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ORIGINAL PAPER

Evolving technological systems for diesel engine emission control: balancing GHG and local emissions

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Abstract The Triad—North America, Japan and Europe—now addresses diesel vehicle emissions by requiring 40–80% reductions from new heavy-duty trucks and passenger car diesels. The requirements imply introduction of new technology and fuels stepwise during 2005–2012 that will leave emissions from new diesel vehicles on par with the levels of gasoline passenger cars. This paper studies the recent development of diesel engine emission control in response to new regulation. The role for Swedish actors, including two of the world's major truck manufacturers, is especially studied. The increasingly global Technological System for diesel engine emission control is compelled to manage further reductions of nitrogen oxides emissions and fuel consumption and CO_2, the balance of which has been the subject of several large legal disputes. Swedish OEMs are at present split into two technological sub-trajectories, while the future may be multi-pronged and include new engine types and fuels. Interestingly, similar commercial advantages that were sought by the pioneers introducing advanced feedback loop catalysis in gasoline cars in the 1970s are now sought by some heavy-duty diesel engine manufacturers by conversely avoiding the mainstream—Selective catalytic reduction—solution. Incremental innovation is the new radical.

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List of abbreviations

ACEA	Association des constructeurs européens d'automobiles/European automobile manufacturers' association
AOP-II	Auto-oil program II (EU)
BASF	Swiss chemistry multinational
BFSC	Brake specific fuel consumption
CCFA	Comité des constructeurs Français d'automobiles/Association of French automobile manufactureres
CFD	Computational fluid dynamics
CO	Carbon monoxide
CO_2	Carbon dioxide
CRADE	Joint research center for advanced diesel engine systems (Japan)
DME	Di methyl ether
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
ECMT	European Conference of Ministers of Transport
ECU	Engine control unit
EGR	Exhaust gas recirculation
EMIR	Emission research (Automotive emissions research project, Sweden)
EPA	Environmental protection agency
EPEC	European parliament's environment committee
ESC	European stationary cycle (heavy vehicles)
ETC	European transient cycle (heavy vehicles)
EZ	Environmental zone
GRPE	Working party for pollution and energy (UNECE)
GTR	Global technical regulations
HC	Hydrocarbons
HCCI	Homogeneous charge compression ignition

hp	Horsepower
IVECO	Italian truck manufacturer
JAMA	Japanese automobile manufacturer's association
JE05	Japanese vehicle test cycle
KCK	Competence centre for catalysis
LPG	Liquefied petroleum gas
M&A	Mergers and aquisitions
MAN	German truck manufacturer
MAUT	German highway toll
MECA	Manufacturers of emission controls association (USA)
N_2	Nitrogen (gas)
NIRA	Swedish engineering company, now owned by Actia (France)
NMHC	Non-methane hydrocarbons
NOx	Nitrogen oxides
NSR	NOx storage catalyst
NTP	Non-thermal plasma
OBD	On-board diagnosis
OECD	Organisation for economic co-operation and development
OEM	Original equipment manufacturer
PGM	Platinum group metals
PM	Particulate matter
RPM	Revolutions per minute (engines)
SAE	Society of automotive engineers
SCR	Selective catalytic reduction
SIKA	Statens Institut för Kommunikationsanalys/ Swedish institute for transport analysis
SINOx	NOx reducing technology for heavy vehicles
SUV	Sports utility vehicle
SwRI	Southwest Research Institute (USA)
TAC	Toxic air contaminant
UBA	Umweltbundesamt (German EPA)
ULS	Ultra-low sulfur (diesel oil)
UNECE, ECE	United Nation's Economic Commission for Europe
US BTS	USA Board of Transport Studies
VINNOVA	Swedish agency for innovation systems

Introduction

Coming regulations in the leading regions of EU, North America and Japan on diesel vehicle emissions will reduce non-CO_2 emissions to the same level as gasoline passenger cars. This means that the rolling stock of heavy-duty vehicles in the coming decade will take a big step forward in emissions reduction for all regulated emissions. The diesel-powered truck is the backbone of commercial road transportation, and increasingly diesel also fuels passenger cars. The main areas for regulation are nitrogen oxides (NOx) and particles. In USA, Europe and Japan—the three dominant global markets for vehicle emission regulation—the limit values are reduced by 40–80% following regional regulation.

In a report to the Swedish Agency for Innovation Systems (Bauner and Laestadius 2005), competing diesel emission control technologies are described, and the industrial consequences and potential for Sweden is analyzed. While based on the findings of the report, this article focuses on describing and analyzing the national technological/innovation system for diesel emission control and its role in a global technological/innovation process given developments to date.

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Objective

This paper analyzes the technological system for diesel emission control systems in relation to international development and actors, regarding different technologies and regulatory regimes. A focus is placed on the position of Swedish actors/stakeholders.

Research questions from the objective can be defined as follows:

- What characterizes the technological system for diesel emission control?
- What role can a regional cluster, here the Swedish actors, play in this system?

Although technologies and the position of individual actors are discussed, it is not the objective of this report to evaluate the merits of individual technologies and actors.

Method

Fact finding for the paper has been done by means of semi-structured interviews, database searches and literature studies. Two of the authors have technical experience in the field. Over 30 interviews have been carried out. After presenting a theoretical overview, the global market demand, technology and the different actors are presented. The evolutionary system moving innovation is presented. An analysis of the system and its components is concluded with recommendations.

Theoretical framework

The problems investigated in this study are far from unique in character, even if actor studies on exhaust aftertreatment have not been seen in any frequency. The areas of competence/knowledge that we judge as most relevant are—starting with the most related to technology—those that relate to the character of technological development, inherently confined in trajectories, and how these processes stabilize in industrially valid systems and products, dominant designs (Utterback and Abernathy 1975). Further, we delve into the issue on which contextual dependencies—geographical, technical, cultural and political—that characterize this process. All this may of course be described within the wider notion of innovation theory, but that would constitute a theoretical approach with far too low resolution.

As to the character of technical development, there is ample research around *technological paradigms* and how these cognitively orchestrate the search for solutions and cause rigid trajectories (Dosi 1984; Nelson and Winter 1982; Vincenti 1990). A famous essay by Constant (1980) shows the difficulty for professionals and engineering collectives to change the train of thought when facing technological shifts. The present study, however, remains inside the present paradigm of road vehicle propulsion—namely internal combustion engines and related technologies—because neither the supply nor demand sides opt for fuel cell or other "Zero emission" technologies at present, for example. The inherent problems of low energy efficiency, incomplete combustion and noxious emissions have been known for decades and resulted in incremental improvements for the dominating working principles of Otto and Diesel engines, as well as new concepts such as HCCI.[1] *Incremental innovation* is another name for the daily product development that is the mainframe of engineering. Resources are often dedicated to manage new problems arising as a result when solving the old, such as when new catalytic technologies increase emissions of nitrogen dioxide. New systems are added along with the old, resulting in higher complexity (and costs). The problem with increasing complexity, as devices are gradually refined, was noted by Adam Smith already over 200 years ago (see Laestadius 1992). Increasing complexity should constitute a warning signal not only for techno-politic units supporting new technology, but also for the companies and institutes that develop complex solutions. Christensen (1997) has shown that such behavior leaves opportunities for more simple (and which may also be more sophisticated) systems to succeed in the market.

Further on the intra-paradigmatic level, trajectories appear: a number of types or families of technical solutions come out as more attractive or natural, and increase their survival rate by cumulative processes (see Arthur 1989). From a variety of technical solutions, one usually will develop into a de facto standard in the market, i.e. a *dominant design*. It can be assumed that it is not necessarily the most advanced, most performing or most costly solution that wins (see Utterback 1994).

Drawing from innovation theory, the technical change that we study is well described by the concept pair *variety* and *selection*. On one hand we have the technology generating process—mainly with companies and research institutions—that create variety, and on the other hand the market and policy level reactions that create selection (Nelson and Winter 1982). A precursor to selection, a *demand shaping* process has been described by Hollander (1995) as proactive, not only selecting among existing alternatives but requiring improved processes and products, so as often slow, but also persistent and an important driver for sustainable technical development. The selection process is often initiated long before the technologies reach the market, in the cultural and political processes that can be named *protomarkets* (see Coombs et al. 2001) as regulation fosters innovation (Jarratt et al. 2003).

In the context of technological change, we can note the spatial dimension that is often present in an innovation/technology policy context. The actors that we study are to a large extent located in the industrial area in the middle of Sweden, where 60% of the manufacturing industry is located and an even larger share of the vehicle industry. Sectorial, regional (sub-national) as well as national levels of analysis are thus possible. Several research approaches, with some similarities, are relevant in this context. *Cluster analysis*, rooted in Porter (1990) and *innovation systems* (Edqvist 1997) are two perspectives. This article focuses on a sectorial or technological innovation system rather than a regional or a national system. The *technological systems* discourse may be closer to the issues at hand than the innovation system approach, to which it is related. A technological systems approach can be carried out in different ways (see Carlson 1995; Hughes 1998) and focuses on the industrial, engineering, culture of technology and institutional *network* that ties the system together. The approach does not assume that the network is regional or national in character. Some technological systems are local and some are global in nature; this may change over time—more or less malleable by policy measures.

The notion of *development blocs* developed by Erik Dahmén (1950) appears as relevant to our research. In the spirit of Schumpeter, Dahmén describes the imbalances that always appear in the industrial system, and the resulting dynamics counteracting these imbalances. The fact that the major share of the world's diesel engines still emits considerable amounts of harmful emissions can be viewed as such an imbalance. Just as well, it can be seen as a *reverse salient* in commercial development with a

[1] An outline of the Homogeneous Charge Compression Ignition (HCCI) engine is given in the "Vehicle, engine and transmission" section

reference to Hughes (1992). The development blocs described by Dahmén do not have an explicit or even necessary territorial aspect: the imbalances can appear throughout the economy. Even if Dahmén had a Swedish economic perspective, the area of system coverage is more of an empirical issue (cf. Laestadius 2005).

The aforementioned discussion can be carried out also in cultural terms. Over what territory, and in which way is a critical mass of problem solving activities towards the diesel engine emission problems created? How should incentives be structured? Given the globalization involving product development and research such an approach may be valid. It is especially relevant for the automotive industry system in a wider context because it is highly globalized regarding production. It is our understanding—without focusing on this aspect—that our specific area of technology has advanced its state of globalization in the most recent years.

This paper has some focus on the Swedish role in development of technology for emission abatement. It should however be stated from the outset that many of the companies that are involved in a national innovation system for catalysts are not Swedish, at least not regarding ownership. A strong "development culture" in combustion engine and emission aftertreatment thus cuts through national and corporate borders. This complicates the establishment in a globalized economy (cf. Kenney and Florida 2004; Dunning 2000). In short, we deal with the partly contradictory phenomenon that we can observe *sticky places*, i.e. locations that attract industrial activities, in contrast with an increasing globalization which signifies *slippery space*, i.e. a global and friction-free physical movement of production processes, knowledge generation as well as traditional trade (c.f. Markusen 1996).

The development of new technologies in one area is characterized by interactivity with other areas of technology, as well as with societal institutions and with companies. This phenomenon is labeled *co-evolution* and contributes to the momentum of a developing trajectory once it is defined and is under development (Nelson 1998). All technical development is not characterized by such interdependence. Innovations are often *modular* or *architectural*, meaning that a new technology is added onto an old, without changing the initial structure, or rearranging established technologies in a new pattern (Henderson and Clark 1990). We would argue that all these models relate to the development of catalytic exhaust aftertreatment systems in different phases of development. The end-of-pipe, modular and scalable character of the technology did facilitate the introduction. In later stages, development is better characterized by co-evolution.

Fogelberg (2003) cites Gibbons et al. (1994) and others in discussing the different knowledge cultures or *epistemic cultures* or communities in engine innovation, more common mergers between science and society, and the development of knowledge 'in the context of application' as a new research tradition. Different cultures would have greater difficulty in communication than was previously thought, e.g. between different scientific disciplines or between research and commercial development. Specifically relating to diesel engine emission abatement technology, Ng (2006) has shown that the setting of standards is often based in part on demonstrations of effectiveness of new technology. Demonstrations are real-life indications of which new technologies may commercially comply with more strict emission standards. This shows that the rules of the market are not set only by the regulators, but by interaction on a *protomarket* between regulators, the scientific community and commercial actors with an interest in change. Ng defines *non-market strategies* as aimed at enhancing a company's competitive position by altering, advancing or retarding the development of a new regulatory policy. The "language" in this dialogue, labeled *trans-epistemic objects* by Fogelberg, is the emission results from demonstrations and proposed limit values for standards, using common test methods and technology which would be interpretable by different types of actors.

A complex setting

The development of low-emission diesel engines is complex and a great challenge. The advancements to date depend on solid demand and co-evolution involving the vehicle producers, suppliers and the respective regulating bodies. To the extent that new engine technologies involve improvement of fuels and other infrastructure-related technology, a wider network must be committed. Coordination of the technical, commercial and legal initiatives for emission reduction can be instrumental in bringing about change, especially in protomarkets or earlier phases of technical development (Bauner 2007a; Bauner and Laestadius 2003).

