracts support from EU member states, active involvement in European programs directed at improved fuel efficiency and reduced CO_2 emissions from vehicles is required. In this context it is also possible to act as a front-runner, setting even tougher national threshold levels and implementing subsidies for low emitting vehicles. This can be illustrated by the Belgian subsidy program for cars that emit less than 105 g/km. By not implementing any scrappage programs like most EU member states did in the late 2000s, the Swedish government missed an opportunity to act as a front runner in this respect. Moreover, as Swedish vehicle manufacturers enjoyed support in other countries while no support was provided in Sweden, the Swedish government lost credibility vis-à-vis other EU member states through this "free riding" behavior.

While the influence of national governance may have been limited in the Swedish hybrid-electric vehicle TIS, this does not mean that it is not possible to influence. In particular, national governance has a major advantage over international governance in that it relatively quickly can adapt to immediate requirements of the innovation system. Hence, following the analysis presented in this report, it is possible to discern four distinct areas in which national governance level serves (or has served) important roles for the development of the Swedish hybrid-electric vehicle TIS. Firstly, directed national initiatives may serve to offset periods of low legitimacy for the technology, ensuring that a certain level of knowledge is maintained in the system. Secondly, national education system fills an important role to serve the system with resources in terms of persons with appropriate competencies.

Thirdly, national initiatives may be used to stimulate local nursing markets and thus facilitate interactive learning processes between producers and users. Such incentives may also support further market development and the forming of bridging markets. In this process however, it is very important to anchor governance arrangements in a thorough understanding of the current state of development for the technology. Fourthly, by acting as a front runner and imposing even stricter national requirements and threshold levels for subsidies, national governance may serve to amplify global signals demanding reduced emissions from vehicles.

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APPENDIX 1: DATA SOURCES AND METHODS

INTERNATIONAL GOVERNANCE AND INDUSTRY DYNAMICS

Interviews

Unless otherwise stated the interviews were face-to-face. The length of the interviews was 1-2 hours.

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SWEDISH GOVERNANCE AND INDUSTRY ACTIVITIES

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INTERVIEW GUIDE

Background

Position?

For how long?

Worked with hybrid technology since when?

General experiences?

R&D-support hybrid technology

Vinnova's role?

Division STEM – VINNOVA and other agencies?

Development since start 2001?

Magnitude of funding?

Design of programs?

Swedish hybrid electric vehicle TIS 1990-2010

Strengths/weaknesses?

Differences cars/heavy vehicles?

Change over time?

What has influenced this development?

International level?

National level?

APPENDIX 2: TIS-FUNCTIONALITY INDICATORS

Function	Selected indicators
1. Knowledge development and diffusion	Product: Patents, R&D activities, Prototypes and field tests Production: Vehicles available for purchase, Accumulated production volumes Market: Field trials with users, Actual sales
2. Influence on direction of search	Concept vehicles, Official project plans and specific targets (e.g. for market launch and production volumes)
3. Entrepreneurial experimentation	Variety in hybrid configurations under development, Variety in product applications under development
4. Market formation	Stage of market development (including availability of nursing and bridging markets)
5. Legitimation	Strengths of motives to conduct hybrid R&D and ability to justify investments
6. Resource mobilization	Number of available engineers with competence in relevant fields in relation to the experienced need.

APPENDIX 3: FUNCTIONALITY ASSESSMENT

Function	Indicator	1990-1995	1995-2000	2000-2005	2005-2010
1. Knowledge Development and Diffusion	Patents	-	-	-	-
	Reported R&D activities	+	C++, HV+	+	++
	Prototypes & field tests	-	C++, HV+	-	++
	Vehicles available	-	-	-	C+1, HV+
	Accumulated production	-	-	-	-
	Field trials with users	-	+	-	C+, HV++
	Actual sales	-	-	-	+
2. Influence on Direction of Search	Concept vehicles	C+, HV-	+	-	+
	Plans & targets	-	-	-	+
3. Entrepreneurial Experimentation	Variety in config.	-	+	-	+
	Variety in appl.	-	+	-	+
4. Market Formation	Stage of market development	-	-	C+, HV-	C++, HV+
5. Legitimation	Strengths of motives	+	-	-	++
6. Resource Mobilization	Number of available engineers	+	+	+	-

