Towards a sustainable automotive industry –
experiences from the development of emission control systems

till Ebba

(To the President of the Chrysler Corporation)

December 1, 1954

Dear Mr Colbert,

My mother always told me that if I had anything of importance to discuss, to go to the top. […]
I […] think that if a device could be installed on the carburetor (I understand there are such things) that would eliminate the belching of carbon monoxide through the city streets, the Chrysler Corporation could create an enormous amount of good will, particularly in big cities where the carbon monoxide problem is especially acute.[…]

Sincerely yours,

Groucho Marx

KTH Industrial Engineering
and Management

Towards a sustainable automotive industry –
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Sammanfattning

Sedan mitten av 1970-talet har utsläppen av kolmonoxid, kolväten och kväveoxider från bensindrivna personbilar reducerats genom samordnad utveckling av lagstiftning och kommersiell introduktion av katalytisk avgasrening, som nu är en del av hundratals miljoner bilar, lastbilar och bussar över hela jorden.

Denna avhandling är en disaggregerad studie av den i det närmaste globala introduktionen av katalytisk avgasrening för fordon, som åtgärd för att minska lokala luftföroreningar. Introduktionen av ”trevägskatalysatorn” för bensinbilar studeras i fyra länder. Pågående innovation för dieselavgasrening studeras. Teknisk förändring analyseras med avseende på innovationsprocessen, innovationssystemet och dess respektive intressenter. Resultaten används för att analysera konsekvenser för styrmedel för att åtgärda miljöproblem i vardande.

Fordonskatalys är ett exempel på en miljömotiverad innovation, inklusive problemdefinition, lagkrav, företagens marknadsstrategier och marknadspåverkan, innovation, utbud och urval, tekniköverföring, storskalig spridning samt den fortlöpande ömsesidiga utvecklingen av teknik och policy för att reducera emissioner.

Gemensamma nämnare för exempel på lyckosamma introduktionsprocesser är en inkluderande dialog kring etappvisa lagkrav, internationell konkurrens, stöd och samarbete i internationella nätverk samt en tydlig opinion för förändring. Introduktionen av trevägskatalysatorn var och är komplex och beroende av lokal kontext och regionala villkor. Kommande ”globala” teknikförändringar måste utvecklas med en förståelse för varje enskild nation eller marknad och dess specifika barriärer och drivkrafter för miljömotiverad innovation. Givet intressenter och tekniska utmaningar i olika teknologiska regimer med potential att reducera klimatförändringar är ökad bränsleeffektivisering och introduktion av s.k. plug-in-hybrider möjliga utvecklingsvägar för hållbar mobilitet.

Abstract

From the mid-1970s and on, the contribution to air pollution of carbon monoxide, hydrocarbons and nitrogen oxides from gasoline passenger cars in the developed world has been reduced through co-evolution of regulation and commercial introduction of catalytic emission control technology, now part of hundreds of millions of cars, trucks and buses worldwide.

This dissertation is a disaggregated study of the global introduction of catalytic emission control technology as a measure to reduce local air pollution. The introduction of the "three-way" catalyst for gasoline passenger cars is studied for four countries. Present innovation in diesel engine emission control is studied. Technological change is analyzed regarding the process of innovation, the innovation system and its stakeholders. Results are evaluated for implications for innovation and regulatory policy for coming environmental challenges.

Automotive catalysis is an example of environmentally motivated innovation, including problem definition, public regulation, corporate market and non-market strategies, invention, variety, selection, technology transfer, mass diffusion and the ongoing co-evolution of emission-abating policies and technical development.

Common denominators for successful technological or market innovations is a participatory dialogue around structured and tiered regulatory roadmaps, international competition, support by international networks and conducive local public opinion. The near-global introduction of the three-way catalyst was complex and highly dependent on local context and conditions, suggesting that any general "global" innovation and regulation strategy to address present and future local or global problems must be reviewed with an understanding of local barriers and drivers for environmentally motivated innovation.

Given the stakeholders and technical challenges of different technological regimes to mitigate climate change, it is concluded that increased fuel efficiency and the introduction of plug-in hybrids are possible trajectories for sustainable mobility.

Abstracto

Desde los años 70 y adelante, la contribución a la polución atmosférica de emisiones de monóxido de carbono, hidrocarburos y óxidos de nitrógeno proveniente de la combustión de los autos a gasolina, ha sido mitigado, por co-evolución entre regulación e introducción comercial de sistemas catalíticos de control de emisiones. Esos sistemas ahora forman parte de cientos de millones de autos, camiones y buses en todo el mundo.

La presente tesis es un estudio desagregado de la introducción cerca de global de sistemas de control de emisiones catalíticos, como medida para reducir la contaminación atmosférica local. Se examina el proceso de introducción del convertidor catalítico “de tres vías” para autos a gasolina en cuatro países. Se estudia la innovación presente en el área de sistemas de control de emisiones de motores diesel. El cambio tecnológico es analizado viendo el proceso y el sistema de innovación y los distintos grupos de interés. Los resultados se usan para analizar las implicaciones en cuanto a innovación y política de regulación para enfrentar los desafíos medioambientales actuales.

Catálisis automotriz es un ejemplo de innovación motivado ambientalmente, incluyendo definición del problema, regulación pública, estratégicas corporativas dentro y fuera de mercado, variedad, selección, transferencia de tecnología, difusión masiva y la co-evolución continuo entre política de reducción de emisiones y desarrollo tecnológico.

Denominaciones comunes para innovaciones exitosas, tecnológicas o de mercado, son un diálogo dinámico sobre planes de regulación estructurados en etapas, competición internacional, apoyo y coordinación de redes internacionales, y opinión local beneficiario. La introducción global del catalizador de tres vías fue compleja y altamente relacionada con el contexto local y condiciones locales, sugiriendo que estrategias “globales” de innovación y regulación para tratar los desafíos de hoy y mañana deben ser diseñados con entendimiento de factores locales a favor y en contra para innovación ambientalmente motivado.

Dado los grupos de interés, los desafíos tecnológicos y las trayectorias presentes en el área de mitigación del cambio climático, se concluye que el aumento de uso eficiente de combustible y la introducción de vehículos híbridos enchufables (*plug- in*) son alternativas viables para el transporte sustentable.

概要

1970年代の中頃から今日に至るまで，先進国においては，自動車触媒技術の導入と規制との相互作用によって、ガソリン乗用車から排出される一酸化炭素CO，炭化水素HC，窒素酸化物NO_xによる大気汚染への寄与率は減少している。現在では、この自動車触媒はディーゼル乗用車、トラックやバスなどを含めて何億台もの自動車で使われている。

この論文は，各地域での大気汚染を解決する手段としての触媒の地球規模での導入に関する調査研究である。ガソリン乗用車への三元触媒導入の過程を４か国比較で行うと共に，現在取り組まれているディーゼル機関の排出ガス制御についても研究した。これらの例の技術革新について、その内容を、技術革新に係る利害関係者（ステークスホルダー）の観点から技術の変革について分析した。これらの結果から，将来の環境問題に対応するためのイノベーションと規制に関する政策への示唆を行なった。

自動車用触媒は，問題定義，規制，市場原理に基づくないしは市場原理に基づかない戦略，開発，多様性，選択，技術移転，技術普及，そして今もなお進化する排出ガス削減に関する規制（政策）と技術開発との相乗効果，等々を含んだ「環境保護に起因する技術革新」の良い例である。

技術革新、および普及の成功例に共通していることは，
1. 構造的かつ段階的な「目標へのロードマップ」を巡る相方向の会話，
2. 国際競争力，
3. 国際的ネットワークによるサポート，
4. 地域社会に支持された意見，
等が挙げられる。

三元触媒の導入はほぼ全世界に及ぶが，その過程は複雑で、地域（国）の事情に強く依存する。つまり、現在または未来の、各国（地域的）または地球規模の問題に焦点を当てた「世界的」技術革新や規制戦略は、地域よって異なる障害の存在や、環境保護の視点に立った技術革新を推進する潜在力への理解なしには成り立たないことを意味するのである。

気候変動を緩和するための様々な技術体系からの技術的挑戦および関係者（ステークスホルダー）の意見を考慮すると，燃費向上とプラグイン・ハイブリッドの導入が，交通部門における持続可能な発展への道のりであると言える。

List of papers

This thesis is based on work reported in the following papers, referred to by roman numerals in the cover essay.

Cover essay: *Towards a sustainable automotive industry: experiences from the development of emission control systems*

I. *International Private and Public Reinforcing Dependencies for the Innovation of Automotive Emission Control Systems in Japan and USA,* D. Bauner. The paper is a modified version of the revised submission to International Environmental Agreements: Politics, Law and Economics.

An earlier version of this paper was presented at the IPSI-2004 (University of Belgrade) Conference, Montenegro, 2004.

II. *Global innovation vs. local regulation: introduction of automotive emission control in Sweden and Europe*, D. Bauner, International Journal of Environmental Technology and Management, Vol. 7, Nos. 1/2 (2007)

III. *Entrepreneurship in a Routinized Regime: Catalytic Suppliers in Environmental Product Innovation,* D. Bauner. Resubmitted to International Journal of Entrepreneurial Behaviour & Research.

An early version in Swedish of the main case study was published as a section of D.Bauner & S.Laestadius; *Nya Emissionskrav för Dieselmotorer- En Katalysator för Svensk Industri*? Vinnova Rapport VR 2005:09, VINNOVA (2005)

IV. *The Introduction of the Automotive Catalytic Converter in Chile,* D. Bauner and S. Laestadius, Journal of Transport Economics and Policy, Vol. 37, Part 2, pp. 157–199 (2003)

V. *Evolving Technological Systems for Diesel Engine Emission Control: Balancing GHG and Local Emissions,* D. Bauner, N. Iida & S. Laestadius. Submitted to Clean Technologies and Environmental Policy.

A first version of this paper was presented as a report, D.Bauner & S.Laestadius; *Nya Emissionskrav för Dieselmotorer- En Katalysator för Svensk Industri*? Vinnova Rapport VR 2005:09, VINNOVA (2005). The paper is a shortened, translated and updated version of the report.

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1 Introduction

1.1 Background

As we entered the 20th century, different propulsion technologies developed in the Western hemisphere. Vehicles using electricity, fossil fuels and crop-based fuels such as ethanol competed, initially with fairly even success, for consumer approval. An electric vehicle was the first to reach 100 km/h, and Henry Fords A-Ford model and the original Diesel engine were designed for crop-based fuels. However, in the course of time the Diesel and Otto engines, driven by fossil diesel and gasoline fuel, came to dominate regarding road vehicles. Dominance was so strong that it took almost a century for any alternative to return to compete. In the 1990s, interest for alternative propulsion technologies such as electric and hybrid vehicles was on the rise in the Triad area: Europe, USA and Japan. However, the different initiatives did by no means result in the proliferation that was envisioned. Maruo (1996), Fogelberg (1997, 2000), Calef & Goble (2007) and other scholars have analyzed what factors hampered the entry of electric vehicles as it was mandated in California. Between 1992 and 1997, I worked with different projects aiming at introducing electric and hybrid vehicles in Sweden, Europe and the world, involving public and private institutions as well as consumers. The lack of sustained commercial response to public initiatives to introduce the electric drivetrain[1] in Europe, USA and Japan raised questions. To set the agenda for change, it appears interesting to study innovative behavior that in fact did entail widespread commercial introduction. Seemingly, a lot of research has focused on inventive activities, i.e. creating new technology, rather than on the production and distribution side, which actually brings new technology to effective use. Looking to success stories, the automotive three-way catalyst (TWC) system stands out as the hotly debated but highly functional technology that directly and indirectly played a central role in modernizing the mechanical combustion engine to a chemically more effective and environmentally more compatible powerplant. The developments have been studied from different aspects in some detail (Maruo, 1996; Mondt, 2000; Berg, 2003; Gerard & Lave, 2005; Amey, 1995; Boehmer-Christiansen & Weidner, 1995; Burke et al 2004) but the networks, the industrial dynamics and complex, institutional innovative behavior in different stages of the multinational introduction has hitherto not been thoroughly analyzed. This study aims to fill in that gap.

As we have entered the 21st century 'mild' hybrid vehicles are a commercial reality, mostly thanks to Japanese carmakers, but electric vehicles and plug-in (or 'full') hybrids are not. Given the hitherto limited success of new electric powertrains, why study the innovation and commercial introduction of a "successful" technology instead of the failures? At least three reasons can be identified:

The *first* reason is to understand the logic for environmental innovation and proliferation, here focusing on the automotive field. The immediate and visible benefits of mobility, in part related to freedom, is a centerpiece in modern society, including great breadth and width in the technological and commercial attention to moving people and goods for optimal utilitarian value**.** The more distant and non-visible costs connected to mobility are often neglected, including environmental impact and the political resources required to maintain sound development. The *second* reason is**:** by relating the empirical findings to theories on

[1] Here: plug-in hybrids, battery electric and fuel cell vehicles

innovation and diffusion in the different phases and perspectives of the development, to discuss the aptness of theories or where there is an apparent glitch regarding environmentally motivated innovation. The *third* reason is to balance the prevalent focus on the invention and initial innovation phase of the introduction and use of a new technology. Often, the pioneer and the pioneering market is closely monitored and analyzed. Here, I study also the incremental and less glamorous phases of innovation and the characteristics of the introduction and 'muddling through' processes where the technology is mature, but the market and its institutions are not.

I will in this dissertation shed some light on the nature of innovation in a large socio-technical system (cf. Carlsson, 1995 & Hughes, 1989), focusing on technological, legal and organizational details of a major internalization of external cost, local air pollution from gasoline cars, brought to wide public attention in the 1960s, accelerated in the 1970s and 1980s, and completed in many developed countries in the 1990s. The solution, reducing regulated emissions per vehicle with over 90%, was the three-way catalyst emission control system that gradually became dominant in the 1980s and 1990s, and recently manifested by the 2007 Nobel prize in chemistry, awarded to Professor Emeritus Gerhard Ertl for his advances in catalytic processes research. The system is *embedded* - a term usually reserved for information technology - in hundreds of millions of vehicles all over the world. In a similar bout of regulation and innovation, local air quality problems from trucks, buses and diesel cars are now addressed in dominating markets.

The backdrop is thus an interest in understanding the chain and its links that translate problems to solutions, and that pull technology out from laboratories to global market penetration. I have sought to contribute to this understanding by characterizing how innovations for an environmentally motivated technology have developed over the past four decades. Automotive technology is part of the individual mobility society; in turn an important part of the transportation system with widespread impact on the economy, society and environment. An understanding about the complexity at introducing emission control systems so far will hopefully be of importance when turning to the challenges we now face regarding greenhouse gas emissions.

There are many aspects of this development that deserves attention. One of the Swedish interviewees for this study said "it is easier to propose a 5% improvement to a vehicle manufacturer than a 40% improvement". What does that say about innovation in the automotive industry? Another strand is to examine the Porter/van der Linde (1995) statement that there are an abundance of win-win potential in the intersection between company product development and environmental goals. Yet another strand is the Latourean (1997) view of a "construct" that can be followed from birth to adulthood, and in this case the complexity of what may appear to be a straightforward diffusion process around the world.

This dissertation focuses on identifying factors relevant to the introduction of automotive emission control. The scope is to study the management of a technological system regarding innovation, supply and demand in different regions over time. The specific objective is to analyze the development from three perspectives:

1. What can the global introduction of the three-way catalyst tell us about trajectory development in environmental (environmentally motivated) innovation, as the catalytic emission control system goes from a chemical method to a commercial fact?

2. What can actor analysis tell us of the relation between stakeholders and technological change?
3. What does this imply for policy and innovation to address coming challenges, especially regarding fuel infrastructure and vehicle drivetrains?

1.2 Method

My own background in being actively involved in the introduction of renewable fuels and electric & hybrid vehicles has influenced the method chosen in studying the introduction of a new technology. While creation and verification of econometric models and research based on database statistics may be the backbone of economic research, this cover essay aims at analyzing and summarizing disaggregated studies of development of legal requirements as a precursor to innovation. It also bears evidence of the opposite: that innovation can lead to advancements in regulation, and thus speed up diffusion of technology to reduce environmental impact.

Empirical studies and developing the analysis for this dissertation was carried out over ten years, 1998 to 2007. Work has been carried out in the shape of literature studies, “technological” studies and interviews in Europe, North and South America and Asia. I have tried to relate interview answers to documentation and balance results from one interview with another – e.g. what part of achievements of a competitor of the affiliation of a given interviewee, which would be instrumental to understand the development, was <u>not</u> brought up in a response? In several cases, initial contacts with scholars and industry professionals led to other contacts, sources and insights that have proven valuable. Important when gathering material for understanding this co-evolution of technical, commercial, environmental and political issues has been to understand that a lot of what happens as the “mix“ is not documented in all respects. Especially in the history of environmental actions and inertia, tailoring the facts “to get a place in the sun” - to receive goodwill for an action taken - may be fairly common. Regarding the initial research and innovation efforts in the history of environmental catalysis, the different interviews concern people that were initially involved up over 20 years ago. Ex-post accounting of an event may then leave room for ambiguity. For every interview, I have noted the person’s background (CV) to be able to interpret answers and to put them in context of current and previous positions. I have secured second opinions on sensitive or unclear issues. For the technical evaluation of the development, initial interviews and other professional coincidences brought me into the field of emission control, and so into emissions, and 2001-2006 I held a part-time employment with *Motortestcenter*, initially a national automotive emission test laboratory in Sweden. In the end of 2002 this laboratory was privatized, shifting its role towards engine consultancy to the vehicle industry, and I have thus been able to work closely in emission testing and emission control technology development both from a state and a private perspective in parallel with this research work.

The rich empirical findings or *thick history* also pose problems of selection of sources. A very large number of people were part of shaping history in the different countries and phases of the development. In the myopia of smaller and larger trajectories, material that would support different standpoints as to cause and effect may be found, and an exhaustive analysis of all existing experience and material is impossible to do even in the decade-long timeframe of the project of which this dissertation is the main result - an attempt to cover enough ground both in theoretical background, empirical evidence and analysis to understand the prerequisites for survival for environmentally motivated technology. Limits are set by how representative the artifact is for the more general term of environmentally motivated technology. Thus, it is not a study on how environmental innovation excellence can induce market advantages. Neither is it an exhaustive study on all innovation involving catalysis in the automotive sector. This is thus one of the possible accounts.

1.3 Structure of the thesis

The dissertation is structured in this cover essay and five papers. To understand the development logic, if the reader has not previously engaged in engine development or environmental regulation, an initial reading of section 3.1 is recommended. Thereafter, the rest of the thesis can be read in any order desirable.

1.3.1 Cover essay

From close to a decade of study an outline of the origin and proliferation of an environmentally motivated technology, this cover essay defines a structure and synthesis of the dissertation, including the adjoining papers, to give a brief outline of the development to which the adjoining papers bring depth, to motivate the specific issues brought up in the thesis and to summarize the main results. Finally, present and imaginable/needed future technological innovation trajectories are discussed with a background of what we have seen for the TWC and diesel emission control systems. The objectives of this cover essay naturally coincide with that of the thesis (see page 2). To this end, four main themes were identified:

Section 3.1 gives an overview of the introduction of catalytic automotive emission control systems detailed in the five papers

Section 3.2 provides definitions and analysis of the links between environmental impacts, regulation and ensuing innovation and

Section 3.3 is an Actor study of the stakeholders involved

Section 4 evaluates the applicability of the results, as an example of analysis of the dynamics in a technological system

1.3.2 Five papers

The core of this dissertation consists of the five papers which may be looked upon as five different aspects of analyzing the development and introduction of modern automotive emission control systems. Paper I – IV are process oriented longitudinal studies, capturing the dynamics, the trajectories and the evolutionary character of the processes. The fifth paper is a partly comparative study focused on the structure and complexity of (parts of) the system and may be looked upon as more static. Together, the intention is to contribute to the understanding of the mechanisms involved in the complex transformation of the automotive system towards sustainability. The time interval in parenthesis indicates the main period concerned for each paper.