Based on the massive demand for individual mobility, goods transport and other more "soft" factors such as status and respect, the vehicle industry has successfully developed products regarded as one of the main desires—let alone necessity—of almost every professional and family on the planet (cars), main ingredient in most public transport systems (buses) or main tool in most companies' distribution system (trucks). The French vehicle manufacturers association CCFA states that each truck has four different phases of use in society (Table 1).

Each vehicle sold must comply with emission (and other) regulations in the country of registration. Historically, the early and larger markets, here dubbed *dominant*,

Table 1 Vehicle manufacturer's association view of the life span of a heavy-duty truck

Usage phases	Period	Use	Note
1st phase	2–3 first years	Optimization, intensive use, international routes	150,000 km/year
2nd phase	2–3 years to 8–10 years	Regional routes	Engine renovation (the truck may have run 1 million km by then)
3rd phase	10–12 years	Local use or exportation	(1.2 million km)
4th phase	Up to 20 years	Minor use	

Press statement, 27 March 2005 by CCFA, the French Committee of Automobile Manufacturers

have contributed to the development of emission control systems and guided development for other markets. Each of the Triad economies, Europe, North America and Japan, are dominant markets in that they are large enough to sustain a regulatory demand profile by their own virtue. They have stayed ahead of other markets with more strict requirements and development on fuel quality and air quality monitoring, while laggard countries or regions have hardly begun a journey that has taken decades for the pioneers. Also vehicle production has been dominant in these regions, with North America pioneering in the early twentieth century, Europe following, and Japan taking on the challenge a few decades later.

This chapter contains a description of the market for diesel engine road vehicles, the technology to achieve low emissions and the actors which jointly and in competition develop and produce vehicles and components.

Market

Diesel engines are used in a wide variety of fixed and mobile applications such as power generation and propulsion of ships, locomotives and road vehicles. This paper focuses on road vehicles, where emission regulation has been at the forefront due to the higher exposure of emissions to the public. Diesel-driven road vehicles can be divided into passenger cars, trucks and buses.

For most customers of diesel-driven vehicles, exhaust aftertreatment is "embedded technology";[2] part of an engine propulsion system. As to market impact, its function is not directly visible or beneficial to the user, and thus requirements are set and enforced almost exclusively by governments. The market for emission control systems is split between originally mounted systems and retrofits.

OEM[3] systems, mounted on the original vehicle, is the vast majority and usually directly developed to comply with the regulations for the market where the vehicle is sold. Retrofit[4] systems are aftermarket products for some user segments and on certain markets. The objective is here to enhance the environmental performance of an in-use vehicle. The retrofit market exists partly as a function of fleet requirements for buses and delivery trucks serving in cities or applications such as school buses or where air pollution has called for measures beyond the national or federal requirements. A retrofit particle trap and/or catalyst may considerably reduce nitrogen oxides and particle emissions.

The commercial development of emission aftertreatment systems is, in reality, in global terms geared towards three markets. The requirements set for Europe, USA and Japan have hitherto fostered technology development and selection for the remaining world with different time lags.[5] The setting of these requirements is a complex process that is carried out differently in the three markets, historically shared in some cases (Bauner and Laestadius 2005), and increasingly so. The process is also different for light and heavy duty vehicles. It is accentuated in especially exposed regions, such as California, in a number of megacities and for special applications such as underground mines—in these areas requirements are pushed, especially for heavy-duty vehicles. China adjoins the more international development in the UN Economic Commission for Europe, fostering EU regulation and the Euro emission requirements for all road vehicles (see "Europe" section). So far, emission limits have concerned engine emissions over specified driving cycles. This leaves a risk that the vehicle is designed to emit higher levels of, e.g. nitrogen oxides, favoring lower fuel consumption, outside of the drive cycle. The risk for illegal *defeat devices* increases with more strict emission limits. The remedy can be to introduce *not-to-exceed* emission levels, which may not be exceeded for any combination of engine speed and torque.

Environmentally sensitive local markets/areas, such as the Environmental Zones (EZs) found in the three largest cities in Sweden, e.g. have in some regions required the

[2] A term usually reserved for electronic products.

[3] Original Equipment Manufacturer. Term here used for vehicle manufacturers. It is slightly misleading due to the outsourced structure of today's vehicle manufacturing industry, where the main role of the "auto makers" could be described as system integrators and assemblers.

[4] Systems fitted on in-use vehicles after a number of years in use.

[5] A few countries in the world are still unregulated as to vehicle emissions.

best commercially available emission technology for some time. Typically, emission standards comparable to what is required for new vehicles are required, and state-of-the-art emission control retrofits are given incentives, e.g. in procurement of public transport. Vehicle owners operating in such EZs have often had the option to choose between retrofit particulate filters or renewal of the vehicle fleet. Also retrofit programs have been initiated in Japan, e.g. and on state level in USA. Retrofit equipment is supplied by aftermarket producers, in some cases separate companies from the major suppliers.

The road vehicle market can be divided into light, medium and heavy vehicles. Diesel engines can be found in all segments, with some important differences: Diesel completely dominates the heavy-duty vehicle segment. For light-duty vehicles, the diesel share for Europe is 49% (ACEA 2005). In USA only a few percent of passenger cars, predominantly "Class 2" trucks (SUVs), are diesel driven, something which may change as the present discussions on fuel economy and CO_2 emissions are transformed into incentives and demand for diesels. This could imply increased demand for imported vehicles, because European manufacturers, e.g. have considerably more light-duty diesel engine experience.

Table 2 shows the magnitude of sales and working fleet for the different markets. The numbers come from different sources and depend on where the respective sources have drawn the line between light and heavy vehicles, etc; numbers should be seen as indicative of the size of a given segment.

The difference of about one order of magnitude between the number of in-use vehicles and yearly sales in Table 2 would suggest that fleet renewal is carried out over approximately a decade. However, given the different phases in the useful life of a truck (Table 1), the vehicle in its original, high-intensity application is renewed in about half that time period, and the older vehicle is used in a secondary application close to the region of original registration or exported to a developing country.

As late as 1997 the Triad accounted for more than 70% of total global vehicle sales. However, during 1990–1997 sales in the rest of the world increased by 3.8 million units, while Triad sales only reached 230,000 units (Humphrey and Memedovic 2003). The vehicle market is global, but patterns can be discerned. Volvo (heavy-duty only) sells more than half of its production in Europe, and more than one quarter in North America[6] (emcc 2004a). Scania shows similar sales proportions, but instead Latin America (including Mexico) is a strong market—Scania is not present on the USA market.

[6] 57 and 28%, respectively (2004).

The total emissions control market for original equipment, aftermarket and retrofits depends on regional and local regulation and enforcement, incentives for fleet renewal, retrofit, and vehicle scrapping, as well as the availability of suitable technology, The value is large—the international engine consultant Michael Walsh presented a study in 2000 stating the total market for diesel engine exhaust aftertreatment to increase from 5.8 billion USD in 2000 to 21 billion for 2020 (press announcement by MECA,[7] May 3 2002). This figure is likely to concern only USA and Canada, given that the MECA in another presentation estimates the global turnover for diesel exhaust emission control for 2010 to be 72.3 billion USD. These figures are estimates and the results depend on the method used for calculation.

In each advanced market, ultra-low sulfur fuel is being introduced to reduce emissions and to allow the use of diesel particulate filter/traps (DPFs, see "Technology" section) and other emission control technologies.

Europe

In Europe, test cycles and limit value proposals are developed in the Working Party for Pollution and Energy (GRPE), a subsection of the UN Economic Commission for Europe (ECE). The procedure is managed by a committee with participants from countries both inside and outside of Europe, so that the outline and effects of new regulation are discussed beyond the European perspective. A completed GRPE proposal is then—usually—developed into an EC Directive, making it mandatory for EU member states. This participatory process in developing new regulations is likely the main reason that many countries outside the Triad adopt the EU roadmap for vehicle regulation.[8] At the SAE TOPTEC-meeting in Göteborg in 2003, the UBA (German EPA) representative announced that for Euro V (Oct 2008), Germany wanted not-to-exceed levels from heavy-duty vehicles, emission limits that could not be passed at any combination of load and RPM. This is still discussed in GRPE. A joint project "CARS 21" is established between public and private automotive actors to enhance the global competitiveness of the European automotive sector by definition of a predictable regulatory environment for the future.

Euro IV limit values became operational from October 1, 2005 for new heavy-duty vehicle engine families and from October 1, 2006 for all newly registered vehicles. Compared to the previous level Euro III, maximum

[7] Manufacturers of Emission Control Association—the North American catalyst manufacturer organization.

[8] ECE regulatory work, of course, involves many other areas than emissions.

Table 2 Approximate number (in thousands) of vehicles per market (Source: OECD, ACEA, JAMA, US BTS, SIKA et al. reservation for errors)

	Market	New registrations (2003)	In use (year)
Light-duty vehicles (diesel and gasoline[a] passenger cars and light trucks)	Europe (EU-15)	15,500	211,000 (2003)
	whereof Sweden	289	4,420 (2003)
	USA	*7,610*[b]	226,000 (USA, 2002)
	Japan	4,460	55,200 (2003)
Heavy-duty vehicles (heavy diesel driven trucks and buses)	Europe (EU 15)	339	3,800 (2003)
	whereof Sweden	6	86 (2003)
	USA	*7,520*	22,600 (USA, 2002)
	Japan	1,370[c]	17,300 (2003)

[a] When looking at light vehicles, it should be noted that the diesel engine fraction is around 45–50% for larger markets in Europe (around 12% in Sweden and over 60% in Spain, France, Luxembourg and Belgium) but as low as 3.5% for passenger cars in USA. Also Japan has few diesel passenger cars

[b] USA sales statistics for passenger cars does not include light trucks. It is assumed that a majority of the truck sales (in number of vehicles) should really light duty trucks, given that the USA fleet of light trucks is around 73% of the total number of trucks. The statistics for heavy versus light-duty vehicles in USA depends to a large extent on how SUVs and midsize vehicles are accounted for. They are here included in the light-duty tables regarding in-use vehicles, but in heavy-duty regarding sales. This may hold some logic, into which we will not delve here

[c] In Japan, a large fraction of the distribution trucks are small by European and USA standards. What would be a 'standard' Class 8 truck in USA is only around 20% of truck sales in Japan

permissible limits of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NOx) were reduced by 30%, and particulate emissions (PM) were reduced by 80%. October 1, 2008 (for new models) and October 1, 2009 (for new registrations of vehicle models certified earlier) mark the advent of Euro V regulations, where NOx are further reduced, by 60% compared to Euro III. Emissions for heavy-duty vehicles are measured in g/kWh over specific load/engine speed (rpm) points, the so-called *European Stationary Cycle* (Table 3).

In addition, smoke is measured in a separate procedure. Diesel- and methane-driven vehicles must also pass slightly higher or equal emission levels over a so-called "transient" cycle (European Transient Cycle, Fig. 1) that is designed to resemble real traffic. Emission limits are thus more than halved for NOx and PM, and all regulated emissions are reduced.

The so-called Stage 2 of *On-Board Diagnostics* (OBD), that detects the function of vital components such as emission control for heavy vehicles, would *inter alia* actively reduce engine power in the case of failure of the emission control system, will be required from 2008 or 2009.

Table 3 EU heavy-duty truck emission requirements over ESC (European Stationary Cycle) (g/kWh)

Name	Enforcement date	CO	HC	NOx	Particulates	Smoke
Euro IIIb	October 2000	2.1	0.66	5.0	0.10	0.8
Euro IV	October 2005	1.5	0.46	3.5	0.02	0.5
Euro V	October 2008	1.5	0.46	2.0	0.02	0.5

In addition to regulation, special incentives exist in different countries. One example is economic support for exhaust retrofit equipment for vehicle owners. The European Commission (EC) approved in July 2004 that Denmark leave 30% support for procurement of retrofit DPF for heavy vehicles (EC 2004). In Germany, there is a special road toll for heavy vehicles, MAUT, depending on Euro class with up to 30% fee reduction if using cleaner vehicles.

The sale of light-duty diesel vehicles in Europe is about equal to sales of gasoline vehicles.[6] The diesel fraction is growing and is described as an important measure to reduce the increase in greenhouse gases. ACEA agreed in 2003 with the EC to voluntarily reduce average carbon dioxide (CO_2) emissions from all passenger cars by 25% regarding sales from 1995 to 2008, i.e. from 190 to 140 g/km CO_2 (ECMT 2003). The EC does not see this agreement being realized. On February 7, 2007, a new, more binding strategy to reach its long-established objective of limiting CO_2 emissions for newly registered vehicles to be on an average of 120 g/km by 2012 was presented (EC 2007). A legislative framework to reduce CO_2 emissions from new cars and vans will be proposed by the Commission at the latest by mid-2008. Further, the Commission has developed an "EU code of good practice" on car marketing and advertising aimed at the vehicle manufacturers. The societal benefits of the new 120 g/km average limits are contended by ACEA.[9] Maximum permissible tailpipe emission limits are shown in Table 4. There are no limits on CO_2 emissions.

