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Energy and Environmental Challenges for the Japanese Automotive Industry

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This report addresses environmental priorities and tradeoffs, especially as they relate to US public policy and Japanese automotive industry investments. The focus is on energy and air pollution issues associated with light duty vehicles.

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The challenge for automotive companies is to correctly anticipate policy and market demands, position oneself strategically with respect to environmental and other market issues – to distinguish opportunities from threats -- and design and develop products accordingly. The most critical environment-related issues facing the automotive industry are regulation of particulate matter and greenhouse gases, and the development and marketing of electric drive technologies. Depending upon a company's forecast and assessment of market demands, technological opportunities, and forthcoming regulations, it will invest in some mix of advanced diesel powerplants, direct injection gasoline engines, fuel cells, battery EVs, and various hybrid-ICE technologies.

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This report addresses environmental priorities and tradeoffs, especially as they relate to US public policy and Japanese automotive industry investments. The focus is on energy and air pollution issues associated with light duty vehicles.

The Challenge

The automotive industry has been remarkably successful. For over a century it has steadily improved the quality and sophistication of their product, adjusting shifting worldwide demand. It has provided huge benefits to society. Since 1950, the global automotive population has soared from about 50 million to over 600 million. In terms of per capita ownership, two in 100 people owned a vehicle in 1950; now 10 in 100 do so. The US has about 70 in 100, and many other countries are not far behind. With the global population and global economy continuing to expand, vehicle ownership will also continue to expand. Various forecasts anticipate another tripling of the global population of vehicles in the next 20 years.

The downside of increased mobility is increased consumption of resources and increased discharge of wastes. Since the market system treats pollution as an externality, it is widely accepted that governments are obligated to intervene. The US, Japan and other OECD countries, as well as many others, have an extensive set of rules in place to reduce unhealthy and toxic air pollutants and a variety of voluntary agreements and rules to reduce fuel consumption. It is widely expected that OECD countries will soon introduce rules limiting greenhouse gas emissions. These rules will build upon the foundation of fuel economy standards and voluntary agreements already in place.[1]

In the coming years, the most critical environmental policy initiatives affecting the automotive industry are likely to be particulate emission standards, fuel economy and greenhouse gas standards, and requirements and incentives for electric-drive vehicles.

Particulate Emissions[2]

Particulate matter (PM) is beginning to be recognized as the most critical and threatening vehicle pollutant (in OECD countries where lead emissions are already well controlled). Unfortunately, though, the source and characteristics of particulate matter, as well as their effect on human health, are difficult to specify, especially those particulates emitted from vehicles. PM is the general term for the mixture of solid particles and liquid droplets found in the air.

Particulate matter causes a series of human health problems, and also damages materials and impairs visibility. Of greatest concern to humans are fine particles (those less than 2.5 micrometers in diameter). Motor vehicle particle emissions and the particles formed by the transformation of motor vehicle gaseous emissions tend to be in this fine particle range. Fine particles are of particular concern because they easily reach the deepest recesses of lungs. The California Air Resources Board (ARB), after extensive studies, concluded that diesel exhaust is

[1] An important related issue, not addressed in this report, is the relationship with rapidly expanding countries in Asia and Latin America. Will these countries, which are a small but growing part of total worldwide automotive production, start to mimic rules and incentives adopted in OECD countries, or will they be far more lax? Will they seek to use different technologies, fuels and vehicle types? What is the appropriate and strategic role of automakers in dealing with government intervention in these developing markets? And how might demand in developing markets feed back to production and technology decisions for the OECD market?

[2] Much of the discussion in this section on PM comes from Michael Walsh, *Motor Vehicle Pollution Controls*, prepared for European Conference of Ministers of Transport (OECD), CEMT/CS/ENV(99)12/REV1, January 2000.

a toxic air contaminant and that there is a causal association between diesel exhaust exposure and lung cancer.[3]

The US EPA recently tightened ambient air quality standards for particulates and, along with California, adopted very stringent PM emission standards for light duty vehicles (see Tables 1). These new standards present a major problem to automakers, especially for diesel and direct injection gasoline engines. The effect of these new standards, as indicated below, could be to stifle commercialization of these two types of engines, both of which provide major improvements in fuel economy and greenhouse gas emissions.

Climate Change

Many believe that climate change is the most serious environmental issue facing human civilization. According to a growing scientific consensus, if current emissions trends continue, the atmospheric build up of greenhouse gases released by fossil fuel burning, as well as industrial, agricultural, and forestry activities, is likely to seriously disrupt weather patterns. In late November 1995, the IPCC Working Group 1 concluded that "the balance of evidence suggests that there is a discernible human influence on global climate." In December 1997, acting on this consensus, countries around the world approved the Kyoto Protocol to the 1992 Climate Change Treaty. Key aspects of the agreement include reductions in greenhouse gas emissions between 1990 and 2012 of 8% by the European Union, 7% by the United States, and 6% by Japan. While these nations have not formally committed to these reductions, there is a growing sense of urgency that something must be done soon. Indeed, many companies that had been actively opposing any government action are now becoming more conciliatory and even supportive of climate change action plans. For instance, in late 1999 and early 2000, Ford Motor Company and DaimlerChrysler both withdrew from a group that was lobbying against government action on climate change. At the time of Ford's withdrawal, in December 1999, company spokesman Terry Bresnihan commented that:

> "…over time, being in GCC has become something of an impediment to pursuing our environmental initiatives in a credible way, We do believe there is something to climate change, There is enough evidence that something is happening that we ought to start looking at this seriously."