Paper I (1950-1983) describes agenda setting, initial linking of environmental problems to the source and understanding technological fixes. Focus is set on the interplay between domestic car manufacturers and their respective governments in USA and Japan in early innovation, development of regulation and introduction of three-way catalyst equipped cars. Since problem definition, regulatory development as well as technological research and development was to a large extent carried out in coordination between public and private actors in the two countries, findings are aggregated into one paper. Paper I deals with path dependence (Arthur), industrial dynamics (Rosenberg), disruptive innovation (Christensen), systems (Hughes) and the emergence of a dominant design (Utterback).

The other market in the Triad, Europe, was chosen for its role in industrial and technology development. **Paper II** (1960-1995) illustrates the interaction between industrial policy and emission regulation in a more diversified market both regarding production and government. Differences in industrial capability and consumer demand between different European regions lead to a staged introduction completed only in the mid-1990s. Paper II deals with dominant design (Utterback) and the common passage point of emission standards (Law and Callon), Development blocs (Dahmén) and shaping of demand (Hollander).

To identify the role of the supplier in environmental innovation, **Paper III** (1982–2004) outlines the development of actors and behavior in an area of supply, and gives an account of a commercial initiative/startup JV to produce catalytic converters and its development and market adaptation over a decade. The complexity of market entry in an established supplier structure is demonstrated. The paper also touches upon the transfer of knowledge from gasoline engine emissions catalysts to the diesel engine catalysts. Paper III deals with capabilities (Nelson and Winter, Pisano, Fujimoto), Competence Blocs (Eliasson), Relationships (Håkanson & Snehota), entrepreneurship (Schumpeter, Kirzner, Arrow), Regimes (Marsili) & Catching up (Perez & Soete) and Architectural innovation (Henderson & Clark).

To understand the characteristics of diffusion of mature environmental technology in a less industrialized context, **Paper IV** (1985-1998) studies the introduction of strict emission regulation and vehicle emission control technology in Chile. Here TWCs are mature technology and the crucial task is to adopt feasible requirements and the means to make compliant technology, both regarding vehicles and fuels, available to consumers. Paper IV deals with regulated markets (Dobers), win-win environmental innovation (Porter & van der Linde), a now global level of dominant design (Utterback) and path dependence (Arthur), Regime shifts (Kemp), and diffusion models (Bass, Dosi, Rogers, Griliches).

To assess the dynamics of catalyst (and non-catalyst) development at present, where end customers are commercial rather than private, **Paper V (**2005-2007) describes and analyzes present regulation and industrial response regarding Diesel vehicle emission control. A greater variety of technological alternatives and different regulatory regimes in the Triad creates diversification also on a commercial level. Paper V deals with trajectories (Dosi, Vincenti), evolutionary economics (Nelson & Winter) in a non-growth context, Cluster analysis, Dahméns development blocs anew, Technological systems (Carlson, Hughes), globalization (Kennedy, Florida, Dunning), Co-evolution (Nelson) and epistemic cultures (Fogelberg, Gibbons).

The five papers have been submitted to peer-reviewed scientific journals. Two of the papers are published and another two are being reviewed after initial comments at the time of printing of the dissertation.

2 Theory and concepts

As each of the five papers contain the theoretical framework necessary for the analysis in that respective paper, the theoretical discussion here focuses on the questions raised in this cover essay. The topical structure in this section therefore adheres to that of section 3.2.

Formulation of demand

Pollution can be seen as an external cost (Coase, 1937), and demand for cleaner technology created from regulation or incentives can be seen as internalization of such a cost. A regulated market mimics much of the behavior of a natural market (Dobers, 1995). The initiation of a demand profile for new technology in line with what can be invented or developed is a process in itself, often with considerable time lags as different stakeholders are included (Hollander, 1995). Apart from regulation, investments can be more or less geared towards creating products and services that addresses environmental issues. Investors may acknowledge minimum environmental and ethical considerations for an investment, and the environmental performance of a company can be monitored by environmental accounting and certification (Cerin, 2004).

Policy and technology

Policy drives technology, and technology drives policy. Boehmer-Christiansen and Wiedner (1995) propose a three-stage taxonomy for environmental policy development: *ecological ignorance,* an initial shunning of facts and lack of interest in the warning signals from the surrounding environment; *symbolic policy,* initial recognition but lacking power to deal with the real issues, and finally, *technocratic effectiveness*, where policy is developed to accommodate the different concerns of government in relation to the 'real' costs and benefits of different tools.

Kemp (1997) discusses *control regimes*: incentive-based (e.g. carbon taxes, pollution fees, tradable permits and investment subsidies) and command-and-control based (performance standards, product bans). Different kinds of policy instruments drive different kind of innovation. *Direct regulation* in general fosters abatement of pollution and end-of-pipe technologies. Tiered regulation[2], as done in the Triad, may foster both incremental and more radical innovation since the lead times are longer and issues preceding regulation can be addressed prior to enforcement. *Policies for the "greening" of industry* – stick and carrot measures - drives process changes towards cleaner technology. More general *sustainable policy* – framework policies for industrial ecology and lifecycle analysis - promote resource efficiency and potentially more radical innovation. Sustainable policy-making generally involves long-term planning horizons and consideration of equity implications. Opportunities for international cooperation should be sought (OECD, 2001). There are also *technological regimes*, such as the system of fuel, roads, vehicles and their users that constitute the present road transport system. Kemp et al (1999) suggest that a shift from one regime to the next on a market often takes place over several decades as demand is defined, and include whole new systems of related technologies. A new technology or system can become embedded in society by means of establishing a tailored "niche" (e.g. through subsidies, public

[2] A legal roadmap with gradually more severe regulation is set up in dialogue with affected industries, enabling a long term view on cost and benefits of measures to curb e.g. pollution.

procurement or a pilot project), where a new technology may mature to survive in a conventional market. A regulated market may constitute such a niche.

Wallace (1995) has described the co-evolution between regulators and industry in different national contexts. He stresses the link between adaptability to new, more strict emission regulation and new industrial development and production processes, specifically the introduction of lean production in Japan and the UK (Rover), and concludes that regulatory and industrial development can profit mutually from cooperation in fostering innovation.

Legitimacy is a key aspect that guides cooperative behavior (Leveque, 1995; Hanberger, 2003). Legitimacy is hard to identify and define, and is perhaps easier understood negatively, as what follows from a lack of legitimacy in policymaking. Rajan (1996) argues that policy is not formed, and the formation of policy cannot be understood, out of formal authority and immediate necessities alone, but based also on a more broad political resolution made by the governing power. Automobile pollution regulation is referred to as technological rather than ethical and usually placed outside the field of politics. By presenting scientific evidence in support of the chosen policy approach, legitimacy is protected. Different nations have different traditions in policymaking – while Japan is more inclined towards consensus driven policy process, state intervention in USA is traditionally questioned in civil courts (Laufer and Paradeise, 1990).

In the initial phases of evaluating environmental impact and routes to mitigation, regulation and technology is in a liquid state. Research and debate on impact, solutions and consequences precede policy making and involves public and private stakeholders. Ng (2006) has shown that the latter include "non-market" activities such as lobbying and technical demonstrations for or against regulation and incentives to support corporate objectives.

Innovation

Nelson and Winther (1982) propose an evolutionary view on economic change, where equilibrium is constantly offset by changes in the market by e.g. innovation, creating variety. The market adapts by selecting according to the present variety, creating a new temporary equilibrium in anticipation of a new offer. Rosenberg (1994) and Laestadius (1998) sustain that policy analysis requires understanding of innovation and technical development.

Schumpeter (1934, 1942) dealt with innovation in large companies, during a formation phase of "large combines" in the West. Innovation was defined as including invention, innovation (from R&D work to first commercial introduction), and diffusion. Schumpeterian innovation involves the creation of new markets, often by breaking down structures and eliminating old solutions in favor of new. The development of a new technology is focused on product improvement, and as the technology matures this focus typically shifts to a process focus, reaping increasing returns and impeding entry. In the words of Christensen (1997), 'disruptive' innovation can break trajectories by introducing new technology, often involving new actors in a co-evolutionary (Nelson, 1998) fashion. Non-tyrannical regulatory change requires legitimacy, which can be facilitated by a *common point* of *passage* (Law and Callon, 1992) in some form between the different stakeholders – limit values, measurement technology or a dominant demand where diverging tendencies in the development of a technology or practice can be defined and aligned. Fogelberg (2003) argues that communication may be difficult between different knowledge or *epistemic* cultures, and that *trans-epistemic objects*, such as measurement methods and technology, can be used to bridge the communication gap.

Innovation is often found to form and follow a trajectory. A *technological paradigm*, a concept defined by Dosi, involves an artifact and a trajectory - a set of *heuristics* in the words of Dosi (1988). Arthur (1994) discusses the dependency to such a trajectory or path of development – several types of self-reinforcing mechanisms often causes *lock-in* of such trajectories. An example is the strong path dependency of the automobile, where the car, the road network and the fuel provisions have co-developed into a working whole with strong increasing returns and economies of scale.

Scaling up from companies towards systems, we find a Competence Bloc, defined by Eliasson and Eliasson (1996). It contains the components necessary for growth: Inventors, entrepreneurs, venture capitalists, exploiters (customers), second hand actors and industrialists. An innovation system (Edquist, 1997) would then hold one or a number of related but discernible competence blocs. Cooperation in alliances and partnerships facilitate development of attractive products and components and are increasing (Maheshwari, Kumar & Kumar, 2006) following the restructuring of the automotive industry that was already well underway in the 1980s (Volpato, 2002). Taking a Technological System (Carlsson, 1995; Hughes, 1989; Jacobsson and Johnson, 2000) as unit of analysis of innovative behavior is motivated by that innovation in a given firm cannot be understood in terms of the independent decision-making on firm level; political conditions, market integration dynamics, regulation and collaborative patterns guide development as well as the actions of individual companies.

A set of guiding rules or principles for the development and proliferation of a technology are said to form a regime (Kemp, 1995) or paradigm (Kuhn, 1970). Also inside a paradigm, trajectories appear; the V8 engine in USA cars is an example. Part of the reason for lock-in is that an established regime encourages co-evolution between synergetic systems by reducing investment risk. Building on the innovation theories mentioned, Unruh (2000) introduces the notion of a *Techno-Institutional Complex* as technological, organizational and institutional forces holding together technological systems and government institutions, causing technological lock-in by self-reinforcing and conservative mechanisms. Unruh (2002) and Unruh & Carillo-Hermosilla (2006) argue that policy to reduce GHG emissions must be designed in view of global carbon lock-in, and that forces exogenous to the often self-referential TICs are likely to be needed.

Innovation patterns may differ between different types of actors – suppliers and entrepreneurial startups may take interest in leading change where the incumbents may not. A market or a product area may be more or less suitable for entry; Marsili (2002) proposes a typology to distinguish entrepreneurial and routinized regimes, where the latter would favor innovation by incumbents, e.g. due to entry costs or a high degree of vertical integration. Porter and van der Linde (1995) suggest a potential for manufacturers related to Christensen's disruptive technologies – by renewing the offer in view of the cost of pollution cleanup, a new generation of clean product and production technologies may be innovated that avoids the tug-o-war between regulators and polluters in many routinized industries.

Environmentally motivated innovation (EMI), introduced here, can be loosely defined as an innovation that is brought about in response to an environmental problem. "Environmental" is especially difficult to contain within the concept of innovation since it is something that reduces the environmental burden on humans, on a species or on nature or society as a whole.

A reduced burden may be achieved by abstaining from an activity just as much (or even more) compared to doing something (such as polluting) in a better way. The difference between an EMI and the seemingly more straightforward "environmental innovation" is that the former is conscious development; it is an innovation, i.e. a concept which is turned into an artifact or system used in society, that by intention has a positive or less negative impact on the environment. For an environmental innovation, the intention is not an issue. As an example, while environmental concerns was not the rationale of inventing the Internet, the introduction of electronic mail has theoretically reduced the need to send documents by physical mail, thereby reducing transport.

Global introduction

Most of the innovation processes described in literature discusses parts of the chain from politics-regulation-technology-diffusion in a national context. International agreements (Sjöstedt, Svedin & Aniansson-Hägerhäll, 1993) leave the protective armor of national legislation and enter an area historically hard hit by broken promises and conflict. The diffusion of technology and adoption of innovations is thus dependent on strong drivers for change. Such drivers can be economic, legal, sociological, or technical. It is widely discussed why technologies often linger so long before taking off. Griliches (1960) suggests that diffusion occurs when the new technology is profitable or useful - a time lag between invention and wide-spread diffusion is not necessarily a consequence of bad information or conservative behavior. Change also requires change agents. Dosi (1991) highlights the learning needed by adopters and technological asymmetries between different organizations as decisive to diffusion. Huber (2004) discusses the evolutionary technical, spatial and temporal developments of the innovation lifecycle, where different generations of a technology play the same role in a technological system. In the course of development, components of the system are defined which can then Rodgers (1995) distinguishes Agenda-setting, Matching, Redefining, Clarifying and Routinizing as steps that must be taken for an institution that adopts an innovation. For the transfer of knowledge and implementation of innovation in larger technological systems (Carlsson, 1995; Hughes, 1989), a multinational network is necessary. A global introduction of a given technology or a demand profile would coordinated require a number of levels of policymaking. Notwithstanding, national legitimacy for regulating or giving incentives to the use of such technology is required for each nation involved. Jacobsson and Lauber (2004) list *institutional change*, the *generation of markets* (niches), entry of *advocacy coalitions* and *entry of new firms* as crucial elements of diffusion development. Such (national) coalitions may then be natural representatives and mediators in an international network

Grübler (1997) describes the discrepancy between a resulting smooth "S"-curve describing macroeconomic diffusion and the complex and diverse microeconomic interaction that shapes the statistical result. This complexity is also discussed by Rosenberg (1982, 1994).

3 Results

This section summarizes the results over a number of topics and across the attached papers

Innovation, including invention, commercial development, regulation and enforcement, the artifact or innovation lifecycle and its diffusion on different markets involves complex interaction between different actors. While "just" being a technical system, the three-way catalyst has played different roles for each actor type in the course of its development. The interest in using or promoting a given technology is related to the goals of the respective organization or actor type. Catalytic emission control systems, as all other technological systems and a great deal of other systems, go through different phases of maturity in the course of development. The roles of the TWC for each stakeholder have thus also shifted during its journey from research topic to dominant technology. To understand innovative behavior, the image projected on the emerging technology and the actions taken by the different stakeholders as a result of this interpretation is thus understood as important. This is further complicated if a technology is spread across different cultures and levels of economic development. The chain of events and the development outlined in section 3.1 and the five included papers may be applicable in addressing the challenges of today and tomorrow.

3.1 Overview of innovation of catalyst based engine emission control systems

This section outlines the trajectory of advanced catalyst technology development, specifically the three-way catalyst (gasoline/petrol or Otto engine) emission control system, from its inception to maturity, complemented by the present innovation in diesel engine emission control systems. Material from ***Paper I-V*** *is included.*

Catalysis is a chemical process widely used, applied to change chemical qualities of gases and liquid chemicals. A catalyst is (in general) a material that increases the rate (molecules converted per time unit) of a chemical reaction while itself not undergoing any permanent change. *Homogeneous* catalysis, when the catalyst (including substrate) is part of the reaction, is used for cracking of petroleum. The catalytic material is applied to ceramic (usually zeolite) pellets and mixed with the petroleum substance for a short period, during which the catalyst enhances the chemical reaction. *Heterogeneous* (when the catalyst is fixed) or environmental catalysis was first mentioned in a reference in Scientific American in 1920[3]. An automotive catalyst (reducing hydrocarbons and carbon monoxide emissions) with a monolith structure similar to today's catalysts was patented in the 1950s in USA (**Paper III**). Both precious and non-precious metals can be used for catalysis, although Platinum (Pt), Palladium (Pd) and Rhodium (Rh) dominate. Platinum is the classic catalyst support and palladium and rhodium came later. Essentially palladium is a better support metal, but requires absolutely lead free fuel. Non-precious metals are cheaper and less prone to lead poisoning, but have shorter life and lower catalytic activity. The bulk use of catalytic converters up to 1975 was for chemical industrial processes, such as cracking of petroleum and production of chemicals (Gevert and Järås, 2002).

[3] Interview with Rob Searles, AECC, 1998

According to Berg (2003), “emission control legislation” has been part of the requirements profile of the automotive engine and vehicle for approximately 50 years. In the end of the 1950s, initial regulatory measures were taken to reduce the emissions from the growing fleets of passenger cars in USA. Japan followed as the number of passenger-kilometers traveled by car rose from around 10 billion in 1960 to 200 billion in 1970. Emissions took the form of smog in larger cities, worsened by local atmospheric conditions. Initial technical screening showed some promise of solution[4]. National processes began or accelerated in the 1960s in several countries where regulators, having identified vehicle emissions as an important contributor to air pollution, sought to compel the domestic car companies to change. In USA the Clean Air Act (CAA) in 1970 required 90% reduction of hydrocarbons and carbon monoxide compared to vehicles without emission control by 1975. Later, emission requirements were extended to include also nitrogen oxides. Such improvement was not technically proven or feasible at the time. Mostly in USA, different methods and technologies were proposed to reduce local pollution, including trials with fuel rationing and engines outside the internal combustion engine (ICE) regime (JPL, 1974; AOS, 1974), as well as different emission control technologies. It was not clear if the ICE was the salient solution. Nevertheless, the principle requirements spelled out in the CAA – both regarding levels and timing of introduction – was adopted also by Japan, where pollution from industry and traffic had induced public reactions as the country shifted away from initial awe for industrial development and disregard for environmental sacrifice (**Paper I**). Several options to reduce emissions were explored (see Table 1), mostly in USA.

Table 1. Alternative technologies investigated to reduce engine emissions in passenger cars in the 1970s and 1980s (JPL, 1974; AOS, 1974 and other sources)

Internal combustion (piston) engine regime	Non-ICE alternatives
Ignition timing retard Closed crankcase ventilation Thermal reactors Pulsair (air injected into exhaust pipe for improved combustion of exhaust gases) Stratified charge Lean-burn engines Exhaust gas recirculation Oxidation catalysis Three-way catalysis (TWC) (including fuel injection and feedback-loop engine control) Rotary (Wankel) engines Electronic ignition Mechanical and Electronic fuel injection Diesel engines Hybrid technology Alternative fuel engines	Gas turbine engines Rankine (Steam) engines Stirling (external combustion) engines Electric drivetrains (full/plug-in hybrids, battery electric vehicles and trolley buses) Fuel cell technology

Soon, however, it was understood that the cost of leaving the ICE would be high and discussions gradually turned to means to adapt the present regime to coming requirements.

[4] An early test, including contact between the car industry and catalyst technology, was carried out in 1958 by USA process development company Universal Oil Products. A straight 8-cylinder engine provided by a car manufacturer was fitted with low-density aluminum porous pellets impregnated with platinum. At that time, CO and HC emissions from a normal uncontrolled engine were several orders of magnitude higher than from today’s vehicles. The pellets were placed freely in a housing which was then fitted to the manifold. As it turned out, the negative pressure pulses from the 4-stroke engine actually sucked some of the pellets back into the engine and ruined it. However, the device functioned initially (Interview with Jim Thoss, Johnson Matthey, Pennsylvania 1999).