[9] Press release by ACEA, February 7, 2007.

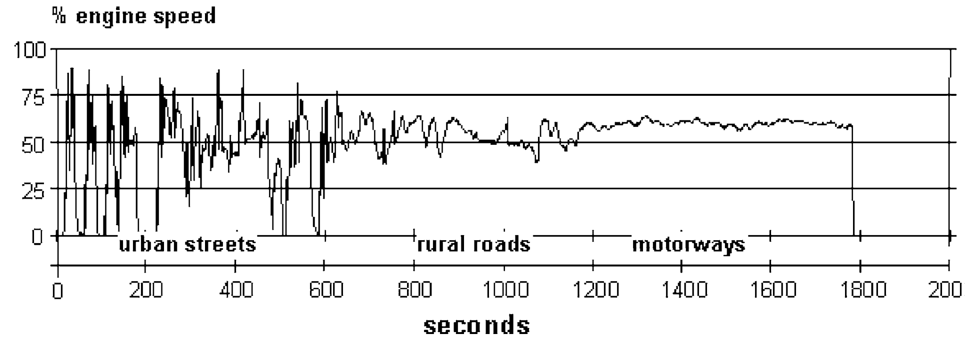

Fig. 1 European Transient Cycle (for certification of heavy-duty engines/vehicles)

Table 4 EU emission limits (g/km), light duty diesel vehicles, NEDC (New European Driving Cycle)

Class	From year	CO	HC	HC+ NOx	NOx	Particulates
Euro 4	2005	0.30		0.30	0.250	0.025
Euro 5 (EPEC prop)	Oct. 2008	1.0	0.075		0.18	0.005
Euro 6 (EPEC prop)	2014	TBD	TBD		0.07	TBD

TBD to be determined

On September 13, 2006, the European Parliament's Environment Committee (EPEC) approved European Commission proposals to tighten *light-duty vehicle* emission standards, but voted for longer transition periods (up to 2009) before the new rules take effect. The new rules must wait approval by the full Parliament and by the European Council. The proposed Euro 5 limits will reduce the standard for particulate matter in diesel car exhaust by 80% (to 0.005 g/km), nitrogen oxides are reduced to 0.180 g/km for diesel cars. Hydrocarbons are reduced to 75 mg/km. The committee also called for tighter standards, dubbed "Euro 6", to be introduced 5 years after Euro 5. Euro 6 NOx limits will be 70 mg/km for both petrol and diesel fueled vehicles.

The Commission has approved a German request for tax reduction of light diesels that do not exceed 5 mg/km particle emissions up to the introduction of Euro 5 limits (around 2010). Germany encourages vehicles with a particulate trap from 2006 up to 2008 when the German vehicle industry has declared that all new (diesel) cars will be equipped with a particle trap. New vehicles get a deduction of €350, and retrofit implies a tax reduction of €250.[10] The Swedish government has approved similar incentives.

DPFs have been introduced in environmentally sensitive areas in different parts of Europe by regulating EZs, where older vehicles (Phase two or three in Table 1) must be replaced or be retrofitted with particulate filter/oxidation catalysts. This has, as mentioned elsewhere, verified the technology and served as an early market for filter manufacturers.

USA

The USA's view on diesel engine emissions took a turn in 1998, when the Air Resources Board of the state of California identified diesel engine particulate matter emissions as a Toxic Air Contaminant (TAC), calling for a strategy for its reduction. Depending on local conditions, different states and areas have different goals to attain regarding emission reduction.

Emission certification for HD diesel vehicles in USA concerns, as in Europe, only the emissions of the engine as a function of engine power and is normally measured over a *transient*[11] FTP cycle. Engines are, somewhat contradictory, divided according to the weight of the vehicle. USA trucks are divided into different classes: Light (LHDDE; 8,500–19,500 lb), Medium (MHDDE; 19,500–33,000 lb) and Heavy (HHDDE, above 33,000 lb) trucks. Only regulation for HDD is shown here. Passenger car size vehicles are labeled Light Duty diesel (LDD).

Table 5 shows present and future regulatory levels for the heaviest vehicle class.

Particle emissions are thus reduced to one-tenth of the previous levels from January 1, 2007. For nitrogen oxides and hydrocarbons there is a phase-in, so that only half of each manufacturer's production must comply with the new regulation. In 2010 all new vehicles must comply. For the 2007 requirement, most manufacturers will not use particle traps or catalysts, but rely on short-route EGR (see "Technology" section). The technology decision by an engine manufacturer on how to pass 2010 regulations would typically have been taken by 2007.

The OBD have been phased in for light trucks since 2005. For heavy-duty vehicles OBD is proposed to be phased between 2010 and 2013. This represents an obligation for the vehicle manufacturers to develop sensors and

[10] Car Lines, February 2005 (Michael Walsh) http://www.carlines.com.

[11] A transient cycle resembles real driving more closely than a stationary cycle or a cycle with a limited number of driving modes.

Table 5 Emission requirements for diesel vehicles in USA

	NMHC		NOx		PM	
	g/ bhp h	g/ kWh	g/ bhp h	g/ kWh	g/ bhp h	g/ kWh
US 2004 HHDD alt 1	2.4*	3.2*	2.4*	3.2*	0.1	0.13
US 2004 HHDD alt 2	2.5**	3.4**	2.5**	3.4**	0.1	0.13
US 2007 HHDD	0.14	0.19	0.20	0.27	0.01	0.013
US 2010 HHDD	0.19	0.25	0.27	0.36	0.01	0.013
/	G/mile	g/km	g/mile	g/km	g/mile	g/km
US 2007 LDD	0.090***	0.056***	0.070	0.044 (avg)	0.01	0.0062

NMHC non-methane hydrocarbon emissions, *NMOG* non-methane organic gases

* NMHC + NOx

** NMHC only max 0.5

*** NMOG

systems that monitor the function of emission control systems, and indicate to the driver of malfunctions of systems—such as the continuous injection of urea into the exhaust stream of SCR equipped vehicles. OBD is important as the tradeoff set by regulation between NOx and fuel consumption is not necessarily favored by vehicle users; in USA there are already 40 manufacturers of modification kits that by changing engine control system settings, lowers fuel consumption and increases NOx emissions.[12]

Japan

Regulations in Japan are structured a bit different for diesel vehicles, both light-duty and heavy-duty. An *average* regulated emission limit value is set, and is used for certification and for production control, and then complemented by a slightly higher *maximum* permissible limit value that must be passed for each vehicle unit. A new transient drive cycle for heavy engines based on Tokyo driving conditions, JE05, was also introduced in 2005. It has an average speed of 25 km/h, making it difficult for catalytic light-off. The new requirements imply a 40% reduction of NOx emissions and 85% reduction of PM for heavy-duty vehicles (Table 6).

For 2005 H-D requirements in Japan, the values are similar to Euro V (2 g/kWh NOx, 0.02/0.03 g/kWh PM for ESC/ETC), but not entirely comparable since the Japanese drive cycle is different. With the update in 2009–2010, the Japanese requirements become the strictest in the world.

In the so-called *hachi-to-kenchi* area, made up of prefectures Tokyo, Saitama, Chiba and Kanagawa and cities

[12] Article in New York Times, referred in http://www.Dieselnet.com, 2004 (13 Feb). See also "Technological system co-evolution" section.

Table 6 Average emission requirements for heavy engines, Japan (g/kWh)

Year of enforcement	Drive cycle	CO	HC	NMHC	NOx	PM
2003–2005	13-mode	2.22	0.87		3.38	0.18
2005	JE05	2.22		0.17	2.0	0.027
2009–2010	JE05	2.22		0.17	0.7	0.01

Source: Dieselnet

Yokohama, Kawasaki, Chiba and Saitame, a special law regarding emissions of NOx and particles from diesel vehicles was enacted. In simplified terms, vehicles older than 7 years must retrofit a special filter/catalyst. Upon verification, the vehicle receives a unique numbered sticker.

For light and medium vehicles, particle emission levels are reduced, from previously 0.052–0.06 g/km depending on vehicle category to presently 0.013–0.015 g/km, a reduction of 75%. For NOx, permissible limits have gone down 50%, from 0.28–0.49 to 0.14–0.25 g/km. The 10–15 mode drive cycle is "hot start" meaning that the engine (and catalyst) is allowed to heat up before measurements start, giving considerably lower emission levels. For light duty vehicles a new driving cycle was introduced in 2005, to be gradually phased in until 2011 (Table 7).

Other regions/ROW

The problems with high concentrations of noxious substances appear first and foremost in large urban and industrial areas, where the concentration of industries, households as well as transportation contribute to emissions, usually with combustion engine driven transport as the main contributor.

Outside the Triad it is therefore mostly in cities that programs and requirements for air quality improvements are found. Several cities in developing countries have developed programs to shift to natural gas, e.g. driven buses or to require retrofit exhaust treatment for heavy vehicles. Many developing countries, including large nations like China will be able to pass from non-regulation (or not enforced regulation) to good (such as current EU or USA norms) and "leapfrog" (Goldemberg 1998) the evolutionary development of limit values and control technology seen in the dominant markets. China is a growing market where at least in larger cities emissions requirements soon will be on par with Europe.

Hong Kong has stipulated all large (over 4 ton) pre-Euro diesel vehicles to retrofit with a diesel particulate catalyst/trap. Based on engine size, the vehicles are divided into five groups. For each group of vehicles, two procured contractors provide catalytic converter installation services. In total, the Government of the Hong Kong Special Administrative Region has budgeted HK$ 600 million

Table 7 Average emissions requirements for diesel-driven passenger cars >1,265 kg, Japan (g/km)

Year of enforcement	Drive cycle	CO	HC	NMHC	NOx	PM
2002 (imports 2004)	10–15 mode	0.63	0.12		0.30	0.056
2005 (imports 2007)	10–15 mode + 11-mode	0.63		0.024	0.15	0.014
2009	10–15 mode + JC08[a]	0.63		0.024	0.08	0.005

Source: Dieselnet

[a] New drive cycle, to be phased in until 2011

($77 million USD) for subsidizing the retrofit (i.e. both Hong Kong and mainland going vehicles). Participation in the retrofit for vehicles traveling to mainland China is voluntary for vehicle owners. The subsidy covers the cost of the retrofit up to a given cost per unit. In parallel, a scheme for replacing light diesel buses with LPG or electric has resulted in that 80% of new registrations in 2005 were powered by LPG.[13]

On a national level, emission requirements in China are gradually imposed corresponding to European levels starting from Euro 1 in 2000. Emission limits are more strict in Beijing, Shanghai and Hong Kong. A roadmap to reach what is required in Europe today, with a lag of about 4–6 years is presented (Table 8). Unleaded gasoline and lower sulfur diesel fuel is introduced, focusing on cities. These three cities alone have about 27 million inhabitants and constitute an attractive market. A tax reduction scheme is established, favoring those vehicle manufacturers who sell vehicles that comply with Chinese regulations corresponding to Euro III or higher.

In developing countries, the market for commercial (heavy) vehicles is more developed than the light-duty market than is the case in the OECD. In some regions, fuel is manipulated and sold in a "pirate" fashion, e.g. to avoid tax. In such regions it is difficult to introduce advanced exhaust aftertreatment, which requires more precisely specified fuels. Exhaust catalysis also requires low sulfur fuel content. In some coal-producing Chinese regions, relatively large production of coal-based DME, an alternative fuel, is planned. This would require engine and fuel tank modifications.

The role of measurement and certification

The regulatory test development procedure has the advantage that once the limit values for the future regulatory levels are set, it provides a floor for technical development. Early development and sales of vehicles complying with coming lower emission levels may then be achieved in different ways. The major potential disadvantage of transparent future rulemaking and compliance test methods is that technology may be developed to comply with certification procedure without necessarily optimizing for low emissions in on-road, real-life conditions.

Table 8 Emission requirements for heavy engines, China

Req	Date start	CO	HC	NOx	PM	
					≤85 kW[a]	>85 kW[a]
Limit values and date for TA-test (certification)						
1	1 Sept. 2000	4.5	1.1	8.0	0.61	0.36
2	1 Sept. 2003	4.0	1.1	7.0	0.15	0.15
Limit values and date for COP-test (in-use compliance)						
1	2000.9.1	4.9	1.23	9.0	0.68	0.40
2	2004.9.1	4.0	1.1	7.0	0.15	0.15

Source: Chinese EPA. http://www.vecc-sepa.org.cn

The test cycle in China is the corresponding EU cycle/cycles; unit: g/kWh

[a] Engine power

As an example of the present state-of-the-art in regulatory development, there is an ongoing discussion to regulate also the maximum number of particles emitted, and not only a limited weight. The environmental foundation is that smaller particles, which are not detected by the present weight-based method, may be more detrimental to health because they get further into the respiratory system and thus easily may enter the blood stream, increasing risk of cell mutation (cancer) and other diseases. The *Particle Measurement Programme*, an initiative of France, Germany, Sweden, Switzerland and the UK, and currently managed by the Joint Research Center of the European Commission investigates the potential to develop new methods for measuring particle emissions from diesel vehicles. The light-duty vehicle test program has been completed (GRPE 2007) and the heavy-duty program is underway. The program has not yet yielded new regulations for particle measurement, but discussions are ongoing.