Legend: Weak (-), OK (+), Strong (++); Cars (C) and Heavy vehicles (HV) are assessed separately when there are distinct differences

APPENDIX 4: GOVERNANCE ARRANGEMENTS

This is a compilation of governance arrangements that have appeared in the empirical studies. The primary means for selecting these arrangements have been mentioned in interviews with actors in the Swedish hybrid-electric vehicle TIS, directly or indirectly (e.g. many interviews have discussed governmental R&D subsidies in general, rather than specific support programs). The arrangements are divided into an international governance level and a national Swedish level and presented in alphabetical order.

INTERNATIONAL GOVERNANCE

Californian emissions regulations

Volvo representatives described the development of their Environmental Concept Car as a contribution to the debate about the Californian ZEV mandates, arguing that the low emitting and partially zero-emitting characteristics of this concept meant that it should classify as a ZEV (Volvo Personvagnar Miljörapport 50: Volvo ECC 1992).

European and US Emission Standards (PM, NO_x, VOC)

Emission regulations for diesel engines are a very strong driver for technology development in the heavy vehicle industry. For example, in 2007 a respondent representing Scania claimed that they spend more that 50 per cent of their complete R&D budget to development effort aiming to fulfill requirements as stipulated by Euro V (implemented October 2008) and Euro VI (implemented January 2013). (interview Scania).

European scrappage programs

These programs were implemented in Several European countries to support the vehicle industry during the financial crisis in the late 2000s. It provided financial support for people who scrapped their old cars in order to buy new ones with lower CO_2 emissions. In total 17 European countries implemented such programs. Notable exceptions were Poland, the Czech Republic and Sweden. (Head of the Automotive Unit European Commission)

European proposed directive on CO_2 emissions

In 2007, it was clear that the European policy relying on long-term goals and voluntary agreements on maximum CO_2 emissions from new cars had not been effective. The European Commission proposed a directive stipulating that new cars in average should emit a maximum of 130 gram CO_2 per km by 2012 according to EU's test cycle. The directive would follow a similar structure as the US CAFE standards. (Kågesson, 2007)

EU R&D Support (Framework programs)

Swedish vehicle manufacturers have attained some support from EU, primarily Volvo AB/Volvo technology, to some extent Volvo PV and to minor extent Saab. Scania has decided not to apply for such support. This is however a minor part of their public R&D funding, only 5 per cent. (interview Vinnova)

Local exhaust emission regulations

Hybridisation with the possibility to drive in all-electric mode enables zero emission operations for limited distances. This is beneficial in areas with very strict air quality requirements, such as indoor operation, densely populated areas, parks etc. In the U.S. there is already a limited niche market for buses using series hybrid configurations, i.e. battery-electric buses with on-board battery chargers to extend the driving range. In Europe the development was supported by implementation of so called "environmental zones" in inner-city regions. These zones were associated with special regulations and restrictions for heavy goods vehicles and buses to reduce emissions of harmful substances to the air. By 2002 such environmental zones had been implemented in 16 of the largest cities in Europe ((interview Volvo; Trendsetter, 2002).

Local noise pollution regulations

Hybridisation may offer significant benefits in terms of noise reduction. This is favorable in applications such as waste collection trucks that operate in urban areas, where there are requirements for silent operation. Hybridization means that these trucks can operate the waste compression equipment with the engine shut off. Provided that they have sufficient battery capacity they may also use all-electric mode for moving short distances. (interview Volvo)

London Olympics competition on transport solutions

In competition with other heavy vehicle manufacturers Scania aims at supplying hybrid buses to be used during the Olympics. Respondents from Scania explicitly refer to the London Olympics 2012 as a target for their hybrid-bus development (interview Scania).