Since the levels to be required or the *common passage point* had been defined, the industry cooperated to find a solution that would be neutral to competition. Closed crankcase ventilation had already been implemented and focus was initially on thermal reactors, oxidation catalysis, stratified charge ignition, lean-burn and rotary engines. Catalysis became the dominant trajectory in the course of the 1970s. Combustion control was the key to effectively reduce emissions by exhaust catalysis. For oxidizing catalysts, the air/fuel mixture must be kept lean. This could be done either by keeping combustion on the lean side or by forcing oxygen (air) into the exhaust stream with a valve or an air pump. Reduction catalysts required a rich mixture. The better the control of the air/fuel mixture, the better the potential for good combustion and effective exhaust aftertreatment. Only after years of partly successful trials, three-way catalysis (TWC) emerged with a potential to address the three regulated emissions (HC, CO, NOx). Durability of the catalyst and unsatisfactory engine control was in time identified as the main problems for reducing emissions using TWCs. Unleaded gasoline was also required. Car manufacturers teamed up with companies that provided what was needed to provide complete systems – in some cases the competence was created in daughter companies. Suppliers developed emission control system components, often based on industrial experiences from related areas.

The TWC is thus (part of) a system of engine emission control[5] rather than an individual component, as were earlier catalyst types. Non-catalyst technologies for emission reduction existed in parallel with TWCs for several years, but did not reduce emissions sufficiently or were not commercially optimal e.g. in scaling the technology for the range of existing engines with a given car manufacturer. In the early days, there were scientific exchange, cooperation between regulators in the two pioneering countries and industrial joint development were established between car manufacturers and oil companies. Test methods were refined, and unleaded gasoline was gradually introduced – taking two decades in USA, while only one decade in Japan due to a flawed market model in USA and a lead intoxication scare in Japan. The latter made Japan's entire petroleum industry drop lead content in gasoline by half over a few months. Visible air pollution in both countries, and a galloping vehicle export increase of smaller[6] Japanese cars to USA in the wake of the oil crisis of 1973, brought both a public and a corporate momentum for change. Oxidation catalysts were introduced only in USA. After initial controversies regarding timing and strictness of regulation and enforcement, TWC level emission requirements were enacted for new passenger cars in California[7] (1977) and Japan (1978). Some car models had initial driveability problems and high fuel consumption, something that was corrected over the next few years. After several postponements, corresponding regulations were enacted also on the USA national (federal) level in 1981. Here, one of the impeding factors was the economic downturn in the end of the 1970s in USA.

Introducing TWCs in any market thus involves both technical and institutional development. "EPA 81"[8] or Euro 1 has since become synonymous with TWC introduction, even though older model technology was sold e.g. up to 1998 in USA. The regulatory and technical development in USA and Japan was monitored by other countries and regions also suffering

[5] Consisting of the following, jointly developed components: electronic fuel injection, feedback loop air/fuel control system, catalyst and sensors.

[6] In Japan, only about 5% or 209 thousand of the 4,56 million vehicles manufactured in 1971 had cylinder volumes above 2 litres, whereas in USA very few vehicles had engines below 2 litres volume.

[7] California had required emission levels that in turn had brought positive crankcase ventilation, EGR and oxidation catalysts before limits were brought down to where TWCs became the dominant response. Also federal USA required oxidation catalysts, while this step was not taken in Europe.

[8] or "EPA 83", including a diesel engine smoke emission limit added two years later.

from increasing air quality problems. European development was behind, partly due to postwar economic reconstruction (OECD, 1992). In the end of the 1970s, public investigations on the sources, effects and mitigation of pollution to air were developed in several European countries, around 10 years after similar initiatives in USA and Japan. Also European cities had their share of high concentration of primary pollutants. Smog formation was known in some cities such as London and Athens, whereas pollution in other places did not reach the same severity. Eutrophication of lakes, acid rain, mercury, PCB and lead poisoning and forest die-back from flue gas and ground ozone formation became issues in some countries and sparked the dialogue preceding change. Environmental policy development was guided by the sequence of environmental problems and the respective political reactions. In Germany, it was argued that environmental problems could be brought under control only under zero economic growth (OECD, 1992).

While some individual countries started earlier, a more specific debate on vehicle emissions was initiated on a European level in the beginning of the 1980s. Here, technologies were at hand, but unleaded fuel was not introduced and mature industries, especially in the small car segments in southern Europe and the ailing UK car industry, saw substantial disadvantages in a 'forced' adoption of TWC technology. As described in **Paper II**, the manufacturers in Northern Europe were already exporting their relatively large cars to USA equipped with fuel injection and TWCs. However, due to the economic logic of home market dominance, this did not imply that a fast introduction 'at home' was favored by any car manufacturer, even as public opinion against air pollution was stronger in e.g. Denmark, Sweden and Germany than in southern Europe. The north-south differentiation in the European car industry implied a need for balancing of employment, economics and environmental considerations. While Germany and Sweden decided in 1985 to require TWC emission levels for all new cars from 1989, the same requirements on a European level were blocked. At this point, the supplier market for components and systems had become an oligopoly that actively demonstrated the viability and benefits of strict vehicle emission regulation and instructed governments on banning lead in gasoline (**Paper III**). The 'capability gap' between North and South Europe was bridged temporarily by only raising the bar to a level where TWCs were required for larger cars, predominantly manufactured in the north. By the Single European Act (EU voting was changed to majority vote regarding product standards) the timeframe was set in 1991 by the European Council of Environmental Ministers to establish EU emission requirements at TWC levels[9] in 1993, known as Euro 1.

For each country introducing vehicle emission requirements corresponding to those achievable with a TWC, the tasks in Table 2 was completed, not necessarily in this order:

Table 2. Tasks required for national introduction of three-way catalyst emission control system for new gasoline passenger cars (own compilation).

- Introducing Euro 1, USEPA-81 or stricter emission level requirements for passenger cars nation-wide
- Introducing unleaded gasoline

[9] Consolidated Emissions Directive 91/441/EEC, including emission standards equivalent to 1987 U.S. levels. From 1993 new vehicles were certified in accordance with Euro 1 and in general equipped with TWCs. Some vehicles were able to pass Euro 1 certification without TWCs, implying that "TWC levels" strictly speaking only were reached by EURO 2 requirements from 1996. In Paper II, there are two errors on page 259 in this respect: First, Euro 1 emission regulation were set in 1991 for enactment 1993 (and not 1995 as written in the paper) and second, NEDC (the cold-start version of EDC) was not introduced until year 2000.

- Introducing (in the case of a national car industry also developing or adopting enabling technology) vehicles that comply with the new emission requirements
- Educating the public, particularly new car customers
- Establishing a national resource for vehicle homologation

Now the Triad, representing the majority of global supply and demand for passenger cars at the time, required TWCs for new cars. This implied that in the rest of the world it would be cheaper to produce vehicles without TWCs only for larger markets where models were specifically developed and manufactured. Brazil was (and is) such a market, with around a million employees in the automotive sector, where the introduction was debated as choosing between employment or environment over a seven year period. A different case was seen in Chile, where TWCs were introduced in little over a year. The factors in favor of a swift introduction were a common understanding of the grave environmental problems in the Santiago basin, a developed institutional framework that could regulate and enforce decisions, the absence of a need to balance environmental concern and employment, accessible dominant emission control technology requirements and matching commercial compliant technology, economic growth and local incentives for change (**Paper IV**). The supply formed as a critical mass of Japanese car producers decided to redirect (or add to) some of the production aimed for other markets to supply also Chile with TWC vehicles, while USA and French manufacturers where unable to revamp their South American production units in the face of the new requirements. Economic growth was an enabler for sustainable development (Cordero et al, 2005).

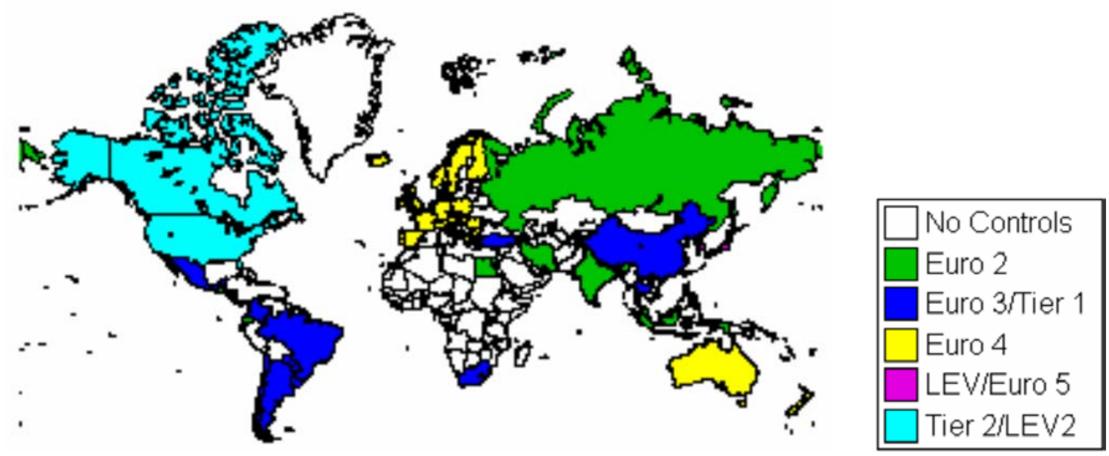

Figure 1. Emission controls (regulation) for gasoline passenger cars in 2007 (Source: M P Walsh, with permission).

The Triad countries have since continued to move along the tiered national (regional in Europe) regulatory roadmaps, gradually requiring lower vehicle emissions[10]. Harmonization of emission standards in North America is an important aspect of the North American Free Trade Agreement (NAFTA) involving Canada, Mexico, and the USA. Present levels (Euro 4 in Europe and Tier 2 in USA) are reflected by further improved emission control, e.g. a second smaller 'close-coupled' metal substrate catalyst that is located closer to the engine and thus commencing emissions reduction earlier in the drivecycle by faster reaching 'light-off' temperature.

[10] As an example, as the catalyst does not reduce emissions from fuel evaporated from the engine or anywhere upstream from the catalyst, evaporated fuel remained a large source of emissions and a carbon canister that stored and recycled gas fumes was later made mandatory for passenger cars in Japan, USA and Europe.

Many other countries, especially burgeoning developing countries, have linked their requirements to the ECE/European levels with different time lags. The United Nations Industrial Development Organization (UNIDO) has supported work to harmonize emission regulations in southeast Asia, supported by e.g. local associations for phasing out lead in gasoline. While introduction in Asia is most disperse (even excluding the early outlier Japan in the comparison) with over a decade in regulatory span between different countries, several Asian countries have established Euro 2 requirements from the year 2000 and on. New emission regulation in China has typically begun in the polluted cities. Euro 1 vehicle emission regulation was introduced nationwide in 2001 and the country is currently introducing Euro 3. This affects the new fraction of a growing fleet - the total number of cars in China rose from 5.5 million in 1989, to 14 million in 1999 and 24 million at the end of 2003, and the government forecasts that number to reach 156 million by 2020[11].Others, like many African nations, have for different reasons no emission regulation in place. Most of the world –again with the exception of most African countries and some Central Asian states - has banned lead in gasoline. Figure 1 illustrates the state of development in gasoline passenger car emission requirements 2007.

Diesel engine development has since the outset been ruled by its different business logic; while passenger cars are essentially developed for private users, trucks have commercial customers and heavy vehicles are almost always diesel driven. In some countries in early development, without access to clean fuel and advanced technologies, most motorized vehicles are used professionally. This has implied that diesel engine R&D focused on larger engines, and there has been a lag in emission reduction development and regulation - both regarding vehicles and fuel – for diesel engine vehicles of all sizes. As illustrated by the main **Paper III** case study, diesel emission reduction capability, especially regarding exhaust aftertreatment, is often developed from experience in reducing gasoline car emissions. From the outset, the work has been a balance between fuel economy – always important to commercial operators – and emissions (**Paper V**). There are tiered regulatory roadmaps for heavy duty (HD) vehicle emissions, co-evolving with diesel engine emission control development, established in USA, EU and Japan. EU HD regulation is introduced in many nations all over the world with different time lag, just as for passenger cars. The first emission standards for HD diesel (Euro I[12]) were introduced in Europe in 1992, i.e. before the pan-European "TWC level" standard for gasoline cars.

In the 1980s, turbo became dominant for heavy-duty diesel vehicles, improving performance, fuel economy and also emissions at altitude. In the end of the decade, mechanical fuel injection (shifting to electronic fuel injection by 2000) became dominant. In parallel, fuel quality was discussed in the same way as for gasoline cars. While for gasoline cars, the lead was the poisoning agent for catalysts, for diesel engines it is the sulfur levels in fuel that poses problems. It is not possible to use a catalytic coated particulate trap on a diesel engine if sulfur levels in the fuel exceeds 50 ppm (parts per million), and preferably 15 ppm should be sought. More than a decade after pioneering nations completed national introduction, 50 ppm sulfur diesel, also known as ULSD (ultra-low sulfur diesel) is now becoming available throughout the Triad, permitting regulation and introduction of catalytic exhaust aftertreatment. In many countries, sulfur content in diesel fuel is already reduced to less than 10 ppm. Earlier emission requirements and incremental innovation had lead to higher fuel injection pressures and other gradual emission reductions (**Paper V**). As electronic engine control was introduced, the risk

[11] M P Walsh Car Lines, August 2004. www.walshcarlines.com
[12] European regulation tiers for heavy duty (diesel) vehicles are normally indicated with roman numerals (I-VI), while arabic numerals (1-6) are used to indicate light-duty (gasoline and diesel) vehicle regulation.

of tampering has induced a need for *on-board diagnostic* (OBD) control of correct engine management to attain emission requirements. Development schemes are technology specific; For gasoline engine emission catalysts, retrofits were never successful – commercially, technically nor environmentally, whereas for heavy-duty vehicles that is historically where the technical state-of-the-art is commercialized and probed prior to regulation. The oligopoly suppliers for gasoline catalysts have competition from a number of other, smaller firms for diesel retrofits, often focusing on different niches such as mining or school buses. New knowledge of impacts on health and the environment fosters debate and subsequent regulations reflecting sustained concerns. An example here is diesel engine particle emissions, where new regulation is proposed in response to both new health research results as well as measurement technology development[13].

Passenger diesel cars have different roles on different markets. In Europe as a whole, passenger diesel cars account for approximately half of sales, while in USA only a few percent are diesel driven. Low USA diesel passenger car sales depend on the adoption of the same emission regulation for diesels as for gasoline cars. In Japan, less than 1 percent are diesel driven. Since 1992, the method for regulation is to define tiers of coming regulations and then define the emission levels and timing of each coming tier through more or less formal cost/benefit studies and stakeholder dialogue. In Europe, levels are set up to four years in advance of the date of implementation. Diesel passenger car emission requirements in Europe and Japan are managed under the same regulatory umbrella as gasoline cars, while in USA regulations are coordinated with heavy-duty diesel trucks and buses. At present, the Triad is introducing more strict regulation for both light and heavy-duty diesel vehicles. A number of alternative technologies are scrutinized by the manufacturers. The majority of heavy truck producers – a handful of large, global corporations and a number of smaller companies – have stated that SCR[14] is the technology of choice for meeting European regulation (2008 and 2010) and on other markets (**Paper V**). SCR consists of a catalyst that uses ammonium from urea (distributed as a non-toxic but slightly corrosive urea solution in water) as a reductant from a separate on-board tank. This choice is contested by a few manufacturers who have developed endogenous competence in fuel injection and engine design to offer a combination of EGR and higher fuel injection pressures to avoid the need for an additional reductant in many engine models. USEPA is reluctant to permit the use of SCR since it is feared that vehicle users will not fill up urea or otherwise defeat the system, saving money but increasing NOx emissions considerably. Secondary particle formation is also feared, due to ammonia slip. In countries with a high share of light-duty diesels, particle emissions are a hot topic. On some markets, e.g. Germany, oxidation catalysts are voluntarily mounted by some carmakers to promote diesels, and German carmakers agreed in 2006 to mount particle traps on all cars produced from 2008. The EC has allowed a tax reduction up to that date to enhance introduction.

[13] Particle concentrations are increasingly also recognized as originating from tire-to-road abrasion, reducing the importance of diesel vehicles as a source.

[14] Selective Catalytic Reduction. In order to meet Euro V and Euro VI regulatory limits, diesel particulate filter (DPF) may be required.

3.2 Global environmental innovation

*This section analyses the "chain of translation" from problem to solution, and environmental policy and organizational alternatives to achieve technical change. The conditions for regime shifts are discussed based on the early part of development in USA around 1970. Results are drawn from **Paper I-V**.*

Innovation is among the central determinants of structural change. Environmental innovation studied here is restricted to Environmentally *Motivated* Innovation (EMI), extended from the definition of innovation by Schumpeter (1942). It involves the formulation of demand, invention, innovation and diffusion of a technology or practice with an intention to reduce environmental impact[15]. There is some risk for confusion since the term innovation traditionally is used to describe the overall concept, as well as the more narrow step after invention, from first demonstrations (proof-of-technology) to the first commercial application of a technology or practice. Also included here are the incremental innovations seen in the years following introduction, and the learning curve of the users, seen both in the original markets and where the mature technology is later introduced. Incremental innovation may be looked upon as progression along the learning curve.

In brief, early innovation for emission control technology was carried out essentially in the Triad, where demand was formulated in reflection of environmental impact and negotiated with stakeholders to form a roadmap with milestones for introduction. The resulting regulation is then enacted with some years delay and introduced on a multitude of markets. Technology then matured and entered a second phase, where their use was regulated with similar limit values and test methods in wider markets.

Global environmental innovation in the case of TWCs, can be stylized to a number of reasonably distinct phases:

Table 3. TWC system introduction phases (own compilation)

phase	time period	note
problem definition	1940-1950	mostly in USA
fluid phase	1960s	lobbying
investigation and regulation	1968-1974	Policy making
R&D	1975-1977	partly led by Japan and Europe and including a protomarket of mandated oxidation catalysts in Japan and USA
early adoption	1977-1981	Japan and USA
first introduction phase	1981-1990	Individual countries in Europe
second introduction phase	1991-2000	Other markets, such as EU and rapidly developing countries like Chile began implementing in early 1990s
laggard adoption phase	2000-2010?	many Asian nations followed around 2000

Inventors, entrepreneurs, regulators, industrialists and final customers or "users" are examples of stakeholders in innovation, together forming a system that translates demand to technology. **Paper I**, **II**, and **IV** show that the context in which regulation and technical change develop are specific for each nation. **Paper IV** lists pivotal factors in the case of Chile: organizational competence and institutional responsibility in the nation, a limited car lobby, grave environmental problems, existing dominant technology, an international support network, strong economic growth and an existing circulation restrictions lever, addressing relevant

[15] See the **Paper III** introduction for a brief overview of definitions of environmental innovation and technology.

pollutants, tailoring of a legal framework that yields the desired changes, costly changes to the end users of the regulated technologies, the initial dominance of leaded gasoline and the absence of a national capability of homologization[16]. On the pioneering markets, requirements were tightened some two decades after the resolution of the initial controversy. New technology was required on behalf of fuel producers, vehicle manufacturers as well as their suppliers. Co-evolution between regulators, fuel producers, manufacturers, suppliers and consultants appear for the definition of each regulatory tier, and slightly different regulatory roadmaps were been established.

Global EMI would range from continuous innovation, normally called engineering, to a regime shift, a pervasive change of technology with reduced or eliminated environmental impact from a type of activity and an impact on demand and supply. Both extremes would – and do – happen simultaneously in different markets (niches) and in different regions.

3.2.1 Environmental impact creates demand

Anthropogenic environmental impact has made a trace all along the development of mankind. Methods have been developed to identify each type of impact, to assign a value to the effect, and a link to the cause. The definition of these different steps is necessary to find a cause to the environmental impact, to be able to regulate and to prioritize between countermeasures.