Reduction of greenhouse gases to those agreed to in 1997 will be extremely difficult in the near term, certainly by the target date of 2012. This is especially true for the US, where total greenhouse gas emissions *rose* 9.5 percent from 1990 to 1996. Transportation is a large part of the problem, accounting for about for about ¼ of total greenhouse gases, and light duty vehicles for 61% of that. Importantly, CO2 emissions from vehicles *increased* 8.8 percent from 1990 to 1996 – the result of continuing increases in vehicle travel of about 2% per year and stagnating fuel economy. Vehicles are likely to be central to any strategy to reduce greenhouse gases.

Technological Transformation

[3] A new report from the Health Effects Institute (Diesel Emission and Lung Cancer: Epidemiology and Quantitiative Risk Assessment) suggests, however, that still more evidence is needed to confirm the relationship (see www:healtheffects.org).

Perhaps the most fundamental challenge to the existing automotive industry is the transition to electric-drive technology. Electric-drive technology provides the means of responding to PM and climate change problems. It also has other advantages that make it highly attractive: it is fundamentally more energy efficient, provides the potential to reduce all air pollutants (as well as greenhouse gas) emissions to near zero, is quieter and more reliable, and is better suited to supplying the high in-vehicle electricity needs of future vehicles.

The question is not if the transition will occur, but how and when. Vehicles of the future increasingly will be propelled by electric motors, but how will the electricity be supplied? Will it come from the electricity grid and stored on the vehicles in batteries, will it be generated on board with a fuel cell or small combustion engine, or will it be supplied as needed from inductive or conductive couplings? Current thinking is that the dominant electric-drive system of the future will likely be founded on fuel cells, with hybridized combinations of small combustion engines and batteries as a back-up option.

And when will the transition occur? The initial stimulus is California's zero emission vehicle mandate and its partial ZEV credit program, described below. While senior executives from virtually every major automaker have acknowledged the inevitability of a transition away from internal combustion engines, automakers appear to be organizationally and culturally ill prepared for the transition.

It is beyond the scope of this report to investigate this issue of organizational and cultural preparedness, but several observations and thoughts are presented here. Consider that a large share of the components for these vehicles will be very different from those used in today's internal combustion engine vehicles; this implies the need for new suppliers, organizationally and culturally rejecting the internal combustion engine as the core technology, and creating new manufacturing methods. There may also be a need to find new ways of marketing, retailing, and servicing vehicles. Thus companies will need new suppliers, new partners, new technology, new marketing methods, new service approaches, and a new electrical engineering culture. In a larger sense, there will be a need to rethink the entire structure of companies – to completely transform the industry. Energy and environmental concerns are a principal motivation for introducing electric-drive technology, and therefore a motivation for this industry transformation.

Current Regulatory Approach in the US

Governments first became active on behalf of various social and environmental issues in the 1960s. So-called social regulation of vehicles (and other products) was first pursued in the mid-60s, initially to improve vehicle safety, then reduce air pollution, and in the 1970s to regulate fuel use. The regulatory system that evolved was a creation of lawyers and engineers whose disciplinary paradigm is one of right and wrong. It was founded on highly specific rules of conduct and design, resulting in an approach that has come to be known as "command and control." While the various regulatory activities affecting vehicles and fuels are not strictly command and control -- they contain an increasing amount of flexibility -- the overriding framework continues to be one of directives that restrict the behavior of vehicle and fuel suppliers. The principal means of introducing flexibility now being considered is the use of tradable credits, whereby companies may average emission rates across their entire vehicle fleet, bank them if they better the standards, and buy or sell excess credits. These trading mechanisms and other means of creating flexibility will become increasingly important as emission levels are tightened. Without flexibility, some technologies may be essentially banned, including diesel and direct injection gasoline engines.

Air Pollutant Emissions

The process of regulating vehicle emissions in the US has been adversarial, highly formalized, and premised on the concept of technology forcing. Government regulators draw upon various information sources, including information provided by industry, in arriving at a judgement about what is cost-effectively achievable by automakers. Based on their interpretation of that information and their own assessment of likely progress by automotive engineers, they adopt new more restrictive rules. These rules are technology forcing in the sense that regulators generally promulgate rules that are significantly more stringent than industry indicates is reasonable in that time frame. California and federal regulators enact rules independent of each other. All other states must choose one or the other of the two sets of rules. California has been given the right by the US Congress to enact their own standards as long as the standards are at least as stringent as the federal standards. Until now, all states have always adopted the less stringent federal standards, though several states are now proposing to follow California standards.

The regulatory process is extraordinarily complex. Automakers receive piles of documents specifying minutiae on the design and conduct of emission tests, with regular updates on changes in reporting requirements, test procedures, and control technology. Until recently, all standards were uniform standards that applied to each and every car, bus, and truck sold in the country. Initially, standards were adopted to reduce lead levels in gasoline and three sets of pollutants from vehicles -- carbon monoxide, hydrocarbons (specified in rules as non-methane organic gases, volatile organic compounds, and/or nonmethane hydrocarbons), and nitrogen oxide. Vehicle standards were defined (and tested) on a grams per mile basis (except for evaporative hydrocarbons that are tested separately). More recently vehicle emission standards were adopted for formaldehyde and particulate matter. Compliance with emission standards is verified by running a sample of vehicles through a standard driving cycle.