Subsidies and tax incentives

Early in 2010, sixteen EU Member States (Austria, Belgium, Cyprus, Denmark, Finland, France, Ireland, Italy, Luxembourg, Malta, The Netherlands, Portugal, Romania, Spain, Sweden, United Kingdom) had elements in their car and/or fuel taxation systems that were totally or partly based on the car's CO_2 emissions and /or fuel consumption. This was a groing trend since the mid 2000s; in 2006 they were only nine (ACEA).

U.S. Corporate Average Fuel Economy (CAFE)

The Corporate Average Fuel Economy (CAFE) standards were with the purpose of steadily forcing automotive manufacturers to improve fuel efficiency. While no respondents explicitly have referred to this standard, American industry specialists mention this as a very important means to promote fuel-efficient cars such as hybrids (Sperling & Gordon, 2009).

SWEDISH GOVERNANCE

FFI

The private-public partnership Strategic Vehicle Research and Innovation (FFI) was established in 2009. VINNOVA obtained the role as a coordinating actor. One out of five collaboration programs was devoted to energy and environment and administrated by STEM. Amongst others, this program provided funding for hybrid vehicle R&D (Faguert *et al.,* 2009)

Green car 1

State funded support program with the aim to develop more environmentally benign vehicle technology through directed R&D efforts. The new technology developed should be possible to integrate in future products and thereby provide improved environmental performance and improved competitiveness. The program was based on a joint agreement between the Swedish state and the Swedish automotive manufacturers Volvo Trucks, Volvo Car, Scania CV and Saab Automobile. The contract stipulated that also Swedish suppliers should have access to research funding through the program. The budget for the program was in total 1 816 mkr, whereof 545 mkr from the state. 45 mkr of these 545 mkr was dedicated to fuel cell and hybrid technology. The program ran from 2000 to 2007. (Faguert et al 2007)

Green Car 2

The aim of Green Car 2 was to support the Swedish development of more environmentally benign vehicle technology, in order to promote the long-term growth and competitiveness of the Swedish vehicle industry. The program stipulated that it is possible to speed up the transition to environmentally sustainable road traffic system through the development of vehicles and vehicle components with better environmental performance. An agreement was signed between the Swedish state and the Swedish automotive manufacturers Volvo Trucks, Volvo Car, Scania CV and Saab Automobile in 2006. The budget for the program was in total 804 mkr, whereof 282 mkr from the state. The program included research in combustion engines and hybrid power trains, as well as alternative fuel vehicles and measures for improved energy efficiency (eg. weight reduction and auxiliary equipment). The distribution between different kinds of technologies was not stipulated in advance, but in the end 105 mkr of the 282 mkr state money was awarded to HEV-related projects. The program ran from 2006 to 2008. (Faguert et al 2007)

KFB program

State funded national support program for research, development and demonstration on electric and hybrid vehicles 1993-2000 with a total budget of 120 mSEK program. Apart from supporting technological R&D and demonstration, the KFB program also comprised an element of social research related to market developments for electric and hybrid electric vehicles and the impact of such vehicles on the society. Co-financing tripled the total resources available for projects within the program. The program budget covered three areas: (1) Surveys of technology and market development in Europe, North America and Japan (8 per cent). (2) Demonstrations of vehicles in Sweden's major cities and infrastructure development (65 per cent). (3) Pure and applied research regarding the effects of electric and hybrid vehicle technology on Swedish society and technology development of electric and hybrid vehicles, especially in heavy vehicle applications (27 per cent)(Hedman *et al.,* 2000; interview Vinnova).

Nutek R&D support

Research funding program directed at electric and hybrid-electric propulsion technologies during 1993-96, with an annual budget of 8 mSEK. Both universities and industrial actors could apply for R&D funds from the program. Volvo enjoyed financial support from Nutek in the development of their ECC concept in the early 1990s. (Faguert *et al.,* 2009; Volvo Personvagnar Miljörapport 50: Volvo ECC 1992)

Nutek public procurement program

In the beginning of the 1990s Nutek initiated a large national procurement of electric cars. By uniting all potential buyers of electric cars the idea was to make demands on the car manufacturers. About 40 different actors took part, mostly public actors such as municipalities but also a number of private companies. The consortium developed an elaborate requirement specification and ambition was that they would purchase between 1200 and 1500 electric cars. However the interest from the manufacturers was very limited and the consortium had to reduce their requirements significantly. In the end only 150 cars were purchased (Hedman *et al.,* 2000).