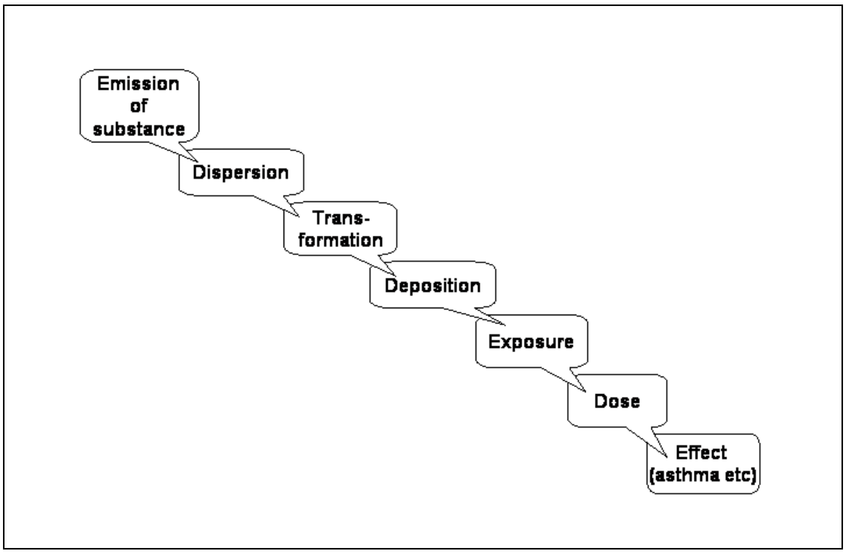

Figure 2: Cause and effect: Simple dispersion model

In the case of impacts from local air pollution, over 20 years passed from the understanding of reasons for smog formation to the first formulation of strict emission regulation in California, where the impact was strongest. Public opinion grew with motorization and industrialization to a point when political reaction was necessary. All links in the chain (Figure 2) were debated, but since the smog appeared so well linked to transport and industrial emissions, the cause and effect were established by research, publicly accepted and thus subject to regulation. Measurement technology of air pollutants, the understanding of cause and effect and the development of air quality standards were important links in the chain of regulation. We should note that while the cause and effect is the same all over the world, the political system in most countries require that the cause-effect link be established on a national level

[16] The (vehicle) tests preceding certification according to stipulated requirements.

before regulation is possible. In many countries, demand is expressed in theory, but not developed to operational policy.

The main findings of Hollander (1995) are on the one hand that the demand forming processes as regards environmental improvements are slow, as it takes a long time to change habits, but on the other hand such processes are often strong, as many parallel actions makes change tenacious and robust. Both sides were seen in the development of TWC level requirements, as demand was first formulated in the 1950s and 1960s.

3.2.2 Policy and technology strategy

The basis for addressing environmental problems is environmental impact from pollution in an unregulated economy. Such costs can then be named externalities (Coase, 1937). The enactment of regulation or other measures for mitigation that makes this cost visible to the polluter can be labeled internalization. In the last century, a number of such externalities have risen, some local, some regional and some global. Some of the issues have been internalized by regulation and different types of incentives in many countries; CFC emissions leading to depletion of atmospheric ozone, use of hazardous pesticides leading to human and animal health problems, local air pollution leading to asthma and cancer, acid rain causing damage both to the natural and to the built environment. The latest, but maybe not the last, call for change are anthropogenic greenhouse gas emissions potentially causing pervasive climate change.

The different governments in the Triad reacted similarly to the increased pollution, albeit with different timescales: by direct regulation, research and incentives to spur innovation, moving up the “policy maturity” ladder proposed by Boehmer-Christiansen and Weidner (1995). Pertinent policy (Norberg-Bohm, 1999) made it possible for industries to undertake innovation with clear short-term economic benefits, yet in support of long-term environmental goals. For the introduction of catalytic emission control systems, both supply and demand type policy was thus used in different phases and markets (**Papers I, II, IV, V**). Since then, focus has gradually turned towards the formulation of internationally coordinated sustainable policy measures.

Kemp (1997) states that in the case of cleaner technologies, market demands depends strongly on government policy. A society where internalization is possible thus includes institutions with the legitimacy to issue and enforce regulations and incentives, a producer/supply market with sustainable actors and at best a strong, environmentally conscious consumer market. Other drivers of internalization is the absence of actors and factors that hampers innovation, including poverty, corruption, unjust competition and lobbying from firms which technology the new innovations will render obsolete. Formal cooperation between USA car makers started in 1963 (initial cooperation already in the mid 1950s), but was formally abolished by litigation in 1969 since it was deemed by the authorities to effectively slow the development of new emission control technology[17]. Intra-industry collaboration can thus be carried out to

[17] The car manufacturers were charged by 18 USA states for “having been engaged since 1953 in a combination and conspiracy in unreasonable restraint of interstate trade and commerce in motor vehicle air pollution control equipment by having agreed to 'eliminate all competition among themselves in the research, development, manufacture and installation of motor vehicle air pollution control equipment; and to eliminate competition in the purchase of patents and patent rights covering motor vehicle air pollution control equipment.'” (In re Motor Vehicle Air Pollution Control Equipment, 311 F.Supp. 1349. Jud.Panel on Multidistrict Litigation 1970, US

reduce costs and uncertainty, and either to slow or accelerate technological development. Teece (1992) argue that rapid technological progress today often requires strategic alliances which may be the opposite of the cartels of yore. Typically, an alliance would drive progress if essentially composed of complementary assets, while an association of horizontal companies (which normally would be considered competitors) with regulated products would signal collusion. Horizontal collaboration may however be motivated to define technical standards for more systemic innovation such as the CAN bus, or to spark the creation or shaping of a common supplier[18].

When environmental impact was recognized and defined, and different solutions for mitigation are proposed, policy and technology can be characterized as being in a “liquid” state. Pros and cons with different levels of regulation and the impacts and implications of different policy measures were debated in the different countries. Companies initiated cooperation to define common ground, propose standards and reduce uncertainty. Preferred technologies were in time translated into technological trajectories typically supported by tiered regulation and incentives. A strong element of co-evolution has emerged and there are strong barriers for laggard nations to present regulation that require a break with the established trajectories. In many cases not only technologies but also the set of requirements from dominant markets are adopted. The different tiers of ECE/EU regulation dominate, but certain countries with strong commercial influence from USA also accept vehicles certified according to USA regulation. Only two nations, Japan and USA, sustains their own set of endemic vehicle emission regulations and limit values. With increasing globalization and call for common test procedures, discussions are ongoing in ECE and other institutions. The risk here is that the common denominator on a global basis is so weak that what can be agreed may help only the laggard countries, while stalling development in more advanced countries including the Triad.

All countries studied, that – on a national basis – introduced the TWC, hold in common an (acquired) understanding of the technology and both its environmental and its socioeconomic consequences. The rationale for each country was however very different, guided by local factors like domestic car industry presence, maturity of the technology proposed, severity of environmental impact and public opinion. The regional adoption of TWC level requirements in the EU was preceded by several national initiatives, but shows the way to international coordination practices.

It should be noted that incentives differ depending on the type of market. Retrofitted catalyst filters have been successful in different types of applications and Environmental Zones for heavy-duty vehicles all over the world, serving to develop new proof-of-concept and protomarkets. When the same measure was tried for but didn’t work as incentives for in-use light-duty vehicles. On the other hand, when a tax break was introduced two years ahead of the mandatory model year 1989 in Sweden, 27% of new registrations for the 1987 model year and 89% of the new registrations for 1988 model year were equipped with a TWC. That means that approx 450 000 cars with a TWC were sold prior to the mandate in Sweden.

A special issue is to which degree the public can interfere with private property. This is individual and dynamic for each nation – it took several decades for most developed nations to go from the legal structures to effective enforcing of strict regulation, and there are

Supreme Court). The defendants were *inter alia* forced by the litigation to open the patents regarding emission control to the competitors in order to speed up the introduction process.

[18] One example is Honda’s and Toyotas joint sourcing of hybrid batteries with Panasonic/Matsushita.

considerable discrepancies on what is in reality tolerated between different nations, and often also between districts within a nation. In the Triad, the grave nature of the impacts allowed for legitimacy in establishing inspection schemes and maintenance requirements (I&M) for the individual vehicles (Rajan, 1996). The timing was however different and introdction of I&M schemes in USA spanned decades between states.

3.2.3 (Environmental) Innovation

Bringing new attractive technology and services to the market continues to be the focal point of the vehicle industry as with many other industries.

> In 2005, Bill Ford, Chairman and CEO of ailing Ford Motor Company, presented a blueprint of the company's future to hundreds of Ford scientists and engineers. The key to the future was simply "Innovation"[19].

Innovation is today used as a catch-phrase both by private and public entities as a means for improvement. This is also the case in the environmental field (see the introduction of **paper III**). Environmental innovations can be done in several areas. Kemp (1997) lists six types of environmental technologies:

1. Pollution control technologies that prevent the direct release of environmentally hazardous emissions into the air, surface water or soil.
2. Waste management: handling, treatment, and disposal of waste; both on-site by the producer of the waste and off-site by waste management firms3.
3. Clean technology: process-integrated changes in production technology that reduce the amount of pollutants and waste material that is generated during production.
4. Recycling: waste minimization through the re-use of materials recovered from waste streams.
5. Clean products: products that give rise to low levels of environmental impact through the entire life cycle of design, production, use and disposal. Examples are low-solvent paints and bicycles.
6. Clean-up technology: remediation technologies such as air purifiers, land farming and bioremediation, which uses plant species to remove toxic materials from contaminated soil.

The TWC, including its impact on engine combustion control improvement, is a combination of the first, fifth and final category. Each company involved in the innovation process at the time selected its strategies depending on its role in an industry (e.g. OEM, supplier or consultant) and the dynamics of this industry. Actions changed during the course of development, often dramatically, and included lobbying for or against formation of strict environmental policy, tacit regulatory compliance or proactive development of products and services in response to perceived demand from market and society. Strategies and ensuing activities were revised as perceived needed, often with turns within a matter of days. In the changing environment that constitutes the trajectory of development of the TWC, companies and governments have shown *dynamic capabilities* in managing the development of regulation and technology. Dynamic capabilities, according to Teece and Pisano (in Dosi, Teece and Chytry (Eds.) 1998), are the kind of capability that makes an institution (Teece and Pisano focus on companies) able to react on a new requirement or opportunity, by reorganizing internal and external capabilities to address the issue. Other denominations are *evolutionary* or *organizational* capability (see **Paper III**). Governments, MNCs and entrepreneurs alike are used to react quickly to *zeitgeist* issues, topics suddenly brought into public attention that require reaction and change, with the potential of bringing triumph or demise to the organization. Examples of this is Honda and Toyota that left racing activities in

[19] Press release from Ford Motor Company, Sept 15, 2005

the beginning of the 1970s and declared environmental adaptation as the key issue for the company at the time (**Paper I**). Another example is the formation of a business unit within Johnson & Matthey for developing catalytic solutions for the car industry (**Paper III**). TWC development may also be looked upon as a successful solution to a *reverse salient* problem. The combustion engine driven automobile had reached a dead end. Solving the emission problem was a necessity and thus became the *critical problem* of the industry (cf. Hughes, 1992). From an innovation point of view it is interesting that the call for cleaner air pushed automotive technological change in other fields: phasing out of leaded fuels and the introduction of electronic engine control and fuel injection, which in turn spurred engine development and innovation in other areas.

Dynamic innovation capabilities are not only created within one company, and technology must not be invented by one man or company alone to be “valid” and effective. The combination of competences to create capabilities for change on different levels in an organization, in a technological system and in society is also an important characteristic brought up in the different papers. From the small to the big, a number of actors form capabilities and products that constitute one of several components in the next “level of development”. In **Paper III** a joint venture to manufacture catalysts is described, formed by joining three complementary competences, and involving production and product technology by licensing. For a supplier of pollution reduction components, equipment and/or substitution technologies, there is no tradeoff between adherence to regulation and profit – the regulation creates a market and represents a business opportunity. As environmental innovation goes, the formal certification/approval routines are often very strict, especially regarding consumer products, a condition which was not studied thoroughly enough by Emissionsteknik. Since the customers’ products were approved on foreign markets using components from incumbent catalyst manufacturers, new certification requests would not only imply a cost to the manufacturer and time-to-market lost, but also a risk that the new component would not be approved and/or not stand the test of time during the lifecycle of sold vehicles. Entry conditions would further be depending on the life cycle stages (see footnote 29, page 16 of **Paper III**) of both the produced component *and* the product to which it contributes. On the component level, market growth and routinization during most of phase II and all of phase III of the component life cycle makes entry difficult. On a product level, it is difficult to approach an OEM outside the *window of opportunity* during phase I model development. This may be instrumental to an entrant which can only keep the offer alive for a limited time, due to lack of revenue from mature products. For an OEM, bringing in a new supplier during component phase IV would be primarily to reduce cost, as a certified component usually is very well defined and an enabler rather than a selling point. The supplier must thus understand the business logic deriving from the component’s or system’s role in the final product. New components and systems can help the final product in other respects than just passing regulation, and give added benefits that facilitates take-up. On another note, in laggard markets suppliers of emission control system components may use product demonstrations or lobbying to speed up introduction of more strict regulation.

Emissionsteknik competed directly against well established, century-old companies in offering gasoline engine catalysts, and entry was not sustained. Nilcon developed the Ecocat technology over more than a decade with limited market breakthroughs, first delivering to Saab through Emissionsteknik, and then to Engelhart through Sandvik. As Sandvik began manufacturing metal substrates, it began to compete with its major customer, and lost. Kemira, who took over the Ecocat license after Sandvik, was less vulnerable than its predecessor and Ecocat production was sustained. With the developing market, only in the final contract with Kemira did a sustainable connection appear where the Ecocat potential was realized (**Paper III**).

Suppliers can lower the hurdles for the customer industry by providing legal/market enabling technology for all OEMs so that the industry as a whole can stay competitive, by effectively progressing innovation and/or sharing development cost for a new technology[20] (Clark and Fujimoto, 1991). Innovation today is global in the sense that a company can innovate to address opportunities in any market, not just in the domestic country or region. The enabling role could concern process or product. This was part of the logic of the separation of the supplier organizations from the large automobile OEMs mentioned in section three. Other examples are Bosch (Germany) offering engine control systems and fuel injection for emission control, Panasonic (Japan) offering traction batteries for several electric and hybrid vehicle OEMs, and Ballard (Canada) producing for several fuel cell car (prototype) manufacturers.

In **Paper I** a catalyst equipped engine system is developed by joining three other, but just as complementary capabilities, namely an electromechanical ('mechatronic') specialist company, a vehicle/engine manufacturer and a catalyst manufacturer. The IIEC[21] efforts involved a larger number of parallel and complementary actors that contributed to realize the potential of the TWC and improved engine control in cooperation between the automotive and petroleum industries. The coordination of Japan and USA government authorities on emission limit values strengthened the scientific case for regulation. These links and bonds of different kinds, that may be long lived or only exist during a brief research stint, relate well to the topology defined in Håkanson and Snehota (1995) and are instrumental to the dynamics of environmental innovation. The links between competences - scientific, regulatory and commercial - helped to overcome the complexities shown.

Each national case study (**Paper I, II and IV**) include legal development, innovation, commercial development and clearly show the complexity of developing and diffusing environmentally motivated technology in a commercial setting. This is not a passive diffusion of technology by acceptance and sales, but a unique process in every new national market. As argued by Rosenberg (1994) – and clearly shown in my cases – what appears as a diffusion process is effectively a sometimes complex set of innovations, enabling incremental adjustments which makes the different parts of a system fit. This process involves technology, policy making and standardization activities. We have, as an example, seen that technology is evaluated differently by similar actors depending on a subjective "status of acceptance" of the specific technology. When emissions were to be reduced in the 1980s in Europe, testing of anything except ICE-based solutions was limited. In 1978, Volvo in Sweden referred to the closed-loop 3-way catalyst as "technology's outermost barricades" (CTH, 1978), suggesting that it was far from feasible to produce commercially. Even so, the technology was already produced for the California market (Eng and Wallman, 1977). Complexity is further pushed as the potential demand from a regulated market can spur new actors, implying that the propensity to innovate is not geographically co-located to the demand. This enhances the globalization of markets and technology.

[20] This is especially important if new regulation implies prohibitive technological or commercial hurdles, so that the industry is no longer competitive.
[21] the Inter-Industry Emission Control program included a number of oil companies and vehicle manufacturers in USA and Japan. The program initially also had European participants.

This is primarily a dissertation on environmentally motivated technological change and not on economic growth, but the phenomenon studied has been important for growth: for the automotive industry as well as for the economy as a whole. Economic growth, public engagement in environmental considerations and technical change go together. The replacement of old, polluting technology with new and cleaner has a cost, but also represent an opportunity - and economic growth is thus an enabler for environmentally motivated innovation and diffusion. This is noted here (**Paper IV**) for the Chilean case and by Kågesson (2002) and Cordero & da Silva (2005) regarding sustainability and growth.

The innovation and introduction of the catalyst was driven by an interactive process, involving environmental problems, business potential and risk stemming from regulatory development and emerging technological capabilities. In order to understand the dynamics of this interaction, not only the innovation of new technology must be taken into account. As described in **Paper IV**, many products have made their way into an unregulated, new market, and only later this market was regulated. This means that the performance of certain goods, services, and/or the production of certain goods or services must be modified to comply with the new regulations. This is the case for the automobile today on most markets of the world. The tug-o-war between car producers and regulators has fostered both what can be regulated, the methods of enforcement and, of course, what can be commercially produced. The first level of requirements corresponding to "EPA-81" were, after all, relatively easy to pass using a three-way catalyst. The TWC and its inherent required setting in terms of engine control, fuel requirements and service capabilities became the commonly accepted *passage point* (Law and Callon, 1992) in developed nations. In response to growing environmental concern, the introduction of the automotive three-way catalysts represents an adaptation of a growing (car) industry to permit continuously increasing demand. Magnusson (2003) has studied *eco-innovations.* He suggests that two dimensions are key as automotive managers interpret the impact of new technology: whether the new technology *complements* or *substitutes* conventional technology, and whether the new technology fits in or implies a break with present organizational capabilities. The catalyst-based emission control system was not destructive to the dominant internal combustion engine regime in the automotive industry, but became an *enabling technology* to extend and develop that regime. Including the TWC meant an enhancement of understanding of the ICE , and once the regulatory barrier was cleared, car companies had around two decades to tune components and system behavior before (in USA and Japan) the next round of requirements came in the late 1990s (**Paper I**). As this second round of regulation was underway, the interactive process resets at the "fluid technology" level described in section 3.2.2. Lobbying for more or less strict regulation from an environmental or a sociotechnical perspective ideally forms an agenda for striking a balance between diverging interests described in section 3.3.

Innovation is executed by research institutions and technology dominant companies, but the trajectories are controlled by a more general discourse. There are several levels, networks or "systems" where innovation takes place and knowledge is created in the automotive world. What is essential here is that a lot of this new knowledge is shared, so that each innovation is rapidly (usually relatively soon after its commercial introduction) publicly presented in detail by means of a technical paper or patents. First, we have the global innovation system for automobiles. It is relevant to talk about such a system, since information is shared in a profound, frequent and extremely accessible way through the Society of Automotive Engineers, based in USA but with many affiliations around the globe. Founded in 1905, its Transactions and Technical Papers (since around 1916) presented at Annual Meetings (since around 1910) and World Conferences (since around 1950) have been a means of first US national and then truly global exchange of knowledge in the automotive field through the European branch FISITA and Japanese SAE. Both these regional organizations hold annual conferences. Its value towards the innovation described in this paper cannot be exaggerated. The means "to get the word out" by means of a SAE paper is used in a variety of ways depending on topic and timing. It is argued that European firms (Volvo and Bosch) could interact with the development in USA both on a market and a technological level so timely partly because of the open and rich flow of information. Also governments use this channel and as an example, the Swedish government presented the coming 1989 national vehicle emission standards as an SAE paper (Olsson, 1983). Since the outset catalyst developers have been admitted in this "global culture of innovation" of which SAE is one of many channels. Many of the people interviewed for this paper know of each other and meet regularly on conferences and in client-customer relations.