A specification for Global Technical Regulations (GTR) for heavy-duty engines has been developed, involving European, Japanese and to some extent USA regulators and vehicle industries. The test method draft has been presented, but does not include limit values (GRPE 2006). A unified certification method would facilitate engineering

[13] Hong Kong Environmental Protection Department website, http://www.epd.gov.hk, and other sources.

and thus reduce cost, but also reduce the ability to coordinate regulation with local vehicle use patterns such as urban speed profiles.

Technology

Emission aftertreatment is needed when engine emissions are too high according to local regulation. In the Triad countries it is only for 2005 that any aftertreatment other than EGR has been implemented for heavy vehicles. Light duty diesel vehicles have had oxidation catalysts for years in some markets. Also engine development and fuel quality are part of the system that affects the resulting emissions.

In pursuit of reducing diesel engine emissions, as in other areas, different technological trajectories develop. Such trajectories are not limited to different bolt-on, end-of-pipe solutions, but range from new engine types, new fuels, friction improvement methods, different kinds of streamlined bodywork and even new transport models. A possible technological solution may comprise one or more elements, and is usually developed as a system with several cooperating organizations. Only certain combinations of fuel and technologies are compatible and imply different compromises between energy efficiency, cost for development, production and use, complexity, attainable emission levels, transferability and other issues. An example of this is a technological system for SCR/DPF (described in "Technology" section).

This section includes an overview of the different options and elements of emissions reduction systems.[14] From an innovation theory perspective we can here talk about mechanisms of *variety* and *selection* where the market and the legislation over time steer development to a limited number (one or more) of dominating compromise solutions that we can label as the *dominant design*. Authorities managing technology policy can enhance development, not the least by *demand shaping*, but will in the end have limited influence on the details of the resulting technology. Technology control policy developed to support a particular technology may—even if it is not always the case—convey unwanted lock-in effects. And in every case there is the market interaction between suppliers and vehicle manufacturers to tweak the technologies to reach advantages towards the consumers.

A conclusion from this train of thought is that the technology innovation frontline never is static or predictable. Each trajectory has its own logic and normally also its special advocators or agents. This is discussed later in this paper. The selection and characteristics of emission control-related technologies and its representing agents will evolve over the coming decade related to the increased demand of efficient diesel engines.

A large number of factors affect the parameters that vehicle designers and engineers must balance in a vehicle, where new characteristics and functions are added each year. What is added must be successfully combined with basic performance like acceleration, fuel economics, payload and driveability. OEMs, customers and regulators set partly conflicting goals.

The limit values for the new emission requirements in Japan are on a level that requires research, not only development of new systems and products, even if great progress has been made in lowering "engine-out" emissions (i.e. emissions before any exhaust aftertreatment). Also considerable lower limits are imposed in USA. This means that there is an increasing need for analysis and understanding of the tradeoff between lower engine-out emissions (i.e. the working principles of the diesel engine) and different exhaust aftertreatment technologies. R&D for new technologies such as catalysis, urea injection in the exhaust gas stream and active regeneration of particle filters are carried out for the development of different markets depending on the timeline for regulatory changes. Goals are not necessarily compatible—the counteracting impact of different emission control technologies and optimization strategies for fuel is well illustrated by a diagram from Volvo (Fig. 2).

As an example, optimization for low fuel consumption (lean operation) will increase combustion temperature and also NOx emissions. Apart from improvement in combustion technologies and a greater understanding of flame propagation and formation of emissions, specific technologies are developed, that alone or in combination, reduce emissions towards the different tiers or stages.

Vehicle, engine and transmission

For heavy-duty vehicles, the potential to reduce weight is limited as vehicle weight in relation to payload is low. However, for passenger cars the trend has, for a long time, been for heavier vehicles. Here, the entire vehicle may be part of the emission strategy. However, in this paper we focus on the engine and the increasingly integrated emission control technologies and strategies.

Engine, control systems, fuel injection, sensors Effective and efficient *engine control* is an important part of the puzzle to reduce emissions. From an emissions point of view its main role is to optimize the engine to function well with the exhaust aftertreatment system used. Control requires measurement of the engine operating conditions, chemical composition of fuel, temperatures, fuel/air mix, flow and exhaust characteristics. Measured data enter an

[14] Please note that the development and analysis of measurement technology is carried out in "Market" section.

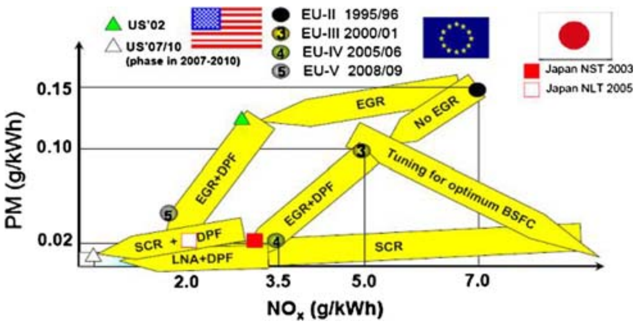

Fig. 2 Impact of technology on emissions (PM, NOx) versus fuel economy (BFSC stands for Brake Specific Fuel Consumption, the "real" fuel consumption of the engine in use (Fayolle 2004)

engine control unit (ECU). The ECU controls the fuel injection pressure, EGR (see later in this section) fraction etc. The ECU is the brain of the engine and may be developed for a new engine family "in-house" by the manufacturer or by an external consultant/supplier. The novel step, taken several years ago but increasingly refined, is the change from mere *feedback loop control*, where control parameters are decided by an algorithm guided by input values from one or more sensors in the engine or in the exhaust stream, to *model based control*, where the control parameters are guided not only from sensor input but also from a matrix or model of the engine's operating conditions.

Furthermore, the fuel injection has an impact on emissions: Common rail technology[15] admits more precise injection control and higher fuel pressures, which in turn improves combustion and lowers NOx emissions. Higher injection pressures can also reduce particle formation. Different fuel injection strategies, controlled by the ECU, therefore can produce widely different emission characteristics for a given engine. Further, more fuel can also be injected after the expansion cycle to e.g. control the regeneration of particulate traps, lean NOx catalysts or NOx storage technologies. Advanced combustion strategies can involve up to five injections per combustion cycle.

On-board tank, fueling and engine feed of urea For SCR (see "Exhaust aftertreatment" section), more components than the special catalyst are needed. A reasonably tamper-proof system for fueling, storage and feeding of urea to the exhaust will be required for each vehicle with an SCR system. It is therefore not evident that a vehicle will be approved for Euro V (in some cases not for Euro IV) even if the emission control unit works well during the test. According to ACEA,[16] the cost of urea can be several hundred € per truck per year, and higher for Euro V and VI. In an economically constrained market there is thus a risk that SCR equipped vehicles are manipulated to reduce costs for the operator. OBD equipment is designed to prevent such practices

Turbo All modern diesel engines have turbo. The turbo supercharges inlet air which improves aspiration, increases power (allows downsizing), reduces fuel consumption and improves performance when driving at altitude. Development during the past years regarding diesel include variable geometry, offering a broader torque curve.

Insulation Increased engine efficiency will further reduce the amount of emissions heat available, required to maintain the catalytic process and also to regenerate particle traps (see later in this section). The exhaust system can be insulated to retain the produced heat, either with double wall pipes or using insulation material.[17]

Homogeneous Charge Compression Ignition (HCCI) is a combustion type that can be described as between the Diesel and Otto principles. It requires advanced electronic control but holds several promising characteristics, not the least of which regards engine-out NOx emissions. Since the combustion of the lean air/fuel mixture is simultaneous in the entire combustion chamber, the flame front that causes NOx emissions is avoided. A HCCI engine can thus potentially attain required emission levels without exhaust aftertreatment, with excellent fuel economy. Such results are obtained principally under light loads. A major challenge is to control ignition without the use of a spark plug. A number of research projects are carried out at vehicle/engine manufacturers and at universities in Sweden and internationally. A first commercial step for manufacturers is likely to achieve HCCI conditions over part of the regular engine speed–torque map. A commercial application of HCCI is not to be expected until the coming decade. HCCI-engine research is a global topic and carried out at the technical universities in Stockholm and Lund in Sweden (Haraldsson 2003).

Hybrid A hybrid drivetrain can save energy, especially in urban public transport and goods distribution. Several manufacturers have presented hybrid solutions in prototype applications and in some special fleets. Light hybrids offer potential energy savings of 10–15% from regenerative braking and smoother torque curves. Plug-in hybrids could offer carbon-neutral and zero-emission driving, depending on the feedstock of electricity used.

[15] A common rail fuel pump increases the fuel pressure before injection much higher than that possible with unit injectors. Each cylinder is then controlled by a separate valve. Most HD engines on the road today in the world have unit injectors—that naturally also have passed several generations of incremental development.

[16] European Automobile Manufacturers' Association, http://www.acea.be.

[17] Interview with Kristian Althini, Faurecia AB, 2004.

Exhaust aftertreatment[18]

The Diesel engine has lower exhaust temperature than the Otto engine; mostly depending whether lean (excess air) operation has been chosen. The diesel process also makes better use of the fuel energy potential. As the diesel engine is developed towards higher efficiency, lower exhaust temperature will imply a bigger challenge in developing catalyst solutions that function well. Exhaust catalysis normally requires a minimum temperature of 300°C (some catalyst types require the double), which can be difficult to reach depending on vehicle use patterns. This means that catalytic solutions may require post-combustion fuel injection to function in urban applications.

Diesel oxidation catalyst (DOC) An oxidation catalyst reduces hydrocarbons and carbon monoxide in the exhaust stream to more harmless gases with little or no need for feedback control systems. DOCs are often combined with a DPF in retrofit systems. Because of the lean exhaust, NOx levels are however not reduced. DOCs are installed in hundreds of thousands of light- and heavy-duty vehicles, notably most German light-duty vehicles. Sweden alone has more than 10,000 retrofit catalytic filters installed in city buses and distribution trucks (Erlandsson and Bauner 2003).

Particle filters/traps (DPF) A particle trap is in most cases a cylinder of ceramic material with fine channels where alternate channels are plugged and exhaust fumes are forced through the thin porous walls of the stone. Different strategies to burn off the particles have been presented, either by enriching the exhaust to combust the soot or by external cleaning or both. The former function is called by the product name CRT©, continuously regenerating trap, a technology which combines a DPF with a DOC. The catalyst stone may also have a catalytic coating on the filter walls and will thus combine the characteristics of trap and oxidation catalyst. Particulates are burned in a combustion process requiring NO. DPFs require ultra-low sulfur diesel fuel. Millions of DPFs are both originally mounted and retrofitted.

A fuel additive, the element cerium, is used to reduce particle emissions for passenger and light commercial diesel cars. Cerium is used together with a particulate trap, and usually in combination with an oxidation catalyst. Since the low exhaust temperature cannot guarantee that the DPF is regenerated regardless of driving condition, engine management is used intermittently to increase exhaust temperature to boost regeneration. PSA Peugeot Citroën has fitted more than one million of the Cerium-enhanced DPFs on their vehicles since 2000.[19]

Exhaust Gas Recirculation (EGR) is a means to lower NOx emissions by recirculating inert (combusted) cooled gases into the combustion chamber, thereby reducing the combustion temperature and thus NOx formation. Soot formation may increase. Controlling the amount of EGR needed at any given moment requires advanced engine modeling. Cooled EGR has been employed on the USA market since 2002.

The EGR is a means to reduce NOx also for gasoline cars and was widely used in the 1980s. EGR is an integral part of the HCCI engine.

Non-thermal plasma (NTP) is a relatively recent but untried method to reduce NOx and particles. Also hydrocarbons (cold start) may be reduced. Plasma can be used together with NSRs to increase the reduction of NOx in the presence of hydrocarbons. Plasma can also be used together with LNA, and with SCR to improve cold start emissions. NTP can also be applied for regeneration of particulate traps. For vehicle applications it consists of altering a gas to desired behavior, by using a reactor (Hammer 2002; Rappe et al. 2004). No vehicle manufacturer has commercial plans involving plasma.

Selective Catalyst Reduction (SCR) is a method for reducing NO_x by means of a special catalyst. Ammonia is added to reduce NO_x to N_2. Urea (see "Technology" section) is carried on the vehicle and converted to ammonia in the exhaust stream. With SCR, there is no increased fuel consumption for reducing NOx. While relatively recent, mobile applications of SCR are considered in all markets. See "Technology" section for a discussion on the peripheral equipment and infrastructure needs for introducing SCR. SCR requires fuel with 50 ppm or less sulfur.

The SCR can, with a margin, attain Euro V emission requirements also after 1,000 h accelerated ageing of the catalyst (Searles et al. 2002). In Table 9 major pros and cons of a broad introduction of SCR and urea infrastructure are listed.