The history of US emissions regulations, as indicated below, can be divided into essentially five rounds of criteria emissions standards.[4] (The latest emission standards are summarized and compared to Japanese and European standards in Table 2-4.) Emission standards were tightened in each round. An important feature of recent revisions is growing emphasis on flexibility.[5]

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[4] The following history of US emissions regulations borrows heavily from Tom Wenzel, "The (Unexpected) Success of Emissions Regulations in Advancing Vehicle Technology," *Procs., Transportation Energy and Environmental Policy for the 21st Century*, forthcoming from University of California, Davis, February 2000.

[5] The earlier uniform-standard approach was attractive in its simplicity and apparent ease of enforcement. These attractions were important; the ease of understanding and the directness and transparency of the regulatory actions helped create a strong positive image for the regulations among the general public. Now with the emissions regulatory process well established and strongly supported by the public, regulators apparently feel secure in introducing more complex rules that are more flexible and cost-effective.

The first important round was embedded in the federal Clean Air Act Amendments (CAAA) of 1970. While minor reductions in emissions had been required by earlier rules, now for the first time major reductions requiring major changes in technology were called for. After considerable debate, the industry settled on the use of catalytic converters as their centerpiece technology. Honda played a key role in the process. While other companies resisted government efforts, claiming that called-for reductions were not feasible, Honda developed and introduced lean burn CVCC engine technology, demonstrating that it was possible to attain the new standards, even without catalysts. The adoption of catalytic converters by the remainder of the industry, and by Honda in later years, obligated the oil industry to remove lead from gasoline, which they did beginning in the early 1970s.[6]

Next came the Clean Air Act Amendments (CAAA) of 1977 and what are now known as Tier 0 standards. These regulations reduced carbon monoxide (CO) and hydrocarbon (HC) emissions from new cars by 95% from pre-control levels and NOx by 75%. The specified levels were determined in part by the expected effectiveness of new control technologies, especially 3-way catalysts, oxygen sensors and closed loop control. These new technologies indeed proved to be highly effective. But because test procedures did not reflect actual driving conditions, and because emission control technologies tended to deteriorate over time, actual emissions of vehicles in use fell far short of the standards (even though cars still technically met the standards).

The third round of regulation arose with the 1990 CAAA, which addressed shortcomings in the 1977 amendments and established the Tier 1 standards. The shortcomings were related to two separate issues: unrealistic test procedures (that allowed manufacturers to mostly ignore fuel enrichment) and emissions deterioration. Fuel enrichment refers to the extremely large amount of pollution emitted for up to several seconds when there was a high load placed on the engine during acceleration (a driving condition that had not been included in the test procedures). Emissions deterioration relates to the deterioration of emission controls as the vehicle ages. These two problems were partially addressed in the 1990 amendments with the use of supplemental test procedures, requirements for inspection and maintenance (I/M) tests by users, and requirements that automakers install OBD (on board diagnostic) equipment on new vehicles. Tier 1 standards reduced (tested) HC by another 24% and NOx by another 40%.

In round four, simultaneous with federal Tier 1 standards, the California Air Resources Board in 1990 adopted its “low emission vehicle” program (now known as LEV I). The new rules were innovative in that they were the most stringent in the world, introduced more flexibility, and included a zero emission requirement. With this LEV I program, California established four vehicle emissions levels for cars and light trucks, plus a zero emissions category. Vehicle manufacturers were required to certify vehicles offered for sale in California at one of these emissions levels. Average emission levels were established that each manufacturer was required to meet. The average “standard” was specified for each year, at increasingly more stringent levels. Each company’s emission level was based on a weighted average of vehicles in each of the five categories, and was expressed in terms of the non-

[6] Daniel Sperling and Jennifer Dill. "Unleaded Gasoline in the United States; A Successful Model of System Innovation," *Transportation Research Record* 1175, pp. 45-52, 1988.

methane organic gas (NMOG) emissions. This fleet average NMOG requirement dropped from Tier I levels of 0.25 g/mile in 1994 to 0.062 g/mile in 2003. The most stringent category, ULEVs, required NMOG to be reduced 80% below Tier 1 standards, and NOx and CO by 50%.

The ULEV emission category was premised on the use of electrically heated catalysts and alternative fuels. Within a few years, however, it became clear that rapid innovation was making it possible to meet the ULEV standard without those costly changes by using more precise fuel control, improved fuel delivery, better catalytic converter performance, placement of catalysts close to the engine to hasten warm-up, and more durable control equipment.

Although only NMOG emissions were directly regulated by California's LEV I fleet average requirement, each NMOG certification level was accompanied by specific certification levels for other key pollutants. In this way, all emissions were regulated. By allowing manufacturers the flexibility to certify their vehicles at different levels (and comply with an average as opposed to a uniform standard), they introduced flexibility into the regulatory process. Further provisions allowing banking of credits and trading of emissions between vehicle suppliers provided even more flexibility.