3.2.4 Global introduction

After a period of use on pioneering markets, a technology may become dominant and more definite (cf. Utterback, 1994). Regarding industrial production, global manufacturers/ assemblers which set up manufacturing or outsourcing schemes for different markets and national governments gain an understanding of technology available on other markets. With the reduced technical as well as commercial risk that typically comes with mature technology, and the reduction in production cost and competitive pricing that comes with the learning curve, mature technology can easier be accessible to (laggard) markets. The cost of adoption is further lowered as second-hand products (here: cars) exported to laggard markets come equipped with a new technology at a low cost.

Today, the large vehicle manufacturers manage – or rather orchestrate - a large hierarchical web of research, development, production (including logistics) and sales units. The organization of each company is geared towards fulfilling the expectations of the final client – partly constructed by the firms themselves - while minimizing the cost for development, production and sales on the markets where the company is present.

The introduction of USEPA 81/83 or Euro 1 or "higher" regulation in the individual countries constituting the world's largest automotive markets represents one of the highest penetrations of environmentally motivated technology in consumer technology. Global introduction of a new technology is a paramount task. Historically, it has not been a coordinated process but rather a result of explicit demand for change or improvement of an activity or a service. Each nation in this study constitutes a considerably different case for innovation and diffusion, and its role in technological change can only be judged from a national perspective. While Chile has banned the import of used cars, and thus has a "natural" substitution of older vehicles for newer, Peru is highly reliant on imports of a few year old vehicles from Asia and Europe for fleet renewal. Virtually all new cars sold in Brazil are flexifuel, and a lot of cars in Argentine and south Chile are converted to natural gas. Two-wheelers dominate in many Asian countries, while they are virtually inexistent in Chile. Virtually all buses in New Delhi run on natural gas, while a project with similar goals in Chile stopped due to severely reduced provisions from Argentine. Cars are considerably larger in USA, in spite of large market shares from Japanese manufacturers, than in Europe and the smaller car segments in Europe are scarce in USA. Diesel passenger cars constitute half of the European market, but less than a percent in Japan. Such specific conditions abound all over the world and effectively call for country, or even regional specific strategies. By the same token, any new technology must be analyzed for attractiveness on a given country market. This can be most problematic for the introduction of new technology, as demand for new and potentially more expensive technology would be hampered if older, cheaper and dirtier technology is an alternative to change. In a market with strong growth, there is also a risk that while new technology will enter the market, old technology will be usurped by the lower, growing tiers in the economical hierarchies. Adding a vehicle to the national or regional fleet will not reduce emissions.

To make changes in set trajectories is not trivial. Fleet renewal in developing countries with a strong element of used car import will affect the global economy, since international circulation of second hand vehicles is part of the formation of second-hand prices in premium markets, and of car-based services in many developing countries.

Countries' diverging characteristics imply large differences in policy: some countries have the capacity, economy and identity to take on change, while others, voluntarily or involuntarily, will act as laggard adopters, if ever, as technologies mature. Also, developing countries with fast growth and strong governments – such as China – may or may not prioritize the introduction of clean technology. The conclusion is that "global" introduction must not be seen as a uniform process, but more or less a large set of national processes. Such processes can however be facilitated by giving access to patterns of regulation and innovation that can be adopted under the conditions of a given nation.

Just as there is a global network for the early phases of innovation, described in the previous section, there are networks for the later phases, i.e. the diffusion. In the case of cars, early adopters of new regulation will either manufacture or import compliant vehicles. Considerably fewer technologies, however, have made it beyond the developed world and into developing countries. As defined in Table 2, regulators and the public as well as manufacturers/importers must understand the merits and conditions of the new technology and cooperate to form a working system. This can be supported by entry of new firms and advocacy coalitions (Jacobsson and Lauber, 2004), which in turn foster institutional reactions and the development of common regulation and standards.

While dominant, not only the manufacturing capacity geographically within the Triad must be considered. Trade agreements, like NAFTA, MERCOSUR, EU and others change the vehicle industry, and globalization may here not go the intuitive direction. As an example, Mexico was a relatively small vehicle producer in 1980, and 98% of exported vehicles were sold in Latin America and Western Europe. Ten years later, exports had increased more than tenfold to over 275 000 units, 90% of which were exported to USA and Canada. At the turn of the century imports from USA were on the rise and by 2003 vehicle trade was unregulated within NAFTA. (Humphrey & Memedovic, 2003). The implications are twofold; first, local and global policy must be coordinated with local production capability, and second, since investment in new production capacity normally is done by an incumbent manufacturer in response to a growing market in or near the country of production, the incumbents must be involved to ensure innovation in secondary markets.

Regarding emission requirements, a linear innovation model would have to be completed with diverse aspects such as regional (e.g. EU) agreements on Maximum Permissible emission limits, to USA hearings with OEMs and suppliers, Japanese consumers' acceptance criteria and international trade wars. Market (commercial competition under regulated and defined trade conditions) and non-market (e.g. lobbying to tailor content and timing of regulation to fit with capabilities and intentions of a company or an industry) issues go hand in hand for the development of environmental technologies. Results can be enhanced by policy that is sensitive to market changes. Sperling et al (2004) notes that government regulations and policies were often operated in unison with changes in fuel prices. When USA shifted to small cars in the 1970s, fuel prices were soaring. During the shift to light trucks (SUVs) in the 1990s, fuel prices were dropping.

Environmentally motivated innovation, especially diffusion of new technology to mitigate emissions, has largely been carried out in response to regulation rather than from incentives. Since the requirements for vehicle emissions were settled at "TWC levels" in the Triad in 1993, development has continued and the spread across the world serves as a good indicator of the complexity of global technology introduction. Europe and USA now have reasonably homogenous requirements, in the third generation after the initial "EPA-81" requirements that brought TWC introduction. Further alignment is also discussed in the ECE. Growing economies like the BRIC countries (Brazil, Russia, India, China) and Mexico have adopted levels corresponding to the previous regulation tier required in Europe (Mexico, for natural reasons, allows certification either by the USA or the EU/ECE framework). Australia and the more developed states of South America have introduced TWCs. Many Asian countries are in the process of introduction while many African countries are still lingering. The real impact of Euro 2 or better emission control technology on air quality is dependent on the renewal rate, i.e. vehicle scrapping, second-hand exports and transfer of old vehicles from city traffic to less densely populated areas. Regarding diffusion of the cleaner vehicle technology, it is also important to note that emissions were not reduced at the time of initial regulation, but when the new technology became dominant in the streets. If ten percent of the rolling vehicle stock is renewed each year, the transition takes ten years. Pollution to air is reduced slightly faster since commonly; newer cars have lower emissions and higher annual mileage.

The main case studied here, introduction of TWCs, represents a turning point in automotive history in many respects, but it is far from the largest one in history and more pervasive changes certainly are expected within the next decades. The general notion of innovation is the creation of a commercial artifact or process, developed and distributed on one or more markets. The TWC is only one milestone or one artifact, and the Triad has now more strict regulation that typically imply multiple catalysts and other system elements to manage emissions during different parts of the drive cycle. This continuing change, or co-evolution with new regulation, seems to be a strong element of commercial technological development in many sectors and is likely to follow the automotive industry both inside and outside of the ICE regime. Catalysts continue to develop and will form part of the competition with other automotive technological regimes.

3.2.5 Shifting regimes

In the end of the 1960s, the question if the conventional combustion engine car was doing its job properly for massive individual transportation was widely debated. Search began, not only on alternative propulsion technology or fuels (JPL, 1974) but also on means to limit the use of cars and fuel (Krier & Ursin, 1975) and mitigation of pollution in other sectors (EAJ, 1997). This had very different implications for different markets. In USA, public transport was often not developed enough to serve as an alternative, whereas Japan and many European cities followed a long and strong public transport tradition. In Japan, the passenger car was one of the means of domestic transportation, but also a product where the growing national industry saw a strong export potential. Growing demand in USA, Europe and other markets called for vehicles at affordable prices – just what Japan had to offer. Fuel rationing during the 1970s enhanced the need for efficiency. The USA vehicle industry were on the other end of the scale and argued that new emission requirements would increase prices and hamper both competitiveness and sales in absolute terms. Chen et al (2004) argue that in spite of such rhetoric, the cost for emission compliance was but one of several factors considered by car manufacturers in their introduction of first oxidation catalysts and then the TWCs - rising and falling fuel prices, increasing competition from Japanese and European automakers, increasing affluence, and shifting consumer desires were just as important as the integration of TWCs with the combustion engine.

On a company level, the complexity of technological development is a central issue. The organization of a multi-discipline R&D team with the ability to create a prototype for production ready enough to be accepted by the production engineers and salesmen requires a unique mix of science, engineering and commercial sense of direction. To bring chemistry, fluid dynamics, production and packaging capabilities together to a product that must function for many years in several hundred degree environment under a car is also highly multi-disciplinary. By including a feedback loop system with severely increased requirements on engine control, complexity is increased. For a given problem, the dynamic creation of capabilities to understand the environmental issues at stake, the opportunity set for solving the problems, the issues regarding R&D to evaluate the different solutions and the transfer of competence to a given supply and demand market are thus immense.

This means that a firm, usually part of an industry, develops along a trajectory into one of many functional units that perform iterative improvement of a product in a given regime. To develop something new – and in this context, the introduction of Toyota Prius Hybrid is as close to a regime shift that the automotive world has seen – a supplier or a car maker often sets up a new unit or at least a separate task force to develop the new technology (Berggren & Magnusson, 2001)[22]. The same pattern was seen when Toyota and Honda set up new R&D laboratories to deal with the coming Muskie requirements (**Paper I**). The old organization was not adequate to deal with innovation outside the everyday.

The role of emission control technology for market building should however not be exaggerated. It is the sunk costs of the entire industry into the ICE that mostly decides the level of resistance of a regime shift. As Utterback (1994) has showed, a given mature technology, developed by its advocators, can develop greatly under pressure from competition, either between competing technologies or companies, or in the face of a regime shift that would render the presently dominating design or technology obsolete.

In Table 1, automotive technologies are divided between the internal combustion engine (ICE) regime and non-ICE. Similar divisions can be done for fuels and a range of other technologies. In the discussion in USA in the beginning of the 1970s, many technologies were tested and evaluated replacing or improving the light-duty Otto engine, such as gas turbines and steam engines. In USA and Japan, the commercial case for catalysts was singled out of the alternatives in Fig 1 where the search for a "new engine" (JPL, 1974) sprung from environmental problems. Within the ICE regime, there were still a large number of

[22] A drivetrain consists of engine, transmission and wheels, including control and support systems. On a vehicle performance level, it should be mentioned that in spite of its innovative drivetrain, the Prius is just a slight deviation from a conventional car in that there is no grid charging – having the engine as system limits, it is an efficient remake of a conventional engine.

alternatives and combinations. In the case of the catalyst, there simply was money to save if the immense sunk costs for developing combustion engine powerplants could be exploited rather than having to invest in the development of new principal technology. It should be noted that it is by no means the ICE alone that makes the combination competitive – gasoline as an energy carrier is just as important part of the recipe. When discussion began in Europe by the end of the decade, few signs of interest to repeat or criticize the wider investigations already carried out in USA and Japan can be noted. Exhaust gas catalysis (and its prerequisite *fuel injection* and engine control as mentioned below), along with the lean-burn approach were the only technologies actively defended for automotive emission control in Europe.

As soon as a "protomarket" emerges, pilot projects start and prototypes are built; each technology often becomes represented by an individual or competence group at the manufacturer, a supplier company in a more developed market or a specialist with the regulating or research authority. Examples of this are the rotary (Wankel) engine commercialized by Mazda (**Paper I**) and the metal catalyst support offered by Ecocat and others (**Paper III**). These representatives become identified with a certain technology and work with demonstrating or advocating "their" solution. Since the potential of a certain technology in many cases is revealed only with considerable research efforts and over time, the level of the engagement and available resources of the body evaluating or developing the technology may be decisive for the outcome. Research funding with the potential to extend the environmental feasibility of these established solutions is assumed to be more attractive since commercial uncertainty would be considerably reduced. This would in itself support the notion of trajectories or paths which are difficult to change (Dosi, 1984; Nelson & Winter, 1982). It may be argued that the different technologies "competed" for a position as the preferred solution, as Latourean (1996) "constructs". An argument against such a description could be that each technological alternative has a theoretical potential that can be realized by R&D, but can not be changed – the "competition" thus has a predestined winner, assuming that this potential is exploited. The case studies suggest, in line with social constructivist theories, that the technology variety and selection process in effect share characteristics with the notion of competition in the sense of e.g. sports.

Each technology has its advocators, related to the local or corporate drivers for innovation. The difference between technology and market as a basis for cooperation is reflected in the international organization of catalyst manufacturers and component suppliers. The European 'Association for Emissions Control by Catalyst' (AECC), the European producer interest or advocacy group with office in Brussels have eight members, of which four are major manufacturers of the catalyst monolith itself[23]. The 'Manufacturers of Emission Controls Association', MECA, the North American analogue to AECC, operate since 1976 from Washington DC and represent the emission control industry both for mobile and stationary sources[24]. The need to develop precompetitive strategies related to regional (different) abatement targets and strategies in different political realities may partly explain the existence of the lobby groups on each of the two continents.

Keeping within the ICE regime, a similar scheme is now repeated for diesel emission abatement technologies. Interestingly, the two main commercial alternatives for achieving Euro IV emission requirements are not two alternative "end-of-pipe" technologies, but two principles of engineering. A small part of the market has chosen to intensify development of base engine characteristics, while the majority has chosen to stay with a more fuel economy

[23] Interview with Rob Searles, AECC, 1999
[24] Interview with Gerald B Smith, JM, 1999

optimized engine and applied an effective, but perhaps not efficient emission control system requiring additional infrastructure.

To give incentive to economically efficient technological change, it is thus not enough to apply an incentive or a regulation supporting technical change. The controversy regarding electric vehicles introduction in California in the 1990s (Fogelberg, 2000; Calef & Goble, 2007) show that in spite of strong incentives for change, a combination of hard factors, such as insecurity and high cost for the new technology, investments done for development of the old tech, and soft factors such as the attractiveness of the conventional automobile in the face of untried and less *puissant* technologies, in all reduce the propensity for change.

Catalytic technology has itself large implications also in the future. Catalysis is the basic process both for the fuel cell reaction itself and for fuel reforming (e.g. hydrogen from natural gas or methanol). The competence acquired in environmental and process catalysis, and the access to noble metals is explored for a role in the transportation and electricity generation and storage systems of the future.

3.3 The TWC – opportunity, product, trajectory, enabler, savior and a lead zeppelin

To understand innovation, the rationale or business logic of a given stakeholder is important. In this section, the dynamic role of the TWC (three-way catalyst) for each actor and vice versa is explored. ***Paper I - V***

Callon and Law (1992) say that the same artifact may have different roles for different actors in the network. To understand the logic of innovation, it can be argued that the rationale or the business logic of each stakeholder must be assessed. In this way, its role and actions can be understood and the change process can be tailored to minimize friction and counter forces to technological change. As discussed, to view the TWC and its introduction as a "construct" (Latour, 1996), whose development would include some kind of developing identity and a life of its own may be useful, especially as the original "Muskie Law" was passed on to different regions. The emission control requirements as they were adopted by the Japanese government and industry may have been perceived as a homogeneous set of requirements that would enable or prohibit growth of Japanese cars in USA. It was first a set of demands, in time defined as regulation and translated to solutions of which the TWC became dominant. As a dominant solution and set of requirements, adoption by other states and manufacturers further consolidated the "being".

For the actors affected by reduction of local air pollution from gasoline cars, the "cast" and their respective drivers for action in this context could in a stylized way be described as follows: Car manufacturing is about volume and foresight. As mentioned before, we deal with large systems. Either you go ahead, and then a 800-head-researcher lab and a racetrack is what you need (like Toyota in **Paper I**), or you don't, and then someone else has taken the market share away from you, often short of forever. The downside and the upside are both large. Volvo did a good job in general marketing, and particularly in controlling vehicle tailpipe emissions, in the end of the 1970s. They came to enjoy a large share of total European imports to USA in the 1980s (**Paper II**). Russian Lada flunked emission tests in Chile once the national car emission lab came in place, a few years after regulation 1992. They never came back. Chevrolet didn't even try - instead they had the USA ambassador visit the Chilean president and asked for a regulation delay - for the first regulated year and went from 1st place in sales to zero sales, but did come back. Subaru was aggressive in marketing clean cars, and now have a relatively high market share in Chile compared to other markets (**Paper IV**). Honda's CVCC engine was certified against 1976 USA requirements without a catalyst, meaning that the numerous owners of a CVCC equipped Honda Civic didn't suffer from lack of gasoline as the unleaded quality saw a slow uptake in the USA distribution system. The ensuing commercial success was part of what made Soichiro Honda the first Japanese in the USA Automobile Hall of Fame (**Paper I**). British carmakers – and their government – bet on the lean-burn engine in the 1980s in spite of looming TWC level regulation elsewhere in Europe (**Paper II**). Precious few British cars are now manufactured under British corporate ownership, even if foreign manufacturers have a strong presence in the United Kingdom. Johnson Matthey commenced business with noble metals in the UK in the 19th century and grasped the catalyst opportunity from the 1970s and on. Together with BASF (former Engelhart) and Umicore (Former Degussa), they today manufacture the bulk of the world's automotive catalysts, a business worth several billion USD per year in a dominant oligopoly (**Paper III**). While a score of other factors played roles in the succession of events as exemplified above, it is argued that emission control technology capability and strategy affected the situation in the cases mentioned above.

Vehicle manufacturers (OEMs) go through approx ten-year cycles of market research, design, manufacturing, sales and midlife updates for each vehicle model. Ideally cycles should overlap for different models not to expose a company to the commercial success or failure of a single model. Development and tooling cost of a new model can cost up to and above one billion Euro. This creates a need for stability in demand of specifications, available fuel types and not the least emissions and other regulation. In the case of the EU, a new model must be homologated (tests prior to certification) according to 35 different directives on safety, noise, emissions etc. This means that new regulation is usually applied to all-new car models, and a given model emission certification is costly to change in the course of its commercial lifespan. New regulation must thus be coordinated with the 10-year plan for a given model, and be coordinated with the fuel producers not to cause incompatibilities.

For the smaller car manufacturer Volvo, the TWC introduction was a means to earn a competitive edge by proving technological capabilities in a new market. For major (regarding market share on a given market) vehicle manufacturers, it was a means to allow for a growing car fleet in cities that suffered from environmental pollution. It was thus an enabler to continue production and sales. It was ideal as it allowed the conventional Otto engine to comply with coming regulation. Its easily scalable characteristics made it more flexible than e.g. the CVCC engine (**Paper I**). Interestingly, small but profitable truck manufacturer Scania has taken the opposite approach in offering Euro IV and now also Euro V vehicles without the SCR (catalytic) solution offered by most of the competition[25], alleviating the need to fill up a reductant liquid apart from diesel. By returning to the roots of engineering and developing a new injection system together with Cummins, Scania has chosen to divert from what was becoming dominant technology. Such a position may be taken to relieve customers from the burden of fueling urea, but also to show a competitive and attractive technical ability (**Paper V**). Diverse product quality standards on different markets can be a barrier to widespread introduction of new emission control technology. A proposal for globally unified fuel standards are presented by the car manufacturers in a "World-Wide Fuel Charter"[26].

[25] Only Scania and MAN offer Euro IV engines without SCR. See www.EuroIV.co.uk and **Paper V**
[26] http://www.acea.be/files/Final WWFC 4 Sep 2006.pdf

Petroleum companies, the producers of the vast majority of vehicle fuels, balance the cost of exploration, R&D, production and distribution with the revenues from sales, typically of refined products. The banning of lead in gasoline preceding the introduction of TWCs implied increased cost for refining and a disruptive change for **additive producers (**tetraethyl lead**)** worldwide. The same pattern is repeated as present regarding sulfur content for diesel fuel (**Paper V**). Again, smaller fuel producers of alternative fuels, or entrants to the fuel market e can commence in niche operations, e.g. such as petroleum and chemical company Neste offering low blends of alternative fuels to the conventional market.