NOX storage catalyst (NSR). By controlling combustion, nitrates are stored (adsorbed) in the catalyst washcoat and later reduced to nitrogen during a short "rich" air/fuel mix period. Research is needed to better understand the chemical processes. The system is in production with the Toyota D-Cat for light diesel vehicles, using two parallel NOx wall-flow catalysts, in combination with EGR, post-engine gasoline injection and common-rail fuel injection. The system is sensitive to sulfur poisoning.

Lean NOx catalysis (LNA or LNT), sometimes called lean NOx traps, is interesting because reducing NOx under lean conditions is the main challenge to meet new Triad requirements. The concept is technically challenging, may imply a fuel penalty, and requires very low fuel sulfur levels. Research results still have to be proven under commercial conditions.

[18] Details below are in several cases also based on Dieselnet (http://www.dieselnet.com).

[19] http://www.psa-peugeot-citroen.com.

Table 9 Commercial advantages and disadvantages for SCR technology in response to Euro IV/V (own compilation)

Advantages	Disadvantages
Non-poisonous	Urea distribution infrastructure needed
Accessible (not excessively patented) technology	Cost for urea
No fuel penalty	On-board tank required
Low-sulfur diesel fuel not needed	Urea freezes at −11°C, evaporates at 30°C, its solids crystallize
Scalable for different engine sizes	Only stainless steel and some plastics are unaffected by urea
No EGR needed	
Reuse of engine engineering (Euro I–III) possible	

Nanotechnology, where materials are "tailored" on a molecular level, is seen as a research area with many new potential applications and is the subject of many recent funding programs. While catalysis has been called "the first nanotechnology", it is sometimes not included in research funding schemes as it is a "mature branch of a young tree". New results in nanotechnology may however play a substantial role also in environmental (vehicle) catalysis in the future.

Fuel

Fuel adaptations enhance or for most catalytic solutions also enable the function of a given technology. This can be done either by means of an additive, by reducing a noxious component such as sulfur or otherwise optimizing the characteristics of the fuel. An example of additive is cerium, added to the fuel on-board to enhance the regeneration of particle traps. Ultra-low sulfur (ULS) diesel fuel is required to be used with wall-flow diesel particulate filters (DPFs). In Sweden, the introduction of "City Diesel" with less than 10 ppm sulfur was completed in the 1990s, whereas Europe, Japan and USA introduced ULS diesel (<15 or <10 ppm) in 2005 and later. Europe is ahead in this 'race' whereas fuel in USA may vary both as regards sulfur content and cetane number (key to proper ignition). In growing regions such as China, old and new refinery resources are used side by side, yielding wide variations in fuel quality. Low- quality fuels effectively hamper the global introduction of advanced emission controls.

Introduction of liquid or gaseous alternative fuels is increasing. Especially in developing countries, with an ageing fleet and problems with diesel fuel sulfur etc., natural gas is an option. Each fuel, however, has its own realm of possibilities and challenges. Especially for methane (biogas or natural gas) there is a problem to reduce NOx emissions with exhaust aftertreatment. Methane vehicles need specially developed catalysts, because DOCs have a lifespan of approximately 1 year if used on a methane vehicle. Ethanol, biodiesel and synthetic biofuels such as DME (di-methyl-ether) are other options that may give lower local emissions and, depending on feedstock, reduced greenhouse gas emissions (Murphy 2002). Each fuel has its unique set of implications for emission control. Some biodiesel compositions may not be compatible with certain catalysts. A modern engine fueled with DME may achieve even Euro VI without exhaust aftertreatment. HCCI will be more fuel flexible, but in general, more advanced engines and exhaust aftertreatment technology require better fuels.

Other

A number of sectors of technology have a direct link to development of emission control systems for diesel engines. Measurement of lower emission levels, simulation of components and systems and production and distribution of the SCR reductant urea are some examples.

Measurement technology. What is regulated must be measured. Separate regulations regarding emission measurement means that vehicles are specified differently in EU, USA and Japan (see "Market" section). New methods to measure vehicle emissions have developed strongly in the past decade. The commercial and scientific interest to develop new measurement technology is large (Lehmann and Mohr 2003).

Simulation Technologies for simulation of pressure, temperature, gas exchange and chemical reaction processes, have developed very fast during the past decade and can today reduce development time as well as reduce cost for prototypes and testing considerably. The so-called CFD, *Computational Fluid Dynamics*, is a collective term for different methods and softwares that makes it possible to test a design of a component up to a whole engine in a computer instead of or as a complement to engine bench testing.

Production and distribution of urea (AdBlue). SCR is chosen by the bulk of the heavy-duty vehicle producers to comply with Euro IV and Euro V emission requirement levels in Europe. SCR requires that urea is carried in a separate tank in each vehicle, and thus urea must be distributed in large quantities throughout Europe. For Euro IV emission levels the consumption of urea is estimated to 5–6% of total fuel consumption, whereas for Euro V urea consumption may reach 6–8% of total fuel consumption (ACEA 2003).

Increasing demand for urea is thus expected as Euro IV and V technology vehicles are phased in, and should reach several thousand cubic metres in the next few years. The industry has established a standard urea quality called AdBlue, which is marketed under different names.

Actors

The technologies mentioned in the previous section are managed by the different actors in the system. Typically there is a strong link between a certain technology and one or more actors that defend and manage its development and proliferation. An overview of the actors in the system is given in Fig. 3.

In the following section, the system in which they form a part is discussed. Each actor has its own driver for involvement.

Vehicle and engine manufacturers (OEM) are the main actors in the system or "spiders in the web". Each OEM manages a technological system in its own right, with a mix of in-house and delegated R&D and production. A supply system, normally labeled "chain" including other companies and institutions supply knowledge and hardware for product development and production. For the large manufacturers, assembly is often done worldwide in reflection of demand and regulation in the respective nations that favor assembly in the country of use, so called "transplants". The vehicle manufacturers manage the marketing and sales of the products to these different markets. This means both aligning consumer requirements and profiles with respect to a given market, and complying with regulation for each market. Following the manufacturing trends or perhaps even leading them, large OEMs are increasingly sourcing components on a global basis to reduce cost.

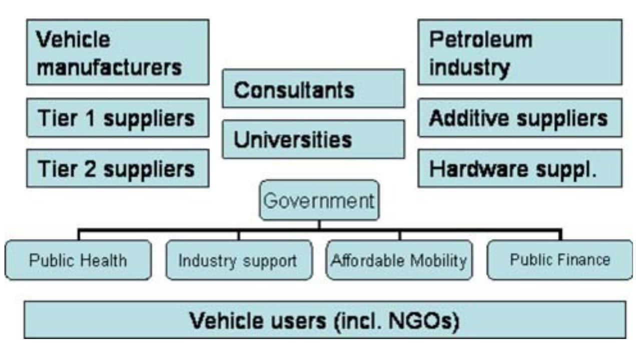

Fig. 3 Actors in the technological system for diesel emission reduction control

There is a handful of OEMs on each continent, and even fewer for heavy-duty vehicles. In Africa, the automotive industry is concentrated to the republic of South Africa. During recent decades, the market has consolidated considerably. New companies in the China and India markets grow fast but consolidation is likely to occur also there. In general, the national brand is preferred if there is one—Volvo and Scania[20] represent more than 90% of heavy truck sales in Sweden, while Mercedes enjoys 29% in Germany[21]—and the rest of the world is divided by regional customer preferences. Given the many cross-market issues, these increasingly are part of M&A and strategic collaboration in reaction to imminent issues. Examples thereof, again from a Swedish perspective, are Volvo's recent procurement of Nissan Diesel, partly for Volvo to gain access to hybrid truck technology, and Scanias strategic alliance with USA brand Cummins in fuel injection technology and engine development.

For a vehicle manufacturer, complying with emissions is only one of a large number of issues that needs to be managed. However, it has repeatedly been stated that in developing a new engine, emission regulation compliance is one of the biggest drivers for R&D and related cost. This is debated by Chen et al. (2004) who argue that only a smaller fraction of development cost can historically be related to stricter emission control requirements for the light-duty vehicle industry. Chen shows that for USA conditions, emission control development cost does not exceed vehicle consumer price variations year-on-year. Including the coming norms for low CO_2 emissions, vehicle manufacturers note a growing imbalance between concerns of citizens and consumer preferences: "*the citizen demands what the customer refuses*".[22]

Suppliers. To distinguish the different roles in the industry, suppliers are usually divided into two or more tiers. *Tier 1* suppliers, those that deliver to and cooperate directly with the OEMs, may also be divided into two subcategories. In the major league we have the multi-technology firms, of which several are spinoffs from GM, Ford and Toyota etc., such as Visteon, Delco and Denso. These are sometimes called "global mega-suppliers" or *Tier 0.5* because of their proximity to the vehicle manufacturers. Despite large volumes, these companies have had severe problems with profitability during the past years. There are also smaller (yet very large), more specialized

[20] Scania has globally about one-third of the production capacity of Volvo Truck, but has traditionally had higher profitability. Volvo has coordinated the engine manufacturing of Volvo, Renault VI and Mack under Volvo Powertrain, now the world's largest manufacturer of heavy truck engines.

[21] Euromonitor International (2005).

[22] Press statement 27 March 2005 by CCFA, the French Committee of Automobile Manufacturers.

companies with fewer product lines, such as catalyst or tire manufacturers. A considerable amount of consolidation in this segment was effected in the 1990s (Humphrey and Memedovic 2003). Many of these companies also offer consultancy services, including a popular scheme in the industry called *resident engineers*. A development engineer works, located at the OEM, with applications that his company offers to the client. This has dual advantages: the supplier gets first-hand info on what the OEM needs, and the OEM gets cheap labor. In some cases, the OEM would require all suppliers to offer resident engineers as part of an agreement.

Regarding the catalyst, the following types of supplier companies are involved:

- Catalyst manufacturers (washcoat and noble metals specification and application)
- Manufacturers, Exhaust system and canning for light-duty vehicles
- Manufacturers, Exhaust system and canning for heavy-duty vehicles
- Substrate manufacturers
- Washcoat[23] manufacturers

Around them is a network of subsuppliers of raw materials, e.g. supplying sheet metal. There are few examples of vertical integration in the sector—only one Finnish company, Ecocat, offer in-house substrate manufacturing, washcoat application as well as canning. Automotive catalysis has thus not gone through the vertical integration found elsewhere in the supply industry.

The catalyst business has a special role for various reasons. The combination of a high rate of innovation, high cost, evolving regulatory demands, the degree of technical integration and the strong link between national regulation and technology choice means that the producers have intensive cooperation with the vehicle manufacturers when compared to other component suppliers. Catalyst manufacturers can be considered an oligopoly with three companies, BASF (formerly Engelhard), Johnson Matthey and Umicore (formerly Degussa) producing the absolute majority of automotive catalysts. Automotive or environmental catalysis is only one of many business areas of these companies. Their market dominance is only reduced in Japan, where the stagnating *keiretsu* system still leaves room for nationals. The same actors now compete for market share in the growing diesel emission control technology business. The catalyst manufacturers offer products both for OEMs and the aftermarket. The rest of the market—two-wheelers and machines, mining applications, aftermarket and others—is split between numerous but consolidating smaller suppliers.

Swedish companies Emissionsteknik AB, a subsidiary of UK/USA Johnson Matthey, and Swenox, owned by English industrial concern Hexadex, both located in Göteborg, have a strong local presence regarding diesel emission aftertreatment, including test labs. The former focuses on the catalyst (monolith) while the latter on exhaust systems including catalyst canning. Both have contracts with at least one of the Swedish heavy vehicle manufacturers regarding emission control components for Euro IV and V.

Engine control system and fuel injection systems are cost-intensive areas where both the assemblers and suppliers develop application competence. Bosch, the global mechatronic company that inter alia specializes in fuel injection and engine control, has a strong position with Denso and others as competitors. In Sweden, Mecel was founded in Sweden and is now owned by Delphi, based in USA. The Swedish company NIRA, working with engine control, was taken over by Actia (France) in 2006.

Aimed at the aftermarket, stt emtec AB and Dinex Svenska AB (a subsidiary of Danish Dinex, formerly Swedish owned Emission Control Systems AB) offer retrofit kits that reduce the emissions from e.g. an Euro III engine to Euro IV levels. Some Swedish owned companies successfully engage in diesel emission control R&D and patents regarding different areas such as EGR, catalysis, control systems and canning. None have a global outreach.

Universities. In a fast-moving commercial world, government and/or industry sponsored projects that are carried out by doctorate students in a 2–4 year timeframe is a unique way to prepare a young professional for an evolutionary technological regime. Swedish universities are strong regarding catalysis, reinforced by the Catalyst Competence Centre and other initiatives.