The other new component of LEV I was the zero-emission vehicle rule. Known as the "ZEV mandate," this new regulation required auto manufacturers to offer specified numbers of zero-emission vehicles for sale. In LEV I, it was required that 2% of vehicles made available for sale in California in 1998 by each of the seven largest vehicle suppliers must be zero emitting (these companies are General Motors, Ford, DaimlerChrysler, Toyota, Nissan, Honda, and Mazda). The percentage increased to 5% in 2001, and 10% in 2003 and beyond. As described below, the 2% and 5% requirements for 1998 and 2001, respectively, were waived in 1996.

Round five was the adoption of LEV II in California in 1998 (see Table 1), and federal Tier 2 in late 1999. Several major changes were made. For the first time, light trucks and sport utility vehicles (SUVs) were required to meet the same stringent standards as cars, to be phased in over a period of several years.[7] Second, under LEV II, California enacted a new, even cleaner category known as SULEV, with further reductions below ULEV of 80% in HC and

[7] The standards for passenger vehicles were merged with those of all light-duty trucks under 8500 pounds Gross Vehicle Weight Rating. (Gross Vehicle Weight Rating is defined as the curb weight of the vehicle plus the maximum payload that the vehicle is rated to carry.) Until this point, certain light-duty trucks were allowed to emit more than passenger cars based on the assumption that these vehicles were used primarily for work purposes. (All trucks rated over 6000 pounds GVW fall into this category. Trucks rated under 6000 pounds GVW but over 3750 lbs. loaded vehicle weight—curb weight plus 300 lbs.—are also held to a less stringent standard under current rules.) Work vehicles generally have larger load carrying capacity and often will be driven 'harder' than passenger vehicles. However, in recent years it has become increasingly common for these vehicles to be used exclusively for simple passenger travel. For this reason, the 1998 LEV II regulation requires all vehicles rated under 8500 pounds – both passenger cars and light-duty trucks – to meet identical emissions standards. To allow for the manufacture of some work trucks in this vehicle class, a special standard has been created in the Low Emission Vehicle category that has a slightly higher limit for NOx emissions than is required for passenger cars. Certification to this standard is limited to 4% of the light-duty trucks rated between 3751 and 8500 pounds sold by a manufacturer in California.

70% in NOx.[8] Third, a partial ZEV credit program was created, providing more options to meet the ZEV mandate. The federal Tier 2 standards are similar to the California LEV II standards, except that they are somewhat less stringent, the fleet average standard is tied to NOx rather than HC, and they do not contain any zero emission vehicle requirements.

Table 1: LEV I and LEV II Standards for Light Duty Vehicles.

Vehicle Emission Category	Vehicle Miles Traveled	NMOG		CO		NOx		PM	
		LEVI	**LEV II**	LEVI	**LEV II**	LEVI	**LEV II**	LEVI	**LEV II**
Tier I	50,000	0.250	**n/a**	3.4	**n/a**	0.4	**n/a**	0.08	**n/a**
	100,000	0.310	**n/a**	4.2	**n/a**	0.6	**n/a**	n/a	**n/a**
TLEV	50,000	0.125	**n/a**	3.4	**n/a**	0.4	**n/a**	n/a	**n/a**
	100,000	0.156	**n/a**	4.2	**n/a**	0.6	**n/a**	n/a	**n/a**
LEV	50,000	0.075	0.075	3.4	3.4	0.2	**0.05**	n/a	n/a
	100,000	0.090	n/a	4.2	n/a	0.3	n/a	n/a	n/a
	120,000	n/a	0.090	n/a	4.2	n/a	**0.07**	n/a	**0.01**
	150,000*	n/a	**0.090**	n/a	**4.2**	n/a	**0.07**	n/a	**0.01**
ULEV	50,000	0.040	0.040	1.7	1.7	0.2	**0.05**	n/a	n/a
	100,000	0.055	n/a	2.1	n/a	0.3	n/a	n/a	n/a
	120,000	n/a	0.055	n/a	2.1	n/a	**0.07**	n/a	**0.01**
	150,000*	n/a	**0.055**	n/a	**2.1**	n/a	**0.07**	n/a	**0.01**
SULEV	120,000	n/a	**0.010**	n/a	**1.0**	n/a	**0.02**	n/a	**0.01**
	150,000*	n/a	**0.010**	n/a	**1.0**	n/a	**0.02**	n/a	**0.01**

Note: Shaded cells indicate LEV II changes to the LEV I standards.

ZEV Mandate

When the 1990 ZEV mandate was adopted, the California Air Resources Board expected huge strides to take place in battery electric vehicle development, and that zero-emission vehicles would be on the road in significant numbers by the end of the decade. Huge strides were made, but not great enough to make battery electric vehicles competitive with conventional gasoline and diesel vehicles.[9]

[8] The creation of the SULEV category (and tightening of other standards) reflected an observation that automotive engineers were making rapid progress in reducing the cost and effectiveness of emission control technology – reinforced by announcements by Honda and other major automakers that they could soon be producing vehicles that beat the ULEV standard by a significant margin. The LEV I certification levels were strengthened by extending the 100,000 mile requirement to 120,000, lowering the NOx standards for the Low Emission Vehicle and Ultra Low Emission Vehicle categories, and creating new standards for particulate emissions. The Board also added an option to certify vehicle at 150,000 miles instead of 120,000 miles, in return for proportionally more weight in the calculation of fleet average NMOG compliance.

[9] National Research Council. *Effectiveness of the United States Advanced Battery Consortium as a Government-Industry Partnership*. National Academy Press, 1998.