For **suppliers**, notably noble metal suppliers that became catalyst producers, TWC introduction was an opportunity to expand into a new area and integrate vertically in offering a value added product. For Bosch, the supplier of fuel injection systems and feedback control technology, the need for competence in feedback control and fuel injection following the regulation of large markets represented a large commercial opportunity. The suppliers of environmentally motivated innovations have a very delicate role in the market. On one hand, such an agent is necessary to carry out environmentally motivated, often radical change. Their market is essentially driven by the regulation of markets. On the other hand, their customers are the companies manufacturing goods to these markets and suppliers could suffer from the market being pushed out of the customer's technological reach.

Non-Japanese suppliers have traditionally worked with several manufacturers at a time. As opposed to the situation in Europe and USA, Japanese carmakers often pursued their own solutions in emission control development. KATARA is an example of a development company in the Toyota *keiretsu* (company group or family) founded to develop and manufacture proprietary technology[27]. One exception was German mecatronics consultant Bosch. Japanese companies, both car manufacturers and suppliers, bought licenses from Bosch on the K Jetronic fuel injection system, including software, air/fuel ratio control and the feedback loop sensor. After some time, some Japanese manufacturers replicated the injection and ignition control functions through internal development.

Governments have the most multi-faceted role, representing the different sectors of society – the natural environment, the built environment, people in the roles of individual, taxpayer, worker, voter and patient, national and international corporations, NGOs national and international institutions and foreign nations. Governments do not only work as individual actors. NGOs and environmental scientists have since long shared knowledge and concerns about air quality problems and their mitigation (e.g. Haagen-Smit, 1954 *in* Mondt, 2000). Together with "environmental" politicians and public servants they describe, valuate and drive the public side of mitigation of social problems in what can be named "policy networks" (Salter, 1995; see also **Paper V**, page 23 ff). The environmental or "problem" part of these networks has developed methods to understand and monitor the chain of events from emission to exposure and effect (see Fig. 2). The "industrial" side of the policy network is constituted by representatives of, then, more industrially oriented public institutions and the industry itself. The two sides are not distinctly separated and ideally have a common view on what is required to foster adequate change. This has some bearing on what the French automakers (CCFA, 2005) calls the growing imbalance between the citizen's concerns and the consumer's demands. Government's responsibilities on both sides of this represent different epistemic cultures that must be bridged with legitimate trans-epistemic objects

[27] Interview with Tokuta Inoue, with Toyota, 1999

(Fogelberg, 2003). International organizations UNECE, OECD develop and unify regulation, but can often only represent the least common denominator.

The policy network can also be seen as a technological network or a knowledge network. Representatives of the different fields of technology included in automotive (emission) research share knowledge both on a personal level and through public conferences. A perspective and/or vision shared between different actors in society is easier taken up as public opinion. Specifically, catalyst research is a global field of knowledge where virtually everyone at corresponding positions knows each other across companies and continents. As a matter of fact, one single individual expert has been a key player in virtually all national conferences surveyed, preceding a roadmap that effectively introduced the three-way catalytic converter on a given national market.

For **people in urban areas** of growing economies and local governments responsible for air quality, the introduction of the TWC meant that the number of vehicles in the cities did not have to be limited because of pollution. As private car use and economic development are positively interdependent on many markets (Ingram & Liu, 1997), it can be argued that the successful regulation of vehicle emissions permitted continuous (urban) growth. Vehicle users, especially commercial groups such as fleet owners, also form networks. However, because most Otto engine (gasoline) vehicles are owned by particulars, users have not affected innovation and commercialization of the TWC to any larger degree. On the contrary, **Paper V** in this thesis deals with diesel engine emission control, and trucks and buses are indeed usually managed in fleets. Here, the larger fleet owners are more predictable than individual consumers. A truck in commercial operation must conform to the general performance and reliability requirements of its class. Cost and vehicle management issues are more closely monitored by the owner, and fuel represents the highest cost fraction in a transport assignment.

4 Implications

This section offers a synthesis of the conclusions in the perspective of needed changes to address climate change.

4.1 A new call for change

From the 1950s and on, local air pollution in Triad cities lead to a call for cleaner vehicles and regulated industrial emissions. After agenda setting with the different stakeholders, regulatory roadmaps and technological solutions were developed and introduced on most markets. The laggards tagged on, and are tagging on, as needed. While many areas still suffer from severe pollution, and inspection & maintenance measures continue to play a role (Ng, 2006), modern gasoline cars have diminutive impact on local air quality regardless of fuel. As coming diesel regulation and technology will be implemented on major markets at the turn of the decade, this is likely to become true also for diesel vehicles. Given that established requirements and emission levels will be heeded also for new generations of governments, fuels and vehicles, it is possible that the main point on the agenda for reduction of local air pollution from road transport on any market can be limited to renewal of the vehicle fleet.

In the last two decades, climate change and the looming shortage of hydrocarbon fuels has come on the global agenda side by side with the dangers of local pollution. This calls for further change. The main cause of climate change is anthropogenic emissions of carbon dioxide. Since carbon dioxide emissions are much more difficult to reduce than today's regulated pollutants, and hydrocarbon fuels just as difficult to replace, more drastic changes in technology and behavior are likely to be needed to achieve the required reductions in greenhouse gas emissions. The scientific foundation for achieving this change is considerably developed both as to solutions and reason, but as the largest emerging markets such as India and China enjoy economic growth and increasingly embrace passenger cars and the lifestyles connected to them in the West, very large economic networks support these new patterns of consumption. Compared to today's situation, where the tarmac, the fuel, the tires and other parts of the vehicle are based on cheap fossil oil, a sustainable road transport system is likely to entail higher costs for fuel and infrastructure, be limited in capacity, and in a neoclassical situation of supply and demand thus the total market volume may be reduced. The task to shift to more renewable and sustainable practices becomes more and more difficult as the potential drop in total market volume under such a shift increases. In this light, research for understanding feasible patterns for change becomes even more important.

A number of conflicting megatrends are likely to dominate the discussion on a sustainable society for the decades to come: poverty, terrorism, the end of cheap oil, economic growth, increasing energy demand, air pollution in the developing economies and climate change. Globalization moves industrial production to low-income countries, meaning that new groups of consumers will in time enjoy increased wealth, in turn increasing demand for products and energy - inducing increased greenhouse gas emissions under the present technological regime.

This section places the results of the previous sections of the cover essay, and the five papers included in my dissertation, in the context of their implications for addressing one of the main threats to a sustainable society. It is a rough sketch to outline how the results from the thesis work can be employed. I'd like to emphasize that the potential of innovation in automotive technology, or any other technology, to serve in mitigation of global climate change is limited and one part of the needed transition. As an example, Baumann (2004) has identified organizing or management of technology and systems as decisive to environmental performance, in addition to access to better technology. Høyer and Holden (2007) argue that sustainable mobility requires a reduction of energy use, along with increased system efficiency and the substitution of fossil fuels. An implemented Carbon tax has a range of potential results, where only some purport technological change. I have studied the introduction of a modification to an established technology, as a means to adapt its environmental impact essentially to urban conditions of intensive use. A word of warning may be appropriate: while the adaptation of transport technology to the call of climate change is instrumental to a sustainable society, there is a risk that necessary attention to values, ethics and change of habits may be diminished in favor of dreams of a technological panacea. From what we can see, Climate change mitigation (CCM) is a transition on a different (part of the) scale compared to the mitigation of local pollution from transport.

So, the experiences from the global introduction of catalyst emission control as analyzed in this dissertation are here applied on one of the main challenges in a growing world economy: reducing CO_2 emissions from road transport. The issue of climate change can be divided in four different disciplines:

- the climate change itself and its consequences
- understanding of the causes of anthropogenic climate change
- mitigation of climate change through addressing technology and activities
- adaptation to the changes not mitigated

This thesis mainly concerns the third bullet point above, but the first two are also discussed in relation to experiences from TWC introduction. The topical framework developed by Sir Nicolas Stern of the UK Treasury in the Stern Review of the Economics of Climate Change (Stern, 2006) is roughly adopted in the following, with one exception: Given the limited role of transport systems in adaptation (except perhaps regarding rescue, migration and the allocation of sustainable goods such as renewable fuels) to climate change, and the limited role of adaptation in the introduction of emission control systems, this aspect is not explored here. The analysis is centered on limiting the role of road transport in contributing to climate change.

> According to Stern (2006), the mitigation of potential severe effects of climate change requires stabilization of the concentration of CO_2 equivalents (CO_2e) in the atmosphere to 550 ppm or lower. This would require that global CO_2e emissions peaked within the next 10-20 years and then declined at a substantial rate thereafter. Present emissions of between 40 and 50 gigaton CO_2e per year should in the long run be reduced to around 10 gigaton CO_2e per year.

Emissions from transport technology stems from environmental impact from transport volumes (goods or people), choice of transport mode, choice of propulsion system and choice of fuel. This would also include environmental impact from vehicle and road infrastructure production and maintenance as well as from fuel production and distribution. The absolute majority of road transport is carried out using fossil fuels.

Also the next automotive technology regime is likely to be guided by mass production - market estimates reflected into large scale initiatives of production and marketing. Since the 'citizen' and the consumer have increasingly different preferences, public 'visible hands' may have an increasing role in fostering technological change. This is in part conflicting, since a salient feature of innovation is a close coupling of the developer and the user (Teece, 1992).

Technology consciously introduced to mitigate a problem thus requires a preceding process of internalization. First, awareness of the problem, understanding and definition of an externality, here in the form of an (anthropogenic) damage to the environment, appear. Second is the development of a method for internalization of this externality in the economy. Third is the technical verification of solutions to the internalized problem, the regulation (and enforcement)[28] of such behavior and initial innovation for compliance. Fourth is diffusion and ensuing co-evolution of technology and regulation.

For innovators, and in the case of environmental technologies also the regulators, the principles for deciding what to do and what not to do involve considerations similar to when developing a new drug. Can the patient afford the pill? Will the therapy be accepted, or even mandatory? Will success be sustained? Given great potential and high costs for R&D, will we incur too high cost to reach our commercial goals in the end? Are the technical and commercial goals even attainable? If so, can we get funding for the research? Will we have to share our knowledge with competitors? Is it an enabler, i.e. will we get access to new markets by developing a new performance characteristic?

Corporations with a global outreach, however, will not let their actions be guided only by regulation and present sales volumes. Hoffman (2005) argues that companies will react to the market transition represented by climate change by strategic decisions, based on new analysis on the opportunities and implications for the individual company. Strategic benefits can be sought under regulation, or on a voluntary basis, in a number of areas:

1. operational improvement
2. anticipating and influencing regulations;
3. accessing new sources of capital;
4. improving risk management;
5. elevating corporate reputation;
6. identifying new market opportunities; and
7. enhancing human resource management.

Technological change, especially regime changes and transitions (Elzen and Wieczorek, 2005) in a market economy is difficult, since the system relies on a large number of individual fragile agreements between producer and consumer, many in some form controlled by public policy. In the face of technological change, such relations are likely to change. There are many sides to the problem; the incumbents know what is there but not how to face change. The market is unpredictable and investment requires limited risk. The potential of any one alternative technology is not big enough to spur a more “modular” change – the ICE or gasoline fuel cannot easily be replaced. The agents of change, such as wind energy, require investments way beyond the capacity of new entrants to an emerging market. Further, investors and consumers will base their decisions not only on product performance but also on company reputation.

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[28] Introduction of one or more technologies (development, production and distribution) to curb the problem can also take place without regulation or incentives. A new, more economical technology may entail also environmental benefits, and then be introduced on other grounds than mitigation but nevertheless reduce pollution. If such a technology is transferred to an entire industry, large reduction of polluting emissions may occur without regulation.

The dear task is then to develop sustainable behavior and technology that is compliant with energy supply and global warming. This requires technological research on primary energy, processing and distribution of fuels, as well as vehicle and drivetrain technology. Beyond propulsion systems, also transport systems e.g. in the shape of advanced goods logistics and efficient urban public transport hold great potential in reducing travel time, energy use and emission levels in cities. Apart from technological advancements, market analysis on different levels is required. Market development is formed as the different *competence blocs* test and probe demand in different regions.

Specifically, the automobile has entered its second century and many voices are heard calling for change in the automotive sector. As to urban problems, local emissions are still assumed to contribute to cancer and asthma in spite of all development described in this thesis. Vehicles tend to increase in size and propulsion power far beyond technical necessity, which in turn increases consumption and emissions as well as the risks for surrounding vehicle users and pedestrians. The ever-increasing (?) vehicle fleets in thousands of cities, rural roads and highways also enhances such risks. The car society offers visions of unprecedented mobility on one hand, and 7-15 yearly dead per every 100 000 inhabitants, air pollution and – to date – reliance on fossil resources on the other.

It is tempting to compare the challenges at hand with the call for and introduction of modern emission control in the 70s and 80s.

For environmental motivation in innovation, the changing roles in the vehicle industry deserve attention. We have seen European manufacturers pioneering in offering TWC vehicles in USA (**Paper I**). Japanese manufacturers pioneered 15 years later in Chile (**Paper IV**). In both cases, smaller actors took the opportunity to gain credibility – and later market share – by challenging the larger actors on the respective markets on technological grounds. This David-vs.-Goliath logic may just be dated. Regarding light-duty vehicles, what is becoming the world's largest passenger car manufacturer, Toyota, is flanked by Honda and others in commercially and technically pioneering in mild hybrid (no plug-in battery charging) vehicles on a global market. Hybrid technology shares characteristics with TWC/fuel injection system technology in that reduction of fuel consumption and emissions are achieved with minimum changes in vehicle performance. Just as for TWC equipped cars, the uptake of hybrids were initially enhanced by incentives. TWCs, however, made its way to the market essentially through regulation. Nevertheless, hybrid technology in the form demonstrated commercially by Toyota is an important step to overcome the low inherent efficiency of the internal combustion engine. The unambiguous commercial behavior of Toyota prove the argument of Hoffman (2005) that also large corporations may opt to lead in the development of environmentally motivated solutions, and that size and market share does not necessarily affect the willingness to press the envelope.

Engwall (ed., 2003) discusses product development under insecurity, beyond established technology, and the importance of updates and user feedback loops for IT systems and products. New C&C industrial products break with the linear development model. While this would be an outcome highly coveted by different stakeholders also for transport, there are fundamental differences between the existence of a mobile phone subscriber service and a new line of diesel trucks. Compared to information technology, road transport is technologically much more locked in: development cost, product lifespan and second hand value, infrastructure investment, access to fuel and compatibility all contribute to create a rock steady trajectory. While novelty is an important part of the offer at the consumer end of the road vehicle production system, many of the elements that build the fundament for the relatively cheap passenger cars are very expensive to alter in any profound way.

The changes implemented to accommodate the TWC included adjustments of fuel quality, new, more modern technology and higher cost. Changes were profound, combated, delayed, complex, differing between nations and depending on individual action and public opinion in parallel.

Introducing new technology, or getting the automakers to innovate under more stiff regulation, is, according to the studies, more difficult if there is no growth. The simple reason is that investing in technological change in a recession is difficult not only for the vehicle buyers, but for car manufacturers as well. As TWC introduction in USA was to be realized in 1978, recession and other factors postponed the federal regulation until 1981 - and exemptions were granted. Europe enjoyed growth as TWCs were introduced 1993-1996 in the European Union - sales of passenger cars in Europe grew strongly in the mid-1990s. Chile had a growing economy, and Japan's vehicle export was booming as the respective countries set corresponding standards. As mentioned in section 3.2.4, Sperling et al (2004) also note that government regulations and policies often operate in unison with changes in fuel prices. There is growth, so that is not necessarily an issue.

The succession of events; requirements for cleaner air, the 'oil crisis' of the 1970s and the ensuing innovations and global regulatory changes may share some aspects of today's call for cleaner diesel emissions, reduced CO2 emissions and shift from fossil hydrocarbons. The technology upgrade and the improved fuel economy (at least in USA) made possible within the "techno-institutional complex" (Unruh, 2000) in the introduction of the TWC should ideally be repeated to mitigate the effects of Global Warming and Peak Oil. While main issues like lock-in and dominant designs prevail in today's globalized markets, there are certain differences between the TWC introduction logic and the way that diesel emission control development unfolds. Multiple alternatives being investigated and demonstrated makes policy more viable and effective. As an example, several alternatives for diesel NOx emission reduction technology are commercially available. Both local and global solutions are discussed – global goals are translated (subsidiarity) to local contexts where alternatives may develop in their own right (**Paper V**). As shown below, different technological trajectories have a potential to reduce CO2 emissions from transport. A diversified and volatile technological future creates insecurity and risk for manufacturers and investors. Betting on one horse may not lead to victory, and alliances between e.g. carmakers to ensure a common technological path and sustained demand are common in history. Therefore, both consumers and producers can profit from a common understanding on the merits of different technologies. E.g. to invest only in fuel cell technology and infrastructure would however be a very large risk, create lock-in effects and reduce legitimacy for early development.

4.2 Definition of the problem

As with local air pollution, a method for understanding the mechanisms that govern our climate and the impact of greenhouse gases has been developed in a collective, or at least shared, process. While the initial understanding of the delicacy of the atmosphere was developed in the 1800s, it was only in 1960 that UK scientist Charles Keeling could confirm that the atmospheric concentration of CO_2 actually was rising. Discussions in the United

Nations led to the formation of the *Intergovernmental Panel on Climate Change* (IPCC) in 1988 and a first assessment, split in *Science*, *Impacts* and *Response Strategies,* was formed. The links in the chain were identified through comprehensive international research efforts (Figure 3).

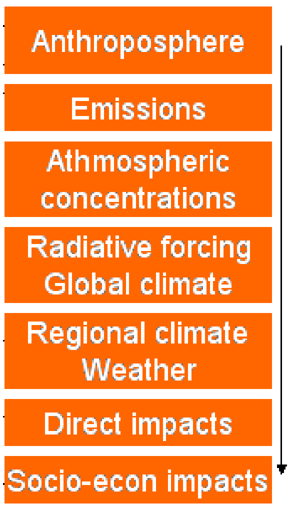

Figure 3. Cause and effect: climate change (Hope, 2005)

The relation between *local* air pollution and health was first discussed over a century ago, widely established in the 1950s and on, while action – regarding real introduction of cleaner technology as a result of implemented policy – became pervasive only in the 1980s (**Paper I, II, IV**). Laggards are adopting the widely accepted tiered regulatory frameworks only in the beginning of the 21st century. There was thus a 30-50 year time lag between knowledge and action on key markets. Taking the 1980s as a starting point for public recognition of the impacts of climate change, and assuming that dedicated (negative) impacts have yet to be directly experienced by a large population, we are still likely to be early in the development towards maturity in the discussions when comparing with the timeframe for development of local air pollution management.

4.3 Environmental impacts on welfare, growth and development

The primary impact of car pollution, as it was perceived at the height of the debate in the 1970s and 1980s, was local effects on human health and other types of detrimental impact on the built and natural environment. There were ample indications of the link between pollution and health problems. In Germany (**Paper II**) especially the effects on forests were observed. In Japan (**Paper I**) the focus was on impact on humans. This spurred strong public opinion in several markets and brought regulatory changes. In the case of Santiago, increased ozone levels affected not only the downtown but also the more affluent outskirts of the city (**Paper IV**). Since the effect of global warming is distributed both in time and in space away from the cause, and also from rich to poor (Stern, 2006), the legitimizing evidence should probably to a greater extent come from scientists rather than from hospital statistics and eyewitnesses.

The spark that brought change in most of the countries studied was public opinion, moved by incidents linked to the issue to be addressed. Public concern wasn't mustered until actual signs of environmental (or even economic) retardation from pollution were visible. In the absence of such public concern, economic incentives may be seen as more legitimate than command-and-control of private and corporate behavior? Drawing from historic cases, technological and behavioral change will depend on a chain of events that to a large extent would develop on a national basis. Certain elements that would support positive development in this case can be discerned. Some examples: Public debate spurred development in Sweden before and during the formulation of regulation. Measurements of emissions and assumptions of health effects were important for changing public opinion (**Paper II**).