Swedish Energy Agency hybrid R&D program

The Swedish Energy Agency established a special program for HEV-related research to ensure available funds between the closure of the Green Car program and the initiation of the FFI program. The program also includes projects on fuel cell vehicles, energy efficient conventional vehicles and lightweight/aerodynamic vehicle designs. Between 2007-02-14 and 2008-02-11, the program decided on funding 72 different projects. In total these projects have budgets on 1134 MSEK, whereof 343 are funded by the Swedish Energy Agency. The program supports both university and industry projects. (Interview Energimyndigheten)

Swedish hybrid vehicle centre

The Swedish Hybrid Vehicle Centre is a centre of excellence established 2007, funded by the Swedish Energy Agency, with three Swedish universities and six Swedish industrial companies as partners. The mission of the Centre is to be a strategic knowledge and competence base for education, research and development within hybrid electric vehicles, and to form a framework for cooperation between industry and academia. The initiative is meant to be a 10-year commitment by the partners, with a first phase extending over a 4-year period. (Program plan Swedish Hybrid Vehicle Center and interviews CTH).

APPENDIX 5: CODING OF GOVERNANCE ARRANGEMENTS

Arrangement	Start year	End year	State money	Total money	Level	Private involvement	Mechanism	Push/ pull	Specificity	Primary sub-process	Secondary sub-process
Californian emission regulations	1990	ongoing			2	1	Regulative	Push	1	MF	IDS
European (Euro) emission standards	1993	ongoing			3	2	Regulative	Push	1	IDS	MF
US (EPA) Emission standards	1991	ongoing			3	1	Regulative	Push	1	IDS	MF
Scrappage schemes	2009	ongoing			2	2	Market	Pull	1	MF	IDS
European proposed directive on CO_2 emissions	2007	ongoing			2	2	Regulative	Push	1	IDS	MF
Subsidies and tax incentives	Different	ongoing			2	2	Market	Pull	1	MF	IDS
EU R&D support	1994	ongoing			3	3	Cognitive	Push	1	KDD	RM
Local exhaust emission regulation	1990	ongoing			1	1	Regulative	Push	1	EE	MF
Local noise emission regulation	1990	ongoing			1	1	Regulative	Push	1	EE	MD
Competition on transport solutions for London Olympics	2007	ongoing			1	3	Normative	Pull	1	IDS	EE
US Corporate Average Fuel Efficiency (CAFE)	1975	ongoing			3	1	Regulative	Push	1	IDS	MF
Swedish Energy Agency hybrid R&D support	2007	2008	1134000000	343000000	2	3	Cognitive	Push	2	KDD	RM
FFI	2009	ongoing			2	3	Cognitive	Push	1	KDD	RM
Green car 1	2000	2007	545000000	1816000000	2	3	Cognitive	push	1	KDD	RM
Green car 2	2006	2008	282000000	804000000	2	3	Cognitive	push	1	KDD	RM
KFB program	1993	2000	120000000	360000000	2	2	Cognitive	Pull	2	MF	KDD
Nutek R&D support	1993	1996	32000000		2	3	Cognitive	Push	2	KDD	EE
Nutek public procurement	1993	1996			2	1	Market	Pull	2	MF	-
Swedish Hybrid vehicle centre	2007	Ongoing			2	3	Cognitive	Push	2	KDD	RM

Legend: Level: 1. Local, 2. National/State, 3. EU/Federal, 4. Global; Private involvement: 1. No/Little, 2. Moderate, 3. High; Specificity: 1. Sector, 2.System, 3. Subsystem; Primary/Secondary sub-process: KDD: Knowledge development and diffusion, IDS: Influence on direction of search, EE: Entrepreneurial experimentation, MF: Market formation, Leg: Legitimation, RM: Resource mobilization

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