As a result, in early 1996, after a series of public hearings and considerable public debate, the California Air Resources Board weakened the ZEV elements of LEV I. The Board determined that battery electric vehicles expected to be offered for sale in California did not appear to have the range necessary for consumer acceptance, and therefore more research and development was needed.[10] The Board removed the zero-emission vehicle requirements for the years 1998 through 2002 and replaced them with a Memorandum of Agreement with each of the seven major manufacturers. The agreements imposed a set of new requirements designed to ensure that the emissions benefits lost from the rollback of the zero-emission vehicle requirements would be offset, and that research and development of zero-emission vehicle technologies would continue. The principal offsetting requirement was early adoption of more stringent national emission standards by the seven manufacturers, thus reducing emissions from vehicles purchased outside the state and subsequently imported.

Meanwhile, automakers stepped up their investment in a number of alternative technologies that achieve zero or near-zero emissions levels.

Under LEV II, in recognition of battery shortcomings and automaker investments in related technologies, California created a partial ZEV credit program as a means of providing more flexibility to automakers to meet the ZEV requirements. It also continued older provisions, allowing companies to buy ZEV credits from other companies selling ZEVs above their quota (including manufacturers other than the Big 7) or to pay a $5000 per vehicle penalty.

The new provisions allow ZEV credits to be earned through production of near-zero emission vehicles, and multiple ZEV credits to be earned for zero emission vehicles with an exceptionally long range. Those eligible for partial ZEV credit include hybrid electric vehicles, reformer-equipped fuel cell vehicles, natural gas vehicles, and conventional gasoline vehicles with advanced emissions control systems.[11]

To preserve the initial intent of the ZEV program – to accelerate the introduction of vehicles with inherently and permanently low emissions – CARB introduced a rule that 40% of the 10% zero-emission credit requirement in the mandate must be met with true zero-emission vehicles (i.e. ZEV credits associated with pure zero-emission vehicles must be equivalent to 4% of the total number of vehicles delivered for sale in California by that vehicle supplier). This 4% pure zero-emission vehicle requirement applies only to the seven “large-volume” manufacturers.

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[10] California Air Resources Board. "Staff Report: 1998 Zero-Emission Vehicle Biennial Program Review," Sacramento: California Environmental Protection Agency, July 6, 1998.

[11] To receive partial ZEV credit, a vehicle must at a minimum meet all of the following requirements: 150,000 mile SULEV (Super Ultra Low Emission Vehicle) exhaust emission standards; “zero” evaporative emissions standards; on-board diagnostic requirements at 150,000 miles; and a 15 year or 150,000 mile performance and defects warranty. Vehicles that meet these criteria will receive 0.2 ZEV credits and will also be eligible to receive additional credit based on zero-emission range and fuel-cycle emissions. Credits above 0.2 credits are earned for the following attributes: low lifetime tailpipe emissions, low fuel cycle emissions, and long ZEV range. For details, see Deborah Salon, D. Sperling, D. Friedman*, California’s Partial ZEV Credits and LEV II Program.* Institute of Transportation Studies, University of California, Davis, RR-99-14, August 1999, 17 pp.

As this report is written, the California Air Resources Board is undertaking its regularly scheduled biennial review of LEV standards, including the ZEV mandate. The automotive and oil industries are expected to undertake strong lobbying campaigns to reduce the requirements of the ZEV mandate, presumably focussing on the 4% ZEV rule. Some changes in the regulations are likely, although the promise of fuel cell vehicles suggests that at least some form of advanced vehicle sales requirement is likely to be retained (at least for vehicles incorporating electric-drive systems, such as fuel-reforming fuel cell vehicles and hybrid vehicles, if not for true zero-emission electric vehicles).

Comparison of EU, US and Japanese Emissions Programs

All OECD countries are calling for substantial reductions in vehicle emissions. Because each region uses different test procedures, it is difficult to make precise comparisons regarding their relative stringency. Ignoring the test procedure question, Tables 2-4 summarize the passenger car standards in the US, Europe, and Japan for nitrogen oxides and particulate, the two most critical standards.

In general, the California requirements continue to be the most stringent. The differences are greatest with respect to light duty diesel vehicles. California and the US are requiring more stringent reductions in both NOx and PM emissions for diesels than Japan or Europe, especially considering the durability requirements (only 80,000 and 100,000 km requirements in Japan and Europe, respectively, versus 193,000 in California and the US).

Table 2: Nitrogen Oxide Standards for Gasoline Passenger Cars

		Year of Introduction	g/km	Useful Life (km)
US national	**Tier 1**	1994	0.373	160 000
	Tier 2[12]	2004	0.043	193 080
California	**TLEV**[13]	1994	0.373	160 000
	LEV	1994	0.186	160 000
	ULEV	1994	0.186	160 000
	LEV2[14]	2004	0.043	193 080
	ULEV2	2004	0.043	193 080
	SULEV	2004	0.012	193 080
Japan	**Japan 2000**	2000	0.080	80 000
E.U.	**Euro 3**	2000	0.150	80 000
	Euro 4	2005	0.080	100 000

Source: Michael Walsh, *Motor Vehicle Pollution Controls*, prepared for European Conference of Ministers of Transport (OECD), January 2000. CEMT/CS/ENV(99)12/REV1.