Economics were a hot topic when new regulation for vehicle emissions were introduced in the different countries studied. There are several reasons for this, depending on the location and the maturity of the compliant technology. When such compliant technology is not mastered by car manufacturers in a given country, this country must balance the risk of reduced sales of domestically produced vehicles due to larger import shares, higher prices and lower performance. Further, export could be severed if requirements on large foreign markets would imply that the domestic suppliers could not deliver. Even without a national car industry, it is essential that fuel and service infrastructure, including the cost structure supporting the change to the new system, is established. An example can be found in **Paper I**: The introduction of unleaded fuel was slowed by the fact that leaded fuel was cheaper. The combination of information and I&M checks did not suffice to deter TWC vehicle users from fueling with the cheaper leaded fuel, around 15% of the catalysts were ruined in the early years in USA. Several heads of major car companies, especially in USA and the UK suggested that employment would be derailed if TWC technology were to be required. Car producing countries with more strict requirements paved the way for continued success while others, e.g. Italy and the UK tried to halt the new requirements because their car industries were already in a slump.

According to Stern there is no shortage of supply of oil for the coming decades, meaning that without a carbon tax, we are likely to increase the use of fossil fuels beyond what current research suggests will keep climate change manageable. Dorian et al (2005) discusses the possibility of renewables to compete in a world where e.g. West African oil reserves and ‘stranded’ natural gas resources are exploited. The large *free-rider* advantages for states not willing to price carbon, at present including USA, will slow investments in renewables. As a recent example, The Peoples Republic of China in June 2007 stated[29] that it prioritizes bringing millions of its citizens out of poverty to countering climate change.

4.4 Policy responses for mitigation

The Stern report and a recent IPCC (2007) report calls for 50 % or more reduction of CO_2e emissions. To analyze the needed change and the impact of such a change, alternative routes or regimes may be identified along with the pertinent stakeholders.

We have seen that the main controlling factors of a transport technology system are:

- the policy measures and enforcement agencies and facilities that governs it,
- the means of fuel production and distribution infrastructure that it holds,
- the presence of vehicle manufacturers and/or sales, including service
- for consumers: preferences and economic purchase power
- for corporate users: general market growth (often cyclic), company growth and strategic decisions taken (and implemented)

[29] http://en.ndrc.gov.cn/newsrelease/P020070604561191006823.pdf

Magnusson and Berggren (2007) conclude that most manufacturers conduct pre-commercial development activities in a broad range of technologies. With such technologies, several different possible sustainable development trajectories are initiated and applied on some markets. Developing sustainable trajectories on a global scale could help reducing CO_2 emissions. Each trajectory, in combination with the present situation and dynamics, is a microcosm with its own set of stakeholders, rationale and regional advantages and disadvantages. As several combinations of fuel/vehicle are present on the market, part of the picture will also be to keep availability of fuel and other crucial amenities (such has spare parts) up for the time that vehicles of a certain combination are circulating. It should also be noted that catalysis has a potential role both for production of renewable fuels and novel drivetrains (Shelef & McCabe, 2000; Spivey, 2005). Apart from final users, stakeholders are governing bodies, vehicle, fuel and infrastructure providers and the parties who will see a business contraction or disruptive technology change as a result of the new technology or service. As an enabler of technological change regarding drivetrains, public transport is an option.

Public (road and rail) transport

Large cities e.g. Paris and London have public transport (PT) systems with different levels of capability to balance the need for individual mobility. In the southern hemisphere, Curitiba in Brazil, with special articulated buses and fare/entrance-exit bus stops, is an example of a public transport initiative started in the 1980s that increased the attractiveness of PT. Follower projects like the *Transmilenio* in Bogotá, *Transantiago* in Santiago de Chile and Bus Rapid Transit schemes in Beijing and elsewhere in China shows the potential for change. In each city, there is active involvement by city administration and technology providers (IEA, 2002). Development of an efficient PT system is not generic work but usually a very long-term and city/regional specific development. It thus requires stable government and an economic climate that encourages investment.

A bus or rail PT system dramatically reduces the number of ICE powerplants needed – one bi-articulated bus carries over 200 people using a single engine and subways are electric. This fact, and the controlled environment of a bus engine in scheduled traffic and maintenance, allows for faster upgrades to cleaner technology, alternative fuels etc as these become available. Apart from potential immediate emissions reductions, bus and other PT schemes also may serve as protomarkets for new propulsion, emission control and other technology. Some of the large bus manufacturers have learned to offer systems rather than products, reflecting what subway system manufacturers like Bombardier and Alstom have done for decades. Suppliers have great opportunities in innovating whole drivetrains and subsystems for bus and rail PT, e.g. easy-to-use charging and information systems.

Carbon tax will provide the basis for the alternatives by motivating corporate and consumer investment in low-carbon alternatives and practices. However, in a democracy there must be reasonable agreement on changes in cost for products and services; the changes will require similar national debates and agreements as in each country where the TWC was introduced. Protomarkets or niche markets where a new system is operational in a confined area, such as the Hydrogen Highway under development in Norway, will help both large scale investments and ensuing public acceptance since factors hampering the intro of new tech are highly correlated - technological problems are followed by investment doubts. Legitimacy to spur and require demand for sustainable mobility differs between countries, and depends on national and international factors. Both mitigation of climate change and the introduction of TWCs have caused raised voices warning of the perils of pioneering. From fear of losing legitimacy, it is less likely that car making national governments will be at the forefront of discouraging sales of domestic automobile models.

Høyer and Holden (2007) discusses three routes or trajectories for sustainable mobility: *Efficiency*, where new technology balances the impact from increased mobility in growing market, and S*ubstitution*, where public transport and rail services become valid alternatives to fossil fueled road vehicles. Last but not least, the *reduction* option, where mobility is reduced. Reduction and substitution could in part be an indirect effect of introducing higher prices of carbon, more expensive transport options (e.g. hydrogen) and urban congestion tax schemes. Here, I focus on vehicle and/or system efficiency, and discuss the potential of four trajectories that could contribute considerably, in view of the developing background characteristics, the perspectives of the involved stakeholders and the respective specific technology hurdles:

- technological change to increase vehicle **Fuel efficiency**
- exploring the potential of **Biofuels and synfuels**
- introduction of **Plug-in hybrids**
- exploring the potential of **Hydrogen fuel cell vehicles**

The trajectories chosen are somewhat overlapping but each have different sets of stakeholders. Beyond these trajectories, and also beyond the scope of this thesis, are issues like telecommuting and restructuring of society to reduce travel demand.

4.4.1 Present regime: Fuel efficiency

Increasing **fuel efficiency** encompasses a wealth of measures, including reducing vehicle weight and aerodynamic drag, introducing type III hybrids[30], engine downsizing, shifting to diesel for passenger cars and shifting to 'hybrid households' (where only the most fuel efficient vehicle available in a household is used day to day). Amory B. Lovins has showed that weight reduction and introduction of mild hybrids has a high potential in improving fuel economy (Lovins & Cramer, 2004), and can be part of 'winning the oil endgame"[31] for USA.

On a program level, the Partnership for a New Generation of Vehicles (PNGV) was launched in 1993 in USA under the Clinton administration. The goal was to create technology leading to a working model of a super-car by the year 2004 - a car capable of getting 80 miles to the gallon while meeting Tier 2 emissions levels or better. The program suffered from lack of coordination with national emission standards, but lead *inter alia* to a presentation of some very efficient diesel hybrid vehicles in 2000. It was terminated by the Bush II administration and replaced by Freedom Car, a long-term research program for fuel cell vehicles. The Corporate Average Fuel Economy (CAFE) regulations in USA, operational since 1975, aims at reducing fuel consumption from the average fleet of vehicles sold in USA.

[30] A "mild" hybrid car with a relatively small traction battery and no external charging capability, see Teden & Bauner (2002)
[31] www.oilendgame.com

Europe launched an Action Plan for Energy Efficiency in 2006 and has a specific average target for passenger cars in 2012 of 130 g/km. Emissions today are on average 160 g/km. Taking the larger cars manufactured (and sold and used) in northern Europe into account, the EC are expected to fix new rules that would permit higher CO_2 emissions for larger cars, but require the manufacturers of these cars to buy emissions rights to compensate for the offset from the regional average of 130 g/km. A comprehensive study is completed to assess the viability of technology to achieve better fuel economy (Smokers et al, 2006).

Increased vehicle fuel efficiency through technology improvement is difficult to measure (Schipper et al, 1993). A recent study shows that the technological potential for increased efficiency was split in improved performance (2/3) and improved fuel economy (1/3) regarding passenger cars (Sprei, 2007) in Sweden.

In Sweden, the automotive industry values the potential for increased efficiency for year 2020 to around 75 % compared to today's cars on the Swedish market. This potential is split into the following changes: general efficiency increase (gear boxes, weight, engines etc) -20%, dieselification (including new concepts like HCCI) -20%, hybrids (general) -30%, plug-in hybrids -30% and changes in behavior and new tires etc -15% (Kågeson, 2007, pp 14). The demand for mild hybrids has been good to date – the number of light duty hybrid vehicles (mostly Toyota Prius) on Swedish roads has gone from 600 cars in 2003, to 6000 in 2006[32].

Technology

The technological potential is very large given the many pathways to higher efficiency.

Stakeholders

The vehicle industry provides locally tailored, yet complex industrial products to the whole world. This is done by an increasingly globalized sourcing, assembly and distribution, while paying attention to the specific conditions of each market. Increased fuel efficiency is not a contradiction to this industrial development, and this road ahead will not disrupt the major market actors. Here, mostly gradual changes and shifts to smaller and more efficient vehicles already on the market are considered, which would retain many of today's players. The incremental innovation required would not disrupt markets to a greater extent - stakeholders that would be affected are e.g. those that deliver materials which would be less attractive in lighter vehicles, such as steel and iron.

In Europe, the same geographical pattern as at the time of the TWC introduction is still present regarding automobile manufacturing and demand: Larger, more luxurious and generally more advanced automobiles are manufactured in northern Europe while somewhat smaller car models are made and favored in the southern parts. This implies that two scenarios can be identified when exploring the potential for lower-carbon transportation. If the main direction of development (or demand) is towards smaller cars, the manufacturers in southern Europe will see increased sales and those in the north will have to shift in that direction or see markets diminishing. If the main trajectory will go towards more exclusive materials and engines, while allowing for similar comfort and performance as today, this is likely to be an advantage for the manufacturers in the north, where more resources are traditionally spent on development for a new model. Examples of the latter are the Mercedes A-Class by

[32] Source IEA Hybrid vehicle http://www.ieahev.org

DaimlerChrysler and Toyota Prius Hybrid. The tenacious north-south dichotomy is likely to persevere also in the discussion – and industrial and environmental policymaking - around the 130 g CO_2 per km car. One stumbling block here is that manufacturing of larger, more exclusive and usually more fuel consuming vehicles generally is more profitable. Demand for smaller vehicles must be explicit to make it more reliably economical for the manufacturers to focus on marketing and producing such products.

French and USA brands producing in Latin America sought to stall the enactment of the "TWC decree" in Chile (**Paper IV**) in the early 1990s. By the same token, producers of mature technology in "cash-cow" markets could aim for business-as-usual demand and regulation to avert costly production changes.

Something should be mentioned also by the other end of introduction, i.e. reduced use of older vehicles, scrapping of vehicles or export. In Japan and on other markets, age-based vehicle scrapping and export schemes are an important contributor to domestic fleet renewal and the introduction of more efficient vehicles. While this improves the result for a given nation, there is often an equally negative effect with the receiver markets of those exported vehicles. There are large economic interests in the second-hand vehicle market and consistent scrapping schemes should be an important element of policies aiming at replacing bad with good. This is especially difficult in developing countries since growth from a low base may to some extent be dependent on an influx of mid-life vehicles.

Suppliers can have great success in participating in this development as long as their proposals do not change the nature of the offer by carmakers. Suppliers are at the mercy of the carmakers since any volume production would have to pass both the quality systems and the assembly hall of the OEMs.

Final User Demand
Development towards efficiency is likely to be effective to the extent that it is cheaper, mandated or otherwise more attractive for the consumer to make a choice in line with sustainable principles than not, i.e. that a Carbon tax is uniformly implemented and that the market is developed accordingly.

While being less efficient due to increased weight, larger high performance vehicles often offer greater comfort and status, making them more attractive than conventional vehicles. As the economy grows, cars become accessible to larger groups and by the same token more and more people can afford larger cars such as SUVs. A carbon tax or similar must counteract such development to reduce fuel use per capita.

4.4.2 Variety: biofuels and synfuels

Several different alternative synthetic and biofuels are available today. For reasons such as limited feedstock or market strategies, such fuels are available on selected markets only. The spread of the production, distribution and use of such fuels are widely discussed as means to reduce CO_2 emissions. **Biofuels** (of organic origin) could substitute part of the fossil fuels currently used, and **Synfuels** ('synthetic' fuels from syngas of organic or fossil origin) could provide a bridge from fossil to renewable fuel markets by offering optimum fuel specifications from both fossil and renewable sources/feedstocks.

Public and corporate actors increasingly include alternative fuels in the main agenda for change. In his 2007 State of the Union Address, the USA President included a proposal to use 35 billion gallons of renewable and alternative fuels by 2017. The first signs of oil companies' involving themselves in biofuels production are arriving[33]. EU has established a target of 10% of petrol and diesel to come from renewable sources by 2020, a measure which has received considerable criticism.

A number of alternative fuels are based on common intermediate production processes like gasification.

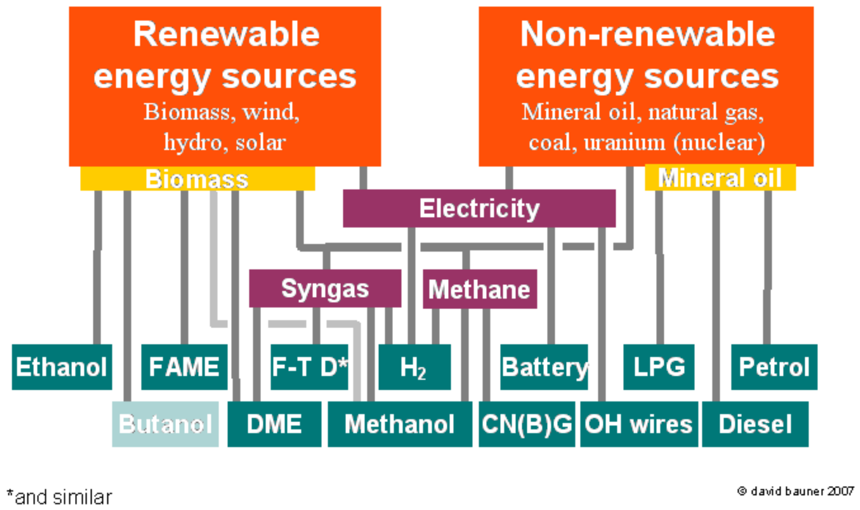

Figure 4. Fuel (energy carrier) options, some intermediate technologies and their respective sources (own compilation).

The only biofuels produced in larger quantities today are ethanol (from sugar cane, corn and wheat), mostly produced and used in USA and Brazil, biodiesel (from rapeseed) with more small-scale and dispersed production, and biogas (from sewage and organic waste) produced industrially mostly in Europe. Interest is increasing, and several countries do or will require renewable fractions in vehicle fuels sold. The development of technologies to produce fuels from cellulose feedstock, called second generation biofuels, has received a lot of attention.

Technology

The original automobile engine of Karl Benz, Henry Ford's T-Ford as well as Rudolf Diesel's engine were first designed to run on crop-based fuels. Low blend biofuels – 5-10 % blend of bioethanol as an octane enhancer in regular gasoline (higher for butanol and ETBE) and low blends of biodiesel are used commercially on some markets for conventional engines. High blends of ethanol (E85) exist on some markets.

Production processes for second generation biofuels are under development. If we assume that today's commercially available alternative fuels (in Sweden ethanol, biodiesel and biogas) may under the present production technology regime each account for a fraction (maybe 10% for each fuel) of the total of the fuel demand for road transport, a shift away from fossil fuels will create a large deficit. This may drive the market in different directions: Towards higher fuel prices, towards the development of more public transport, towards more electric (train, trams, subways and plug-in hybrids) transport or a combination of all of the above. To cover the needs of even a contracted demand profile, commercialization of fuels

[33] British Sugar press announcement on ethanol plant in cooperation with BP, June 26, 2007: http://www.abf.co.uk/media/press_release.asp?pr=20070626_1

based on cellulose and renewable syngas (second generation biofuels) is a condition. Regions with more cellulose feedstock have higher potential to become net producers of renewable synfuels.

Stakeholders
Biofuels is an attractive route for the carmakers since it potentially keeps the ICE regime intact (ref **Paper I**). Any fuels that are compatible with the present infrastructure –fluids with either high octane or cetane numbers - can be blended in or replace gasoline or diesel.

For the petroleum companies it is a difficult issue since the scale of production and the quality certification issues of new fuels may be very different from the present regime. Several of the large producers are now positioning themselves as waiting for the "second generation biofuels" and have in some cases begun to invest in grain based technology, anticipating a shift to cellulose based biofuels in the coming decade. Drivers here could be an ambition to pioneer a new market, or conversely to moderate development that may lead to requirements on minimum renewable fuel fractions. An agriculturally based industry segment is growing fast on several markets in the development and supply of alternative fuels aimed at both first and second generation technology. Especially cost effective enzyme technology is instrumental to allow commercial uptake. New entrants are seen both for enzymes and the production of new fuels.

The environmental and commercial impact from the increased use of agricultural produce for biofuels today is highly debated and monitored. The large acreage required to answer to even a fraction of transport demand create diverging local political visions and volatile local opinions in different regions for large scale biofuel production. As each country has different agricultural conditions, history, stakeholders and institutional dynamics regarding fuel provision, the combination of solutions will differ between countries and regions. In countries with high national ownership of present (fossil) fuel production, there is comparatively little incentive to pioneer in shifting to a sustainable path – routes where domestic consumption is reduced while increasing export may be attractive. Many oil producing countries also have a tradition of subsidizing fuel domestically, constituting an additional barrier to a transition to renewable and potentially more expensive fuels. Moving from subsidies has in many instances caused local riots and protests. Regarding TWC regulation and introduction, nations where domestic industries were affected typically saw slower technological change. Technological change is often faster in countries with higher economic growth. The list of supporting and adversary factors in **Paper IV** gives an overview.

Final User Demand
Individual passenger car users typically will use an alternative fuel if it is attractively priced and will not disturb vehicle operation. Commercial customers are very cost conscious. Low blends in regular fuel are not noticeable by the public and offer great potential due to the large volumes.

Incentives, like a congestion charge in Stockholm excluding environmentally enhanced vehicles, have recently proven effective to promote a shift to such vehicles[34] which in turn drives demand for renewable fuels. The scheme introduced in Santiago de Chile in the 1990s, preventing non-catalytic vehicles from driving in city centers was effective both in inducing technological change and reducing pollution (**Paper IV**). However, many other measures

[34] According to vehicle sales statistics from Bil Sweden, the Swedish car manufacturer association.

have not been accepted by the public. The initial policy responses in USA in the 1970s probed the possibility of a regime shift and gasoline rationing but despite R&D measures that showed potential variety new engines or changes in transport patterns were fought legally (**Paper I**) and not sustained. Any policy measures aiming at changing characteristics for in-use passenger cars have not been successful. Some success has been seen regarding retrofits of heavy-duty trucks and buses.