Consultants and Institutes. A number of large consultancy firms; FEV, AVL, Ricardo, etc. are present globally offering engine and exhaust development services to vehicle manufacturers and suppliers. Some of them also do public projects, e.g. verifying measurement methods and comparing test equipment. The larger tier 1 suppliers also often double as consultants. In short there are two main types of services offered. Consultant companies may just sell consultant time to the supplier or OEM, or develop proprietary technology or methods in a more articulated fashion. All these actors offer their services to Swedish OEMs. In Japan, the Center for Advanced Engine Systems Research (CRADE, opened 2003) is open for use by government as well as the industry to measure ultra-low emissions from heavy vehicles and engines. The lab has not been used by private truck or engine companies as was planned because cost for testing is relatively high, and

[23] The washcoat is a chemical that complements the noble metals in the catalyst by e.g. storing oxygen and enhancing the catalytic reaction.

R&D facilities are developed with the carmakers. In USA, the Southwest Research Institute (SwRI) has a long tradition and much the same role, but is less used by industry. In Europe, the reference emissions lab of the EU Joint Research Center in Ispra can be used for verification.

The fuel industry has answered to regional initiatives and regulation by introducing cleaner fuels. Different qualities (mainly sulfur content) of diesel are thus supplied in different countries. Especially in Germany, biodiesel is increasing as an alternative to fossil fuel, raising questions on its compatibility with advanced engines and catalysts. Alternative fuels are relatively popular in Sweden, but focused on urban buses.

The additive industry plays an important role in developing fuels and emission reduction strategies. Additives like urea and ceria are critical complements to the technologies introduced commercially. For commercial vehicle applications, the demand for urea distribution is geographically similar to the demand for diesel fuel, and will be distributed in large volumes because urea requirements will be approx 5% of diesel volumes for SCR vehicles. As demand increases, this would suggest increased cooperation between suppliers of fuel and additives.

Hardware/infrastructure suppliers Fueling equipment, distribution vehicles and on-board storage for urea are new areas that are crucial for development of an industry standard that is accepted—and used—by the number of customers required for commercial introduction. A number of actors are preparing for strong growth in this area.

Government. Governments must balance different responsibilities—e.g. improving public health, supporting national industry, providing affordable mobility for goods and individuals as well as maintaining public finance. Maximum permissible emission limits from vehicles are set by national governments as presented in the "Market" section. National regulation for developed countries is with few exceptions preceded by international dialogue, e.g. in the ECE flanked by the international work in the EU, ECE/GRPE and numerous bilateral and multilateral agreements. In the case of USA, the size of the country implies that market regulation may be done on state level. The state of California has for 50 years been at the vanguard of research on smog formation and ensuing requirements. In later years it has served as a proving ground for new technological regimes such as battery and hydrogen driven vehicles.

Other actors. Different types of actors have formed clusters or competence centers. The Scandinavian vehicle cluster competes with others, such as West Midlands in the UK or Baden Wurtemberg in Germany. On a smaller scale, the Swedish *Catalysis Competence Centre*, initiated in 1995, is one example (discussed in the following section). S-SENCE, the C*ompetence Centre for bio- and chemical sensor science and technology* at the University of Linköping includes several projects in relation to technology development for coming emission requirements, e.g. sensors that detect ammonium slip, an important application for SCR. Several research projects concerning vehicle emissions and emission reduction are ongoing in EU under Framework Program 6, now shifting to Framework Program 7. The *Swedish Catalyst Society* is a network for companies and individuals involved in catalysis.

In Table 10 we see some examples of actors in the different categories as described earlier. Please note that the list is not exhaustive.

Technological system co-evolution

So far, we have seen the elements of what could be described as a Technological System (TS) for diesel emission reduction, i.e. the *market* including vehicle buyers and regulators/regulations, the different *technologies* and the different *actors* on the producer side that form a system producing and using emission control technology related to diesel trucks and passenger cars.

System overview

The basic assumption in economic literature is that regulators set the market; the opportunity set for the producers is defined by regulations. In our case, then emissions over a defined drivecycle and measurement method/equipment established for each market would provide actors with a clear goal for emission control development. Ng (2006) has shown that standards are set by dialogue between public and private actors, and that interest groups and companies with an interest in the introduction of new technology do have an input in direct and indirect ways to progress regulation and public demand. Other actors may have an interest in postponing stringent norms, and thus would lobby for e.g. further studies prior to regulation. In other words, non-market activities are part of the process. However, as a "regulatory round" settles and the new regulatory limit values are set, they become the "floor" and development is focused on minimizing cost and fuel consumption within the given constraints.

The array of technologies, suppliers and markets constitute a competitive arena, with multiple options for involved actors both up- and downstream of the respective in-house activities. The boundaries of the entire system are set by the demand for diesel trucks, available commercial emission abatement technologies and the present and coming emission regulation. Technological development depends on individual and cooperative action by the members of the system. The system and the dynamics of

Table 10 Actors in the technological system for diesel vehicle emission control

Actor type	Sweden (examples)	International (examples)
Vehicle and engine manufacturers	Volvo AB, Scania AB, Volvo Cars, Saab Automobile	Toyota, Daimler-Chrysler, Cummins, Renault VI, GM, Nissan Diesel, TYanmar, VW, PSA, Fiat m fl
Universities	Chalmers University of Technology, Royal Institute of Technology, Luleå University, Lund University of Technology, Linköping University of Technology	Corresponding
Consultants and R&D Laboratories	Semcon, Caran, AVL MTC, BlueLabs, Volvo Technology, Vehiculum, stt emtec, Ångpanneföreningen, m fl	Lotus, Ricardo, FEV, AVL, IDIADA (Spanien), Westport (Canada), MIRA (Storbritannien) m fl
Competence centers and "clusters"	KCK (Kompetenscentrum Katalys, CTH)	Corresponding projects in Europe and elsewhere—mostly national
	S-SENCE, Kompetenscentrum för bio- och kemisk sensorvetenskap och teknologi (LiU), Chemcluster Karlskoga, national initiative "Gröna Bilen EGT-Avgasefterbehandling" research group	
Interest groups	Swedish Catalysis Association, Swedish Automotive Suppliers Association	AECC, MECA (catalysis), CLEPA (suppliers), Engine Manuf. Assoc., ACEA (engine/vehicle manuf)
Research institutes	*Swedish state supported research institutes are reorganizing*	CSIC (Spain), JRC Ispra (EU "reference" lab), CRADE (Japan), SwRI and federal labs (USA)
Suppliers	Vehicle manufacturers, Mecel, Actia Sweden (former NIRA), Varivent Innovations AB/Haldex	Bosch, Magneti Marelli, Siemens, Denso, Delphi, Visteon
	Albemarle Catalyst, Umicore, Akzo Nobel Catalyst, Perstorp AB	Johnson Matthey, BASF, Umicore, Haldor Topsøe, Ecocat, Argillon
	Faurecia Exhaust Systems AB, Tenneco Automotive Sverige AB	Faurecia, Tenneco, HJS Fahrzeugtechnik, Eminox, Arvin Meritor
	SWENOX, Emission Technology Group, Lubrizol Engine Control Systems Europe AB, Haldex, stt emtec	Lubrizol, Clēaire, Clean Diesel Technologies, Arvin Meritor
	Sandvik Strip Steel, Nilcon AB (entrepreneur)	Corning, Emitec, Ecocat. Underlev: Kawasaki, Allegheny, VDM
		AMI Agrolinz Melamin Int.GmbH, Kemira, BASF, Fertiberia, Grande Paroisse, SKW, Stick stoffwerke Piesteritz GmbH, Yara International
	Identic	Univar (USA/EU), OMV (Austria), Total (France)
Government	National and local responsible authorities, generally implementing EU regulation + local Environmental Zones	EU DG Environment/Science/Entr, USEPA, MLIT (Japan)
Problem owners	National and local governments (including national governments acting through their respective agencies)	

one regulatory round are illustrated in Fig. 4. Regulation is proposed by the authorities, discussed with the industry and other actors that bears on the technology alternatives and fuel specifications in a participatory regulatory process. The resulting regulation has an impact on fuel quality and regulation, vehicle regulation, vehicle demand and the supply of components. A given set of regulations is a milestone in a continuous dialogue around the definition and setting of exhaust limits, drive cycles and testing equipment, and the development of technology to respond to the resulting requirements.

The industry involved in exhaust aftertreatment has matured during the past three to four decades. Decisions on technology now mutually influence a coordinated group of actors (see "Actors" section; Fig. 2) with long-term development ambitions and market presence. At the same time, both catalyst and non-catalyst technologies are commercialized, with different but overlapping advocators.

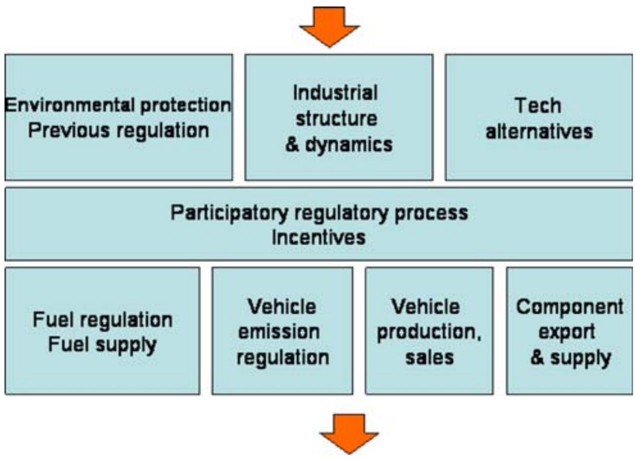

Fig. 4 Co-evolution in vehicle emission reduction

For the vehicle manufacturer, development of a new series truck is a complex undertaking; Simultaneous development in several areas is a hallmark. Generation changes of emission aftertreatment technology, engine development, vehicle technology upgrades and designing new fueling equipment may occur simultaneously in one new engine/vehicle model. Work is divided in areas or levels such as aftertreatment, entire engine and whole vehicle, where for each system level a network of involved agents or actors, both inside and outside of the engine/vehicle manufacturer itself, develop and commercialize new technologies.

For a supplier to develop an emission reduction technology to fit as part of a mass produced quality assured engine and/or vehicle system, competence in a number of areas is required. Examples are gas exchange processes, chemical reaction technology (catalytic reactions), control technology, metallurgy, driving patterns and test methods, serial production issues and ultimately market intelligence. Often the final customer (here the vehicle manufacturer) is involved in the development. R&D is carried out by selecting a number of candidate technologies, e.g. the different methods for exhaust aftertreatment as described in the "A complex setting" section. Then for each technology, a number of core areas are defined where more R&D can enhance the offer, e.g. architecture for control systems, material problems. From that structure, R&D is continued in-house or subcontracted. As R&D goes, material and other problems may be the same for a number of technologies which makes synergies possible. Where synergies are large, research is prioritized. Internally, collaborative or public projects bring the stakeholders together around each of the trajectories to test the viability of a technology.

The catalyst manufacturers engage in development not only by participating in joint development projects, but also through procurement rounds under competition. The nature of technical development in the automotive business, and especially so regarding emission control solutions, is that the different technical alternatives are monitored in-house as long as continued interest is shown by the competition, the scientific community or major customer segments. Another type of knowledge is what is actually offered by the competitors. All major actors keep updated on commercial technologies of any significance, because what is sold naturally is a reflection on what is currently demanded by the customer. It has been claimed that regarding automotive catalysis, advancements are often not patented, but that the producer of a new technology or design feature relies on the market advantage from the 3 months or so when a new feature would have a technical edge, before the competition would have identified and produced a similar design. It is not possible to leave a solution favored by the competition, because through market changes and also regulation and incentives, any given discrepancy could rise to decide what type of vehicle is sold for a given period. The time lag for catching up could in a few months time change the market. This means that in the automotive industry, the Cohen and Levinthal (1989) findings hold true; companies do research with dual objectives—to develop own solutions and to be able to absorb knowledge and (incomplete) information found in the public sphere.

More general technological updates within the system are managed in different ways. Knowledge in the field can be divided into general knowledge, research results, common industry knowledge and individual actor (commercial entity or institution) competence. A considerable quantity of new knowledge is generated in the academic sphere, a lot of which is published in peer reviewed journals. Knowledge is shared at events such as international SAE conferences, the yearly USA Diesel Engine Emission Reduction Conference, TOPTEC seminars in Europe, specialized on diesel emission control, organized by local branches of SAE and carried out in Sweden and elsewhere and the EURO V conference in Milan in November 2003 organized by the European Commission through its Joint Research Center, a one-off meeting to prepare for setting emission standards (including diesel) for light-duty vehicles. Here, scientific studies reviewing different types of measurement technology, emission control technologies and the need for regulation and inspection & maintenance (I&M, yearly vehicle technical inspection schemes) were presented and debated by the different stakeholders including representatives from the different Commission Directorates Environment and Enterprise.

Case examples

The following cases illustrate the development process:

The Argillion case. An example of industrial collaboration is a German-based joint research initiative on SCR in the 1990s. The original consortium included Daimler-Chrysler, IVECO, MAN and Siemens, where the latter had developed anj SCR system, SINOx, for stationary engines, and looked to move towards mobile applications. The consortium initiated work in 1992 with set targets for emission reduction over the older stationary (non-transient) certification cycle, subsequently shifted to the new ESC and ETC European cycles. The results were used by the German government to influence Euro IV and Euro V setting of standards (Ng 2006). The consortium and its commercial spinoff, Argillon, have performed tours in Europe, USA and Japan to demonstrate the viability of the SCR technology, and Argillon now supplies a European engine manufacturer. Argillon technology is special in that it, as opposed to other automotive catalysts, does not include precious (platinum group metals, PGM) metals.