[12] Tier 2 standards will be phased in beginning in 2004 in order to comply with EPA's declining fleet average NOx standard. 100% of the passenger car and light truck fleet operating on both diesel and gasoline will be required to comply on average by 2007.

[13] California's TLEV, LEV and ULEV standards are phased in by each manufacturer in a manner sufficient to comply with the fleet average NMOG standard.

[14] California's revised emissions required for LEV and ULEV certification (referred to in the table as LEV 2 and ULEV 2) and new SULEV category will be phased in beginning in 2004 by each manufacturer in a manner sufficient to comply with the declining fleet average NMOG standard.

Table 3: Nitrogen Oxides Standards for Diesel Passenger Cars

		Year of Introduction	g/km	Useful Life (km)
US national	**Tier 1**	1994	0.777	160 000
	Tier 2[15]	2004	0.043	193 080
California	**TLEV**[16]	1994	0.373	160 000
	LEV	1994	0.186	160 000
	ULEV	1994	0.186	160 000
	LEV2[17]	2004	0.043	193 080
	ULEV2	2004	0.043	193 080
	SULEV	2004	0.012	193 080
Japan	**Japan 2002**	2002	0.280	80 000
E.U.	**Euro 3**	2000	0.500	80 000
	Euro 4	2005	0.250	100 000

Source: Michael Walsh, *Motor Vehicle Pollution Controls*, prepared for European Conference of Ministers of Transport (OECD), January 2000. CEMT/CS/ENV(99)12/REV1.

[15] Tier 2 standards will be phased in beginning in 2004 in order to comply with EPA's declining fleet average NOx standard. Light trucks operating on both diesel and gasoline will be required to comply on average by 2007.

[16] California's TLEV, LEV and ULEV standards are phased in by each manufacturer in a manner sufficient to comply with the fleet average NMOG standard.

[17] California's emissions required for LEV and ULEV certification (referred to in the table as LEV 2 and ULEV 2) and new SULEV category will be phased in beginning in 2004 by each manufacturer in a manner sufficient to comply with the declining fleet average NMOG standard.

Table 4: Particulate Matter Standards for Diesel Passenger Cars

US national	**Tier 1**	1994	0.062	160 000
	Tier 2[18]	2004	0.006	193 080
California	**TLEV**[19]	1994	0.050	160 000
	LEV	1994	0.050	160 000
	ULEV	1994	0.025	160 000
	LEV2[20]	2004	0.006	193 080
	ULEV2	2004	0.006	193 080
	SULEV	2004	0.006	193 080
Japan	**Japan 2002**	2002	0.052	80 000
E.U.	**Euro 3**	2000	0.050	80 000
	Euro 4	2005	0.025	100 000

Source: Michael Walsh, *Motor Vehicle Pollution Controls*, prepared for European Conference of Ministers of Transport (OECD), January 2000. CEMT/CS/ENV(99)12/REV1.

Fuel Economy

In recent years, as fuel prices have dropped, so has the fuel consumption of new U.S. light duty vehicles. The average fuel economy for all model year 1999 light vehicles is 23.8 miles per gallon (mpg), the lowest since 1980, and 2.1 mpg less than the peak value of 25.9 mpg achieved in 1988. The breakdown is 28.1 mpg for passenger cars and 20.3 mpg for light-duty trucks. The increasing market share of light-duty trucks, which have lower average fuel economy than cars and now account for about 50% of light duty vehicle sales, is the primary reason for the decline in fuel economy of the overall new light vehicle fleet.

The reduction in fuel consumption masks very real improvements in efficiency. If today's vehicles had the same performance attributes and accessories as in the mid 1980s, they would have 20-30% lower fuel consumption. But the technical efficiency gains have been used

[18] Tier 2 standards will be phased in beginning in 2004 in order to comply with EPA's declining fleet average NOx standard. 100% of the passenger car and light truck fleet operating on both diesel and gasoline will be required to comply on average by 2007.

[19] California's TLEV, LEV and ULEV standards are phased in by each manufacturer in a manner sufficient to comply with the fleet average NMOG standard.

[20] California's emissions required for LEV and ULEV certification (referred to in the table as LEV 2 and ULEV 2) and new SULEV category will be phased in beginning in 2004 by each manufacturer in a manner sufficient to comply with the declining fleet average NMOG standard.

up in increasing the power and acceleration of vehicles (since the mid 80s, horsepower is up 58%, weight up 20%, and 0-60 mph acceleration up 19%), adding fuel-consuming accessories (such as 4-wheel drive), and expanding their size and weight (substituting, for example, large sport utility vehicles for sedans).

In 1975, the US created the Corporate Average Fuel Economy (CAFE) program, with standards first taking effect in 1978. These rules require each manufacturer of light duty vehicles to meet a specified average standard each year. Compliance is measured by average fuel consumption across all vehicles sold in a particular year. The CAFE standard for cars, set legislatively by Congress, reached 27.5 mpg in 1985, was pushed back to 26.0 for a short while and now remains static at 27.5. The standard for light trucks, set by the US Department of Transportation, was creeping up at about 0.1 mpg per year through the early 1990s, and is now frozen at 20.7 mpg. This regulatory structure is somewhat more flexible than the regulatory structure for air pollutant emissions, but continues to suffer several shortcomings.