4.4.3 Enabler or disruptor? Introduction of plug-in hybrids

A "plug-in" hybrid (externally chargeable and with more than 11 km of electric-only range[35] has two different fuel (energy storage) and drive systems, typically battery electric and ICE. Plug-in hybrids (PHEVs) can reduce CO_2 emissions by allowing vehicle owners to use (renewable) electric power from the grid for e.g. the daily commute rather than fossil fuels, while retaining the ability to perform longer trips. Because of the larger battery and the more complex drivetrain, PHEVs would typically be more expensive to manufacture than conventional cars.

Plug-in electric vehicles and hybrids were an important part of the technological vision of the ZEV mandate in the 1990s in California. The vehicle type has since been advocated by electric power companies represented by e.g. the Electric Power Research Institute (EPRI), USA. Also plug-in hybrids were mentioned in USA president Bush 2007 State of the Union Address. Today's manufacturers of mild hybrids in Japan and USA source their traction batteries from the same source, Panasonic/Matsushita.

The introduction of PHEVs would require charging outlets where the vehicle is parked overnight, and also during the day for corporate vehicle use.

No plug-in hybrid is commercial today. Commercialization is considered by a number of carmakers.

Technology
The introduction of plug-in hybrids requires very large increases in battery production. Infrastructure required is first electric outlets at vehicle home bases, completed with charging units in cities, malls and at workplaces. It represents a radical increase in drivetrain complexity compared to today's conventional cars.

Fueling at regular gas stations would be required less often. With equal size vehicle fuel tank, fueling would only be needed a few times per year. Spatial analysis and simulation is required to predict demand, but may imply that renewable motor fuels could cover a larger fraction of the demand.

Prior to the appearance of a market, stakeholders must make preliminary agreements on what is commercially viable minimum electric-only driving range. A dominant set of specifications may be emerging with around 30-50 km electric (battery) driving autonomy.

Stakeholders
A development of this trajectory would make it possible to retain existing infrastructure (ref **Paper I**), it would bring in new major suppliers of batteries and charging infrastructure but is a limited threat to incumbents. When battery technology takes off, a share of the vehicles are likely to be purely electric, a segment which has not successfully been developed by incumbents beyond absolute necessity.

[35] Type I hybrid according to definition by Teden & Bauner (2002)

The systemic development of the ZEV mandate and the PNGV program in USA may have sent a signal to the Japanese car industry in the end of the 1980s congruent with what the Muskie Law did in the end of the 1960s (**Paper I**), and sparked the development which has produced the Honda Insight and Toyota Prius hybrids. These companies, and their suppliers, today have a learning curve advantage since "mild" hybrids lead towards new regimes. Plug-in hybrids do represent a disruption from today's engines and as such constitute a large hurdle for car manufacturers. Therefore a long initial introduction/protomarket phase can be expected, both to accommodate the new knowledge needed and to reduce market and technological uncertainty.

Producers of traction batteries, power electronics, electric infrastructure and electricity would promote this development. Since it would be early in the business cycle, innovative entry is possible (**Paper III**) but will in time require large ramp-up of production to match demand.

A lot of profitability in modern vehicle fuel distribution comes from the captive customer visiting the gas station-cum-convenience store. Plug-in hybrids would drastically reduce the need to visit fueling stations, and the contraction would constitute a major disruption for fuel distributors and thus a threat to this industry. Changes would however be slow given limited uptake of the plug-in hybrids and the large present conventional vehicle fleet, and a possible upside for fuel producers is that customers fueling intermittently may be less price sensitive. Nevertheless, a widespread introduction of plug-in hybrids would constitute a regime shift.

Final User Demand
Plug-in hybrids can be attractive for e.g. commuters to reduce cost and would reduce the need for refuelling at gas stations. The increased costs must likely be overcome initially by incentives and may over time be reduced by incremental innovation and economics of scale. New types of energy carriers and fueling practices may require new *user scripts* (Gjøen and Hård, 2002) - users adapting to the driving range and other features, such as on-board access to more electric power, of the new vehicle type.

4.4.4 New paradigm: hydrogen fuelling fuel cell vehicles

The introduction of fuel cell vehicles and production and distribution of renewable source hydrogen is one of the technically possible pathways to a renewable road transport system. Earth receives solar energy radiation in abundance, but capturing and distributing the energy as H_2 is costly. Around two thirds of the energy invested to produce a m3 of hydrogen is lost during production, storage, transport and energy conversion in a fuel cell, compared to just 10% when electrical energy is used directly through the power grid[36]. Regarding infrastructure, the Japanese government explored the hydrogen society in a project named WE-NET between 1993 and 2003 with a budget of 141 MUSD. The project identified barriers in production, storage and distribution and was cut short of its initial 2012 timeline.

Passenger car prototypes have been presented by different carmakers, e.g. DaimlerChrysler (DC) and GM, and a number of DC buses have been used (leased out) to EU projects such as CUTE. Iceland has been proposed as a platform for H_2 production, infrastructure development and FC vehicles as demonstrated in the ECTOS project (Andersen, 2007).

Both FC vehicles and more conventional vehicle drivetrains will develop in the coming decades. Schäfer, Heywood and Weiss (2006) argue that hybrid ICE vehicles will achieve similar levels of reduction in energy use and GHG emissions compared to hydrogen FC vehicles for the next 20 or more years - if natural gas is used as a feedstock for hydrogen production. Renewable hydrogen feedstock increases the lead time to comparable FC system efficiency.

In 2000, the Global Environment Facility (GEF) of the World Bank undertook a study on the potential of "leapfrogging" vehicle technology in developing countries. It was seen that hydrogen was a fuel suitable for distributed generation, e.g. with solar cells, and that Fuel Cells was a potentially efficient propulsion technology. Buses showed the best potential for visibility and environmental impact in developing countries (IEA, 2002). Projects were discussed with a number of high growth developing economies. After considerable delay, buses were made available and negotiations were initiated with governments in China, Egypt, India, Mexico and Brazil. As an example MUSD (~20) were allocated, split by local and GEF funding in Mexico for fuel production and infrastructure development alone. Only the projects in Brazil and China were continued. (GEF, www.gefweb.com)

Table 4. Fuel cell bus projects sponsored by GEF (www.gefweb.com).

Location	Project name	Management organization	Cost MUSD	Project status
Global	Fuel Cell Bus and Distributed Power Generation Market Prospects and Intervention Strategy Options	UNEP	0.691	Completed
Brazil	Hydrogen Fuel Cell Buses for Urban Transport	UNDP	12.618	Underway
China	Demonstration of Fuel Cell Bus Commercialization in China (Phase II-Part I)	UNDP	5.815	Completed
China	Demonstration of Fuel Cell Bus Commercialization in China, Phase 2	UNDP	5.767	Underway
Egypt	Fuel Cell Bus Demonstration Project in Cairo, Phase I	UNDP	6.510	Cancelled
India	Fuel Cell Bus Development in India (Phase II - Part 1)	UNDP	6.280	Cancelled
Mexico	Demonstration Project of Hydrogen Fuel Cell Buses and an Associated System for Hydrogen Supply in Mexico City, Phase I	UNDP	5.418	Cancelled

Industry experts are split in *Optimists*, seeing car makers' efforts as a sign of change, and *Skeptics*, seeing the efforts as 'window dressing' with limited commitment to commercialization. Based on patent analysis, real engagement shows a dual face but can be diagnosed as in between the two positions. Commercial introduction is unlikely unless political, technological or economical conditions change considerably (van den Hoed, 2005). Modelling of the GHG reduction potential suggests that fuel cell cars are an option only over the very long term (Turton & Baretto, 2007)

No fuel cell road vehicle is offered under regular commercial conditions on any market today.

Technology

Technology for large scale production, distribution and use of hydrogen is under development. A transport system involving fuel cell vehicles propelled by renewable hydrogen would require ground-up development of large-scale hydrogen production and distribution as well as industrial production of fuel cell electric drivetrains which today have considerably higher cost than conventional ICE drivetrains. [37]Little would remain from today's entire transport system except the tarmac on the roads and fuelling station credit card readers. A shift would represent radical and discontinuous innovation. In early (and maybe later) phases of demand increases, hydrogen is likely to have natural gas as a feedstock on some markets.

An uptake of H2/fuel cell technology would increase the presence of highly compressed hydrogen in society which can be a safety risk.

Stakeholders
As this alternative represents discontinuous change (Christensen, 1997, Unruh, 2000), new infrastructure is required, and the core of conventional automobile technology will be lost. Such a change will create very large insecurity with the manufacturers and the financial community, and former attempts have been rejected or abandoned (**Paper I**).

New stakeholders for hydrogen production and storage are required, as well as producers of equipment for hydrogen production, distribution and storage. Since production can (will) be from multiple sources such as solar/wind, nuclear or hydro electricity, coal and natural gas, a given producer – or even a given region - are likely to focus on certain feedstock depending on capability, market and feedstock availability. A transition to renewable feedstock will depend at least partly on the establishment of a global carbon price.

It is a long term alternative for the automotive industry and decades of development are likely to be required for acceptance. Increased R&D shared between car manufacturers may lead to a better understanding of present and future capability requirements, but may also serve as a tool to ward off any signals of commercialization by requiring more R&D resources, in an effort similar to the emission control research program coordinated by USA automobile manufacturers in the 1960s. The program was terminated by antitrust litigation in 1969 (**Paper I**).

A route in order to *avoid* the need for a new drivetrain is presented by BMW, demonstrating the use of hydrogen in a regular combustion engine. It is not clear if this alternative will be commercially attractive if also fuel cells become commercial. Fuel cell/battery hybrids may be an attractive route that in the future may also offer fuel flexibility. The carbon neutrality will be dependent on the feedstocks for fuel production. Since e.g. China today look to produce DME from coal, it is likely that it will also be investigated if hydrogen from coal is a commercial alternative. It would only be sustainable in combination with CCS (Carbon Capture and Storage) measures.

Governments are driving R&D of hydrogen infrastructure and fuel cell technology to promote domestic industry developments (PWC, 2006). This may be wise as long as such support is balanced and does not induce lock-in.
.

Final User Demand
Customers would typically accept a shift to H2/FC technology if capital cost is acceptable and running costs are attractive. This requires a drop of drivetrain costs of thousands of €/kW down to the 50-60 €/kW that conventional cars offer today, and a developed fueling network. If this technology in a commercial setting will be higher priced, but in a scenario where all other fuel/vehicle combinations would not offer practically seamless mobility to the like of today's conventional ICE car, there would of course be more price elastic segments of the market ready to pay the higher price.

The low system efficiency may be prohibitive in a scarce resource scenario, giving room to e.g. plug-in passenger car hybrids and overhead lines/battery public transport hybrids.

4.5 International collective action

Many of the apparently efficient measures to mitigate climate change are attractive to nations and corporations to the extent that carbon is priced uniformly across markets. In the Stern report, it is therefore clearly manifested that a global valuation of carbon is essential to avoid the free-rider problem. International cooperation for climate change has begun through the UN Framework Convention and the Kyoto Protocol.

The UN Conference on the Human Environment started its work in 1972. At that time, environmental questions in general were new for national governments. The transboundary and often global dimensions of environmental problems that motivated the Stockholm Conference in 1972 has been sustained by scientific development. In 1992, the UN Conference on Environment and Development took place in Rio de Janeiro. Two treaties, the Framework Convention on Climate Change and the Convention on Biodiversity were opened for signature. A number of principles for international environmental co-operation were formally confirmed, among them the Polluter-Pays-Principle and the Precautionary Principle. Through Agenda 21 an action plan for environmental co-operation in the UN system was established.

Decision-making in international cooperation is often equal to negotiation. No guarantees that formal decisions are respected by involved parties can be made due to the absence of a central authority, and parties not willing to enter into agreements (or negotiations) can generally not be forced. Parties that do not like the development of an agreement can choose not to sign a ratified agreement, or simply abstain from implementing it. International environmental negotiations have included a lot of failure and cover-ups (Sjöstedt et al, 1993).

From the experiences of the UNCED process (Sjöstedt et al, 1993) and that expressed in this thesis, it seems that democratic and tyrannical states alike in many cases will internalize external costs when it is evident that its citizens already are at peril - in many cases only when the first victims already have been counted, and in response to explicit public opinion.

Regulatory and technical changes, such as the Transboundary Air Pollution agreements (Acid Rain) and the essentially non-coordinated but approximately contemporary reaction (regulation) to local pollution from cars and industries in many countries have been carried out as part of industrial development and domestic policies. Regarding vehicle emissions, such negotiations have been slow. For the introduction of emission control technology, only now a global vehicle emission test procedure is being developed.

The drive for development in commercial business may also counteract the initiatives from a policy network. At present we may even see activities which would increase consumption prior to more strict caps or 'freezing' of fossil fuel use - a variety of what has been described as a 'race to the bottom' (WB, 2000). As an example, passenger car sales increased 75% in China in 2003, where 180 million cars can be added to its current fleet by 2025 (Dorian et al, 2005). In the beginning of the 1970s, industry leaders proclaimed the TWC as a great risk for employment and the USA society when alternatives were considered (**Paper I**). Dorian et al mention the risk of a *misinformation phenomenon* from the vested interests of trillions of dollars of investments made into unsustainable, but profitable activities in energy production and utilization, employing millions all over the world.

Since climate change is a global threat, there is a need for unprecedented widespread action to overcome it. The 'free-rider' problem is a large threat that will tempt politicians, especially in developing or growth nations to be hesitant in adopting measures that appear to hamper growth. For developing countries, again with reference to the TWC development, a weak institutional framework (e.g. that would not enact or enforce a carbon tax) and lack of continuous growth pose a threat to realizing a roadmap towards a low-carbon society. Given the wide-spread free-rider problem and the inherent difficulties with international environmental negotiations, the lead time to implement a system that will in some way incorporate the laggards in a way that in turn makes it acceptable for the majority – who would then all be early adopters - to participate in some kind of global scheme for carbon pricing, is likely longer for the issue of global warming than for the historical development of a dominant – implemented – solution to local air pollution from gasoline cars.

For land transport to move to a sustainable role along one or more of the four paths outlined in the previous section, a common carbon price accepted by all major economic regions in the world is likely to be required. An incentive based control regime on the global level is clearly more apt to create the combination of measures – both regarding technology choice and its use – than a command-and-control global regime since the optimum combination is most likely to differ between regions all over the world. National goals could be translated to more precise sectorial targets and linked to incentives, regulation and enforcement.

International cooperation is unchartered territory in many respects. While the intuitive progression for GHG reduction involves a host of individual states adhering to "protocols" developed by international institutions such as the UN, experience from the introduction of TWCs suggests that real change may occur as regions (EU) or groups of countries cooperate on a more disaggregated level to align their respective development, sometimes in combination with industrial competition. **Paper I** shows that countries and their respective industries can reinforce development by (voluntarily or involuntarily) teaming up around an innovation goal. **Paper II** shows that industry, both OEMs and suppliers, in country A can support innovation in country B. For mature technology, **Paper IV** suggests that one country's environmental requirements can be the demise, or boost, of the export volumes of another. Therein may lay another potential for progression: one or a group of probably vertically oriented companies from "well to wheel" could decide to provide products and services that constituted a working system, as (in a limited way) was done by local fuels distributors and car importers to Chile in the beginning of the 1990s (**Paper IV**). This vaguely resembles the objectives of a system development in Iceland regarding a hydrogen society. If a regional initiative including fuel provisions, distribution system and vehicles would be made available to consumers and corporate customers, it could offer competitive advantages to the participants by raising rivals cost in an oligopoly setting (Puller, 2005). Such a *development bloc* could create a niche market where the learning curve would leave competitors behind, much to the like of Toyota regarding hybrid cars. Public support for this exclusive network development could come through a competition or procurement round. The protomarket model set by such an initiative would serve as a proof-of-concept for other regions, competitors and investors alike.

One last implication from the TWC introduction: To even bring large CO_2 emitters to the negotiation table, steadfast public opinion at the respective home base would likely be of great help. This suggests that any substitutes for concrete signs of domestic environmental deterioration– comprehensible figures of local contribution to global CO2 emissions, and effective public information on the impact of climate change – may be the best tools available. National governments are less likely to negotiate caps on CO_2 emissions without pressure from their peers.

4.6 Summary of implications

Catalysis is an example of environmentally motivated innovation

The introduction of the TWC has shown that the rationale for action for each country relates to the capability of domestic industry regarding product development capabilities in fuels, infrastructure and vehicles, public opinion and growth (translated to demand for new technology) as well as capabilities in mitigating pollution (efficient and enforced environmental regulation). Regulatory roadmaps (tiers) with defined certification procedures have proven effective in evolutionary change of entire systems in that they can be understood by all parties and adopted into new markets.

Catalysis is also a part of several forward looking drivetrain and fuel production technologies which may contribute to sustainable mobility.

The automotive innovation system is highly locked-in

New technological regimes were examined when impact from pollution became overwhelming in the 1970s, but a technological fix that reduced the change to a minimum was the result. This pattern was largely repeated in the 1990s in California. While the 1970s was a tough setting that required regulatory measures, it taught the actors to be restrictive with production promises - especially those that would company forced the company to produce an unsellable product. It is also important to note that there was a time-lag of 30-50 years between scientific understanding and widespread implementation of mitigating policy and technology.

The introduction of TWCs was reinforced by the simultaneous development of mitigating technology in two car producing countries competing for market space. The same reinforcing mechanism may have been induced as the ZEV mandate and the PNGV program in USA sent a signal to Japan on the advent of electric drivetrains and hybrid technology.

Vehicle manufacturers strike a balance between radical and incremental innovation

Large scale (vehicle) production is to a large extent guided by minimizing risk. A large actor on a market is therefore less prone to radical change, whereas a new entrant, minor actor, or major actor with a new technology needs some kind of motivation for the customer to shift in order to establish a role in the market. This motivation may be technological, financial, based on regulation or incentives or any other aspect coveted by the consumer or final customer. OEM management looks to maximizing the value of R&D, while allowing for sustainable growth. To this end manufacturers may form alliances to foster or hamper radical innovation depending on technological capabilities and market situation. The balance between incremental R&D and breakthrough technologies is likely to be in focus as alternatives in fuel production and drivetrain technology increase in number, and improve.

Strategic niches or protomarkets may foster innovation of radical technology

Public transport and environmental zones may constitute strategic niches for innovation of new drivetrains and fuels, as it does regarding new emission control technology today.

Innovation may spark new environmental regulation, and regulation may spark environmental innovation.

The innovation of the TWC was to a large extent realized due to strict environmental regulation. The roadmap for future emission regulation is fine-tuned by technological demonstrations by suppliers and agile OEMs. Regulatory policy is partly guided by industrial policy and the environmental impact is one of the determinants to decisions on new requirements.

Some future trajectories create less friction between stakeholders and market

A trajectory based on enhanced **Fuel** or **Energy efficiency** appear most straightforward – the final customer here has a dual role of ”consumer vs. citizen”, and demand will be affected by regulation and public opinion. **Biofuels & synfuels** may provide alternatives and reduce the need for fossil fuel while maintaining mobility – but renewables will compete with coal & natural gas as feedstocks. **Plug-in hybrids** are feasible, but potential controversies are identified between fuel & infrastructure stakeholders – proliferation could cause a battle between electric utilities and oil companies. **Hydrogen/fuel cell vehicles** require major innovation re fuel production/distribution and drivetrain – and would null a century of investment in ICE technology. Since the motivation for its introduction would rest on (among other things) higher energy efficiency than conventional vehicles, proliferation is likely several decades into the future

While coming challenges may be global, technological change is highly contextual and dependent on local conditions

The world is divided and diverse as to the relation between problems and measures. Neighboring and otherwise similar countries differed by a decade in adaptation of mature TWC technology. While Japan banned lead in gasoline in the early 1970s, many Asian countries are still grappling with this issue. This disparate pattern is repeated today for diesel emission control and cleaner diesel fuel, and is likely to persist regarding radical new propulsion technologies and fuels. Patterns of adaptation of new technology are historically highly linked to the capability and interests of domestic industry. For laggard countries to enter otherwise accepted technological regimes, competence and technology must be transferred to regulators, to commercial intermediaries as well as to final customers and the general public.

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