KCK case. From a Swedish perspective, knowledge building as well as R&D in diesel emission control are to a large extent carried out in relation to or at the vehicle manufacturers. Pre-competitive catalyst-based research on emission control, such as low temperature catalysis and studies of NOx storage for different types of catalyst and washcoat composition, is dominated by the Competence Centre for Catalysis (KCK), administered by Chalmers University of Technology and sponsored by the Swedish Energy Agency. It consists of six members: AB Volvo, Volvo Car Corporation, Scania CV AB, GM Powertrain Sweden AB, Haldor Topsoe A/S, Perstorp Specialty Chemicals AB and the Swedish Space Agency.[24] Member departments at Chalmers are Chemical Physics, Applied Surface Chemistry and Chemical Reaction Engineering. Former members include Johnson Matthey through their Swedish subsidiary Emissionsteknik AB and the engine laboratory Motortestcenter. Competence developed at the university center serves several purposes, in addition to the typical role of adding knowledge through publication in peer reviewed journals: Forging individuals with relevant competence for the development of the technological system, creation of new strategic knowledge for the center associates and as a problem solver for individual members and external clients. The center has received good ratings for research quality (Baras et al. 2003). The role of KCK is by no means exclusive—research projects on automotive catalysis are ongoing at other Swedish universities. The center's contribution to national knowledge building would mostly be through publications in scientific papers, while only KCK interviewees have indicated using the services of the center.

Gröna Bilen case. A national, lateral joint research program with special focus on environmental automotive issues, Gröna Bilen, has been sponsored by the Swedish state since 2000. Public and private research tasks are carried out, mostly including OEMs. Two subprograms deal with emissions: R&D in emission control (EGT, five projects) and particle emissions measurement (EMIR, two projects). In a review (Persson et al. 2003) the program is described as highly relevant, but not to have spurred innovation and with minimal communication between the EGT projects. As an example, one of the projects has resulted in development of a patented EGR valve, now marketed by Swedish company Haldex. The EMIR project value would relate to the possibility of using results to foster development goals, but since the health risks are not mapped, the reviewers judge it as difficult to be more exact in the interpretation of EMIR results for technical development.

Auto-Oil case. Between 1997 and 2000, the European Auto-Oil II (AOPII) program worked for finding a consensus between industry and the regulators on heavy-duty vehicle regulation for the Euro IV and V tiers. AOPII followed AOPI (1992–1996) with essentially the same objective—"to identify environmental objectives for air quality; forecast future emissions and air quality; establish emission reduction targets (or appropriate functional relationships); collect input data on costs and effects of potential measures to reduce emissions; and carry out a cost/effectiveness assessment as a basis for a future air quality strategy". Air quality objectives in AOPII were derived mainly from recent directives which set limit or target values for air quality to be achieved in 2005 and 2010. Air quality modeling in various European cities indicated which targets to address—PM and NOx were identified as issues. The balance between regulations and incentives was discussed, and general (OEM) and local (retrofit) solutions were seen as efficient complements. AOPII involved a considerably larger stakeholder base including vehicle manufacturers and NGOs.

Environmental Zones case. A special chapter is the different types of incentives or regulation for higher requirements found in retrofit funding schemes and the so-called Environmental Zones (EZ) described in "Market" section. Since here, fleet owners have a choice of retrofitting emission control equipment to older vehicles or buying newer OEM technology, the EZ from an innovation perspective work as a niche market and serve the dual purpose of proving ground and protomarket for new emission control technology. As regards sales, they constitute an incentive for fleet owners to invest in new OEM vehicles ahead of national regulations, thereby enabling gradual phasing in of enabling services such as urea/adblue infrastructure and low sulfur fuels. Together with retrofit funding schemes found in USA, it constitutes the prime market for state-of-the-art retrofit equipment offered by the

[24] http://www.kck.chalmers.se. In addition to the above, KCK is also involved in fuel cell research.

largely separate aftermarket emission control industry. As a result, state-of-the-art technology finds a market niche where technology can be verified for common regulation, and different emission control components can develop until it has commercial and technical strength to survive outside the niche. USEPA has introduced a related scheme or program called Environmental Technology Verification with the objective to provide an independent and credible assessment of the performance of innovative solutions that mitigates threats to health and the environment. Technology such as retrofit emission control systems are tested (USEPA 2002).

"No Diesel without Filter". In Germany, a campaign has created publicity for PM emissions and the efficiency of DPFs since 2003. The publicly advertised campaign contributed to changes; while in 2005 not all diesel passenger cars manufactured in Europe included a particulate filter, this is now the norm.

USA regulatory violation. In the 1990s, the seven leading manufacturers in the USA heavy-duty diesel engine market were charged by the EPA for violating the Clean Air Act by installing so-called "defeat devices", evading emission control. The method used was so-called dual mapping, with one emission level maintained during certification test cycle conditions and another, optimizing for fuel economy and power, under regular highway (off-cycle) conditions. To avoid litigation, the manufacturers settled with USEPA for more than 1 billion USD. In the settlement civil penalties and environmental projects were included, but the majority of the cost was dedicated to agreed R&D, engine rebuild, recalls and new emission testing (Ng 2006). Regarding similar practice in Europe, Ng also referred to material from German UBA from a test in 2002 where Euro II engines were found to have considerably higher off-cycle NOx emissions than the corresponding Euro I engine. In Europe, these findings brought no legal aftermath, but intensified CEC development of a transient cycle for certification and not-to-exceed emission levels regardless of drive cycle, as mentioned in "Market" section.

European cooperation. Some European governments and institutions also maintain a dialogue on vehicle in-use compliance results and special tests through the aftermath of the EU-project ARTEMIS and the network DACH-NL-S, involving Germany, Austria, Switzerland, Netherlands and Sweden.

New regulation

The more long-term regulatory framework for new emission regulation thus allows for research and strategic development, not only involving commercial actors but also academic institutions and inventors. The USA Clean Air Act requires 4 years of lead time for the manufacturers, European legislation involves stakeholders already in the EC Directive amendment drafts, and the Japanese system holds an Experts Committee on Motor Vehicle Emissions that reviews technical progress in the industry by hearings and investigations to form proposals mutually acceptable to government and industry.

At the end of 2004 the European Commission published the directive for Euro IV emission limits for heavy-duty vehicles in Europe, including a transient cycle. This has since fostered industrial development in the area. At a meeting September 23, 2004 in Hannover, where 80% of the European truck producer market—DAF, Iveco, Mercedes-Benz, Renault VI and Volvo Trucks were present, the assembly announced that urea will be used to comply with Euro V (2009) regulation, and in many cases also for Euro IV (for new models since September 2006) and similar regulation in USA and Japan.[25] The vehicle producers also declared their intention to support the development of fueling stations. To function, this option requires sulfur-free diesel fuel, SCR including an on-board system in each vehicle for storing and dispensing urea, DPF, in combination with urea production and distribution in the European area. Each manufacturer must also ensure that the particulate filter/trap, if fitted, is continuously freed from soot. The base engine may, given that the SCR reduces NOx emissions efficiently, have higher engine-out emissions than an engine designed to comply without separate NOx aftertreatment. To comply with Euro IV, a Euro I base engine with SCR may be sufficient. Scania and Man have—separately—declared that they will not use SCR for Euro IV for some models, but that it may be required for coming regulatory tiers.

Since October 2006, Euro IV emission compliance is required for new vehicles sold. Also Euro V vehicles are offered by some manufacturers. For most of European producers, this means SCR technology requiring urea. In realizing the introduction, disadvantages also become more visible. In the period up to the recent regulatory change, according to some interviewees, OEMs favored sales of the previous technology to marketing of the new.

Scania, and also MAN, have taken the opportunity to explore the market's interest in avoiding dependence on filling urea. As an example, Scania has managed to pass regulatory limits for Euro IV without the use a particle filter. A new vehicle series, delivered since September 2004 has a 12 l, 420 hp engine that is compliant with Euro IV. Scania have developed a proprietary engine control

[25] In a press statement from the 3rd "Global Commercial Vehicle Industry Meeting" held in Chicago in November 2005, Japanese, European and USA engine and vehicle manufacturers state that SCR is a promising technology, with 1,300 urea fueling stations in Japan and 800 in Europe established as inroads to functional infrastructure.

system, high-pressure fuel injection, turbocompound[26] and EGR. An oxidation catalyst is fitted. Cooled EGR and high-pressure fuel injection is also used on some Euro V models.[27] By developing proprietary high-pressure fuel injection and EGR, they offer an alternative to SCR for most Euro IV models. SCR is however used for the larger engine models. It is not evident that the sole or original reason for developing an in-house technology was to evade SCR technology—the cost to buy complete high-pressure 'common rail' fuel injection and engine control systems may be as high or higher than the cost for internal development. The fact that MAN was a part of the SINOx/Argillon consortium that developed an SCR solution, but now produces Euro IV compliant engines based on EGR is significant in confirming manufacturers' command of the alternative trajectories. MAN also advocates the advantages of EGR for Euro IV in a specially designed web page.[28]

The infrastructure required to distribute the reductant urea is a new element compared to established technologies. As SCR equipped vehicles now are sold, it would be in the interest of the vehicle manufacturers to see to the establishment of a working infrastructure for distribution of urea. However, few initiatives to distribute urea have been initiated outside the ACEA "FindAdBlue.com" campaign, which is essentially web based. While it can be argued that the responsibility lies with the vehicle manufacturers, there has been no orchestrated effort from the Swedish petroleum companies and their distribution chains. The development of urea/Adblue infrastructure has thus not been as fast as expected, especially not in Sweden where Scania, who does not use urea for most of their Euro IV models, has a market share of approx. 45% for heavy trucks.[29] To date, most urea in Sweden is dispensed at depots of vehicle fleet operators and at trucking companies' co-op fueling stations. Standards for the dispensing nozzle have been developed but not accepted by all actors.

From a regulatory perspective, the system will not be complete as regards enforcement because the use of urea is not monitored nor enforced—OBD will not be regulated and in place for heavy-duty vehicles in Europe until 2009, so vehicles sold from now until then will elude the coercive measures included in OBD. An SCR Euro IV or Euro V vehicle driven without urea may have NOx emissions corresponding to Euro II or even Euro I and thus offset the effect of regulation and the control technology as intended. This is the reason that SCR was not accepted by USEPA in the earlier rounds of discussion (around 2005), as the responsibility with emissions legally rests with the manufacturer. If the vehicle owner/user would not e.g. fill urea as needed for the on-board system to function, the responsibility could rest with the manufacturer rather than with the owner/driver. On March 27, 2007, USEPA presented a letter to the manufacturers on its intention to regulate in the light of a growing interest on SCR.[30] USEPA is highly concerned also with ammonium slip, and it is not likely that SCR will be introduced in USA without an OBD system that would automatically coerce e.g. an empty urea tank.

When 'coercive' OBD systems are in place, future urea sales are likely to become more predictable, suggesting the addition of a new element to the web of relations and compatibilities: timing. To become functional, the principal elements of the system: low-sulfur diesel fuel, SCR or SCR/DPF vehicles, and AdBlue must be made present on each national market more or less simultaneously. This requires concerted and timely actions by the main stakeholders. For SCR to become dominant or even established, it can be argued the following must be in place: a minimum number of SCR equipped vehicles, a clear indication of its advent on the roads—with vehicle technology including OBD coercing SCR dysfunctionality, and distribution infrastructure for urea. This is not yet the case in Europe.

On another note, introduction of DME, a diesel fuel with characteristics resembling LPG, may be nearing. In China, the production of vehicle fuel is a value-add in coal producing regions and promoted locally. In the Triad, DME production would at least initially use natural gas as a feedstock. Since the shift to DME as vehicle fuel would require new fuels infrastructure, new engines and likely new regulation, at least a decade will pass before DME reaches a larger market.

Discussion and concluding analysis

What, then, characterizes the development of diesel emission control systems?

The technological system described can be contained in the broad (fossil) diesel engine-driven paradigm. In the short and medium term, solutions that would not tie in to diesel fuel infrastructure and the diesel vehicle paradigm are likely to meet difficulty in terms of excessive cost, lack of customer acceptance and demand and strong counteractive market forces. The technological system that embodies development and production of diesel engines and emissions aftertreatment for the dominant markets was

[26] A secondary turbine after the turbo on the exhaust side that is linked by a mechanical transmission to the engine driveshaft, providing in the region of 5–6% extra torque and power.

[27] Walsh Car Lines, April 2004 and Scania press statement, Sept 2006.

[28] http://www.euro4.co.uk.

[29] Scania Interim Financial Report, 16 Oct 2006.