The overarching and most controversial issue with CAFE standards is their numeric value. But there are also serious concerns about the fundamental design of the rules. The standards separate domestic and imported vehicles, cars from light trucks, favor large automakers with broad offerings, and are disconnected from market forces.[21] The classification rules – separating cars and light trucks, and domestic vehicles from imports -- were created initially mostly to protect the domestic Big 3 automakers from Japanese competition; they have the effect of encouraging the sale of light duty trucks and distorting, often in unpredictable ways, decisions on where to manufacture cars and parts.

The CAFE program has other perverse effects as well: they hurt smaller manufacturers who specialize in more fuel-consuming vehicles such as sports cars, luxury cars, and sport utility vehicles and do not reward manufacturers specializing in fuel-efficient cars. The principal weakness, though, is the disconnect with market forces. Automakers vigorously oppose increases in the standard because they insist, for the most part accurately, that consumers are not willing to pay extra for better fuel consumption. For their part, consumers are acting rationally. With gasoline costs lower than they have been since World War II (taking into account inflation), an additional 5 mpg generates less than $100 in fuel savings per year.

Circumstances are changing, though. What worked in the past will not necessarily work in the future. Fuel economy regulation was effective and arguably efficient during the late 1970s and early '80s when fuel prices were high. High fuel prices encouraged manufacturers to invest in more efficient vehicles and consumers to buy them, and the schedule of stiffening fuel economy standards created a sense of certainty about the future. High fuel prices and stiffening standards reinforced each other.[22] That dynamic has unraveled with sagging fuel prices. Other

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[21] Consider the following example of gaming to circumvent the rules. At one point Ford Motor Company reportedly transferred the manufacture of some minor components on its large Crown Victoria to Mexico so that the percent of imported parts on the car would exceed 25 percent, allowing Ford to count the car as an import. In that way, the Crown Victoria vehicles would count against the company's fuel-efficient imported cars and not against the larger and less efficient domestic cars, allowing the company to produce more large cars and still be within the 27.5 mpg domestic-car standard.

[22] David L. Greene. "CAFE or Price: An Analysis of the Federal Fuel Economy Regulations and Gasoline Prices on New Car MPG, 1978-89," *Energy Journal* 11:3, pp. 37-57, 1990

changing circumstances include subsiding protectionism, due in part due to the merger of Chrysler and Daimler Benz, new propulsion technologies and fuels entering the market, and increasing political pressure to reduce energy consumption and greenhouse gas emissions. The net result is that CAFE standards almost definitely will be modified, if not replaced, in the coming years.

Actions to strengthen CAFE have been deferred in part in anticipation of the results of an innovative research and development (R&D) partnership between the federal government and the three domestic automakers. However, as indicated below, this Partnership for a New Generation of Vehicles (PNGV), initiated in 1993,has had little effect to date on the commercialization of more energy efficient vehicle technology.

The European and Japanese governments have been more aggressive at reducing fuel consumption than the US. In early 1999, Japan adopted vehicle fuel economy rules, in accordance with the Law on Rational Use of Energy.[23] The standards were drafted based on the "top runner method" (i.e., best-in-class) method. The goal for gasoline passenger cars is 23% improvement between 1995 and 2010, and for diesel passenger cars, 15% between 1995 and 2005. Corresponding goals for light duty gasoline "freight" trucks (under 2.5 tonnes) are 13.2%, and for corresponding diesel trucks, 6.5%.

The Europeans have been particularly aggressive. Reacting to even more stringent proposals by the European Union, the European Automobile Manufacturers Association (ACEA) came to a voluntary agreement with the EU to reduce average new car emissions of CO2 by 25% between 1995 and 2008 (to 140 g/km), with further cuts possible by 2012 (to 120 g/km).

Future Governmental Intervention

The political constituency for clean air has been and continues to be very strong in the US.[24] The US has a created an elaborate set of rules, laws, and institutions dedicated to the reduction of air pollution. Environmental interest groups have been highly effective at using the judicial system to assure that rules and laws are fully enforced. Clean air initiatives have been consistently supported by voters and politicians across the political spectrum. Ambient air quality and vehicle emission standards continue to be tightened. Though business groups have successfully slowed many regulatory initiatives, such as the recent federal proposal to further tighten ozone and particulate air quality standards, it appears that the public continues to be strongly committed to improving air quality. It may be, though, that the recently adopted Tier 2 and LEV II emission standards will be the last major tightening of light duty emission standards (though, as indicated later, some refinements, for instance with particle size and number and with ZEV credits, could have important implications).

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[23] Kiyuyuki Minato, *Automobile and Global Environmental Issues in Japan*, Japan Automobile Research Institute, 1999.

[24] Willet Kempton, James Boster and Jennifer Hartley, *Environmental Values in American Culture,* The MIT Press. Cambridge, 1995, 320 pp.

The political constituency for reducing greenhouse gases is not nearly so powerful.[25] The American public continues to remain skeptical of climate change problems and of the urgency of reducing greenhouse gases. Nonetheless, as greenhouse gas concentrations in the atmosphere continue to build, it appears likely that public opinion and political support for action will build. If either Vice President Al Gore or Senator Bill Bradley is elected president, the federal government is likely to become more activist; if Governor George Bush is elected, federal initiatives are likely to lag.

In thinking about future government initiatives, it is useful to categorize policies into the following groups: 1) standards, which are both performance and prescriptive based; 2) market incentives, which include information, taxes, feebates, and marketable credits; and 3) public R&D funding.