[30] http://www.epa.gov/otaq/cert/dearmfr/cisd0707.pdf

outlined in the previous section. The technological system here is interpreted as industrial cooperation, engineering topics, culture of technology and different types of institutional networks dealing with the diesel engine and emission aftertreatment. We argue that the general view on how diesel emission reduction is developing is likely to be guided by accepted vehicle demonstrations and real engine tests—relating to knowledge building "in the context of application" as discussed by Gibbons et al. (1994). Hughes (1992) describes large-scale technological system development as involving 'transdisciplinary committees, summer study groups, mission-oriented laboratories, government agencies, private corporations, and systems engineering organizations'. If we see the diesel emission technological system as slightly more heterogenouos, and replace the 'summer study groups' seen in Hughes' examples with global, regional and national conferences of both general and specific characters (such as catalysis and particulate matter measurement), indeed 'our' system shares characteristics with the other.

The actors in the technological system (regulators, engine emission control industry and the vehicle manufacturers/assemblers) all form part of a very interactive, innovative and agile market, with links and ties both on an academic, corporate and personal level. The ability of an actor to understand and react to the development elsewhere in the system would be dependent on its absorptive capacity (Cohen and Levinthal 1989), giving reasons to each actor to keep abreast of development by including in-house or funded research in its activities. Knowledge accumulates within and between each of the actors as technical and market news travels across the system—with implications on regulatory changes, acceptance and user preferences. An interdependent, knowledge-rich system evolves, moving in response to new scientific findings, commercial breakthroughs and regulatory development. In a world of ever-incomplete information, OEMs as well as regulators must base their decisions—relating regulatory emission levels to technology or vice versa—on scientific results, laboratory tests and demonstrations.

It is difficult, and perhaps not crucial, to define the optimal level for describing a technological system in this context. Each manufacturer together with its suppliers can be regarded as a managed technological system in its own right that produces compliant vehicles and at the same time follows non-market strategies. A "company-consortium" venture like Argillion is another level, both involving interdisciplinary research, contribution to regulatory fact-finding by public demonstrations as well as production of commercial technology. The different "sub-systems"—or trajectories, to the extent that work is translated to discernible commercial opportunities—engine development (engine-out emission reduction) versus development of catalytic solutions (tailpipe emission reduction) differ in character. The engine represents the core quality and function, usually managed to a higher degree by in-house competence with the engine manufacturer, and produced in-house, while catalytic emission aftertreatment is more of a procured, enabling function. While there are architectural aspects of aftertreatment systems, the development must be seamless between engine and component manufacturer, given required coordination regarding light-off temperature, feedback loop control systems, packaging and other issues. The complexity of each component and its interfaces renders systemic aesthetics to all aspects of development.

Moving inside the paradigm, a combination of several dynamic factors rules the development. To function, diesel vehicles must stay inside a confined space constrained with requirements on cost, emissions, fuel consumption, noise, reliability etc. The truck transport business has small margins and any cost increases has an impact on the demand—including tactical fleet renewal in the face of regulatory change. Technical tall orders for the OEM may have a more general impact on the business logic of land transport.

The market for heavy diesel trucks and buses is volatile, but is in the range of millions of trucks per year. The largest markets are North America, Europe and Japan, while growth is expected to be larger in the rest of Asia and Latin America. The market is driven by the demand for road transport, which hitherto has been increasing. Also demand for diesel-driven passenger cars and other light-duty vehicles is increasing due to the diesel engine's higher energy efficiency than gasoline (Otto) cars, yielding lower fuel cost as well as lower CO_2 emissions. Efficiency gains are however offset as to environmental impact by longer distances traveled and higher road cargo volumes. Emission requirements are reasonably uniform in the dominant markets of USA, EU and Japan, except that the 2007–2008 NOx emission requirements for diesel passenger cars in Europe are more lax than in USA and Japan for the period. Requirements will be added to limit CO_2 emissions.

This concerns only new vehicles. A number of incentive schemes for heavy-duty trucks and buses, such as environmental zones, road tolls (e.g. MAUT in Germany) and subsidies for retrofit filters give the choice of fleet renewal or retrofit. A separate producer market is dedicated to the demand for retrofit catalyst traps. Tighter emission standards, and ensuing higher cost, may also direct the market towards cleaner alternative fuels such as natural gas or biofuels. Such change would foster its own set of issues like fuel certification, vehicle safety and the business logic and logistics of fuel production and distribution.

Preferred technologies differ between light and heavy-duty vehicles, since the heavy-duty segment is commercial, with an annual mileage per truck of around 10 times the average passenger car. While fuel consumption, equipment and service cost are monitored closely by the commercial fleet owner, such costs constitute a minor item in the books for the passenger car owner compared to depreciation. Solutions may therefore diverge between light- and heavy-duty diesels.

The vehicle producer industry is mature in Europe, USA and Japan and OEMs are consolidating. In the growing markets of China and India, some room for new entrants may be found. The catalyst manufacturer oligopoly is poised to maintain its grip as more production is initiated in the new markets, whose standards are based on regulatory development in the dominant Triad, but shares market space with new entrants such as Argillon. Competence has been transferred from Europe and USA for the development of new vehicles and engines in e.g. China. The regulatory dominance, the high cost of components' raw material, complex production technology and the fast changes from innovation would suggest that a considerable share of R&D on core emission control components and the manufacturing of the finished catalyst monolith and feedback engine control systems will also be carried out within the Triad economies in the foreseeable future.[31] Emission control system component production may however be located in countries near the Triad regions, e.g. Central and Eastern Europe, Mexico and perhaps Taiwan, as suggested by Humphrey and Memedovic (2003). In time, growing markets such as China, India and Brazil will be the target for catalyst and exhaust system manufacturing, co-locating with assembly plants in the same fashion as for other components.

The variety and selection process is in many cases conditioned by the protomarket processes before it is available on the market. Regarding emission control systems, only those systems that have passed legal certification—a "preselection" hurdle—may be offered commercially. The immediate demand for emission control comes from regulation meaning that the market is defined by active negotiation between involved parties rather than public demand in a more classic sense. However, the customer may choose a cleaner vehicle along the same regulatory roadmap or choose alternative fuels or other means of transport. Regional or local requirement niches contain entrepreneurial retrofit equipment manufacturers which may be a decade ahead of the bulk of production.

The overall engine technology to respond to the new requirements is highly modular in character. By involving exhaust aftertreatment, development work done for earlier engine generations can be salvaged. Conversely, an engine with low engine-out emissions requires less or no exhaust aftertreatment. In this respect, the engine development and exhaust aftertreatment are complementary, apparently with the exception of reduction of small particle emissions, where the DPF is more efficient. It is however likely that the requirements yet to be defined (Euro VI, US14 and Japan's long-term requirements) will imply exploration of the innovative potential of both trajectories.

Can then SCR be considered to be a dominant trajectory as a solution choice on several markets? In Utterback's model (1994) several varieties are tested before the system trajectory is stable, and one design[32] has become dominant. Only the first generation of emission control technology is seen on the market in response to Euro IV. SCR is advertised as the main solution, but yet to be proven under commercial conditions over time. On other markets it is still being considered by the regulators. This is further enhanced as one European manufacturer involved in collaborative development of SCR technology has chosen to diverge by also offering EGR technology for Euro IV.

What role can Swedish actors play in the evolving system? It may just as well be asked how regional actors—and Sweden with its 9 million inhabitants is the size of a region in a European context, including two major truck manufacturers—can enhance the competitiveness in an evolving technological system for diesel emission reduction. It has repeatedly been shown (Bauner 2007b; Bauner and Laestadius 2003) that defensive or even illicit conduct in the face of dominant technological change is seldom a route to growth for neither governments nor corporations. Conversely, there are several success stories of first-mover nations and companies (Ng 2006). Regarding spatial distribution, research findings are divided regarding the importance and potential regarding *sticky places* in the increasing *slippery space* of vehicle R&D and production. Studies of automotive industry clusters in Europe show that automotive industrial clusters persist[33] even through several changes of ownership (emcc 2004a, 2004b). The fact that Swedish truck manufacturers, two major global players with the home base in a similar legal environment, have chosen different technical routes for managing Euro IV has a number of implications. It suggests that the technological system for emission control is not national in character. This would relate to earlier findings that the targeted markets are more important than the domestic market for the choice of emission control strategy (Bauner 2007b).

[31] Whether the same can be expected for research on the coming regimes such as fuel cells and hydrogen infrastructure is outside the scope of this paper.

[32] For example, concerning the QWERTY typewriter.

[33] An example of this is the UK vehicle industry. It is today to a large degree owned and managed by foreign (including several Asian) manufacturers, but retain a relatively large number of manufacturing plants in spite of the demise of nationally managed firms.

The current differences among technology choices in the face of 40–60% emission reductions in PM and NOx represent a healthy debate on technological ground, reinforcing the offer from Swedish truck manufacturers and promoting a more thorough technical understanding and ability for those involved in development. Investment support and regulations such as environmental zones give equal support to retrofitting as an (temporary) alternative to fleet renewal, and constitute a niche market for new entrants to an entrenched market. For the part of the engine supply chain located in Sweden, the technological variety is important to grasp. With more innovative solutions under evaluation, and possibly more fragmented demand due to local regulation and incentives, innovative entry is more feasible. In addition, a number of companies, e.g. Swenox, are large enough to balance proximity to customer with company size and economies of scale. Otherwise, the future of the suppliers is largely shaped by the sourcing, production and sales strategies of transnational companies.

Most of the heavy-duty vehicle (HDV) market (80% according to press statement) has decided to take on the SCR/urea route. The nonconformist here is smaller truck manufacturers, Scania and MAN, who have managed to stay out of SCR for most of their Euro IV models. It is also announced that Scania has satisfied the Euro V limits using EGR, and may also satisfy Euro VI for some models. This is an example of exploring the potential of less complex, but more sophisticated solutions described by Christensen (1997). By avoiding the need to fill urea, this technology is potentially more interesting for fleet owners operating in less developed markets outside the Triad. On the other hand, the "mainstream" manufacturers can keep their old Euro I engines, "add" SCR technology and reduce development cost and time. One remaining questions as regards health issues is whether the compliant Scania engines would emit a higher number of fine particles, something that may not be detected using the present gravimetric certification methods. Particle number measurement will not be part of the certification method for diesel engines until Euro VI, if even then. Research for both sub-trajectories continue, and while all manufacturers will maintain knowledge on both, there may be advantages that can be reaped by the non-conformists.

Clearly, the decision of the majority of HDV makers to unite for SCR as the favored technology must be based on the fact that this technology can deliver compliant results for the major application. The repeated indications that SCR does not function well for urban bus applications due to low exhaust temperatures could lead to changes in strategic choices taken for the engine sizes/models used in urban buses and city distribution trucks. Advances in LNT and HCCI for part of the cycle may yield further deviations away from the main SCR route.

While limited resource use and a clean environment are favored by all, vehicle buyers specifically require low fuel consumption while the regulators to date specifically require low NOx.[34] The vehicle manufacturers thus balance on the edge of regulatory compliance to deliver the optimal commercial solution. From a technical perspective, fuel economy and low NOx emissions constitute conflicting goals. This has led to market situations where not only individual actors, but also virtually whole markets choose strategies which were deemed illegal and rendered hefty fines and redesign responsibilities. The significant lesson here, arguably, is that these companies by all means understand the importance of harmonizing low local emissions and fuel consumption, the latter directly corresponding to emissions of CO_2, the major greenhouse gas. As climate change comes stronger on the political agenda, this delicate balance will be further explored. Non-market lobbying is strong. As the industry has gone against the letter of the law to improve fuel economy in earlier instances, it would seem that for the conventional emission reduction strategies the manufacturers have almost exhausted the potential to lower emissions further for a given engine size.

A majority of the vehicle producers in Europe have opted for SCR technology, and for Euro V also DPF. While including a new technology, it can be argued that this is the technical solution that would least impact the "business-as-usual" as compared to earlier engines. The most important reasons are judged to be that there is no fuel penalty and that already developed engine families can be used together with the SCR technology, which is a great cost advantage for the engine manufacturer.

It should be noted that emissions from road vehicles do not go down directly as the new regulation goes live. In some cases, only new engine models announced after the date are affected, and so the old models can be produced with lower emission requirements some time after the new tier is introduced. On-road emissions are also dependent on sales of the new vehicles—if regulation is tightened during an economic slump, older vehicles are likely to be used longer and slow down improvements. In many markets, more strict emission levels are phased in—required for a successively increasing fraction of the total sales for a given period—and final limit values are subject to revision.

Thus, the Swedish truck and bus manufacturers are in a dynamic R&D phase with different emission control solutions offered to the market. It is promising both for producers and vehicle buyers that the economic and technological climate is such that different solutions can be

[34] In a recent ruling by the USA Supreme Court (Massachusetts et al. vs. Environment Protection Agency et al.), USEPA were accused of not regulating against high CO_2 emissions.

accommodated on a commercial market. High-level innovative engineering can function so as to move established system boundaries as well as adding complexity, and be part of proposals to the market.

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