Standards for reducing emissions and fuel consumption have tended to be performance based. Two exception to this are on board diagnostics (OBDs) and the California ZEV mandate, though the recent introduction of partial ZEV credits greatly reduces the prescriptive nature of the ZEV "mandate."[26]

The trend, as with the ZEV mandate, is to offer greater flexibility. This trend reflects the realization that, as emissions and other externalities are reduced, it becomes ever more difficult to specify the next level of cost-effective strategies, and that more flexibility generally leads to more innovation. It is becoming widely accepted – especially in the US -- that more flexibility and responsibility must be pushed down to vehicle suppliers. Tier 2 and LEV II contain a variety of mechanisms that increase flexibility.

Market incentives provide even more flexibility than performance standards, and are receiving increasing emphasis. Market incentives include mechanisms to alter price signals to account for externalities, and mechanisms to create parallel markets for externalities. Market incentives include taxes, fees, and marketable credits. Taxes and fees are in theory the most economically efficient means of reducing emissions but are politically anathema in the US. Other mechanisms are politically more palatable. Feebates, whereby buyers and users receive rebates for very clean and efficient vehicles and pay fees for dirty and inefficient vehicles, appear to more acceptable because they are revenue neutral in nature. Marketable credits, the trading of emission reduction credits, appear even more palatable and have been adopted in a variety of vehicle and fuel emissions programs in the US (including LEV I and II, Tier 2, leaded gasoline and reformulated gasoline, and heavy duty emissions). Many experts and the US government tout them as an effective and efficient framework for reducing global greenhouse gases.

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[25] Ibid.

[26] OBDs are specified in detail by a rule that gives no consideration to actual emissions performance. The California ZEV mandate was originally a prescriptive standard, in the sense that battery electric vehicles were the only plausible technology available to meet the rule, but the introduction of partial ZEV credits for non-electric vehicles provides manufacturers with more technological flexibility than was permitted under the original mandate. The ZEV credit trading provision, in place since the beginning, also blunts the prescriptive nature of the program.

The third major category of policy approaches to accelerate the development and commercialization of advanced technology is public R & D funding. Certainly there is a role for government in supporting more long-term technologies, especially those that are potentially most effective at reducing externalities. All OECD countries have R&D programs to advance such technologies, usually focussed on industries and technologies of economic interest to that country.

The US has long supported research and development of automotive technology and alternative fuels. Public R&D programs can be critical to advancing the state of the art of important technologies, and indeed US R&D programs have done so in a variety of technology areas, and will continue to do so. Two recent initiatives, the Partnership for a New Generation of Vehicles (PNGV) and the US Advanced Battery Consortium (USABC), began in the early 1990s time period, focussed on US companies (USABC quickly expanded to include non-US battery companies, because US companies were so few, and PNGV expanded to include Daimler Benz after it merged with Chrysler). The goal of USABC was to accelerate the commercialization of advanced batteries for use in ZEV vehicles mandated for 1998, and the goal of PNGV was to build production prototypes of 80 mpg mid-size family sedans by 2004. Neither has been particularly effective.

In the former case, funding was modest, US capabilities were limited, and the goals unreasonable.[27] In the case of PNGV, no new funding was provided, the funding involved was minimal compared to industry needs and resources, and the program goals discouraged risk taking.[28]

In any case, US automakers have lagged in commercializing advanced vehicle technology. Toyota and Honda both brought hybrid vehicles to market at competitive prices well before US automakers, and the leaders in fuel cell vehicle development have been Daimler Benz (before joining with Chrysler), Toyota, and General Motors, with Ford becoming a major player in fuel cells only after joining a partnership with Daimler Benz (now D/C) in late 1997. In both cases, companies in Europe and Japan have been at least as effective in developing and commercializing advanced technologies as US companies, especially so in the case of hybrid and fuel cell vehicles.

It should be understood that most innovation takes place within companies, and will be motivated by some combination of perceived market opportunities and expected government initiatives. Emission control technology was developed and commercialized for those reasons, and the same will be true of electric-drive technology. Government has been and will be most effective through its adoption of rules and incentives. While the ultimate success of electric-drive vehicles will be determined for the most part independently of government actions, government rules and incentives will have a large impact on where and when they are

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[27] National Research Council. *Effectiveness of the United States Advanced Battery Consortium as a Government-Industry Partnership*. National Academy Press, 1998.

[28] D. Sperling, "Rethinking PNGV," Testimony to US House of Representatives, House Science Committee, Subcommittee on Energy and Environment, Washington, DC, July 30, 1996, Congressional Record; and D. Sperling, "Rethinking the Car of the Future," *Issues in Science and Technology*, Winter 1996-97, pp. 29-34, National Academy of Sciences.

introduced, and even what is introduced (e.g., what set of electric drive technologies). Incentives include not only economic incentives, but also non-monetary incentives such as preferential parking and access to special lanes.

In summary, as technological and fuel responses to pollution and greenhouse challenges become more complex and uncertain, there becomes a greater need for more flexible, incentive-based policy approaches. Indeed, the future of diesel engines and direct injection gasoline engines may depend upon the willingness of governments to adopt more flexible rules and incentives.

Critical Issues for Automakers

The future is more uncertain than ever for automakers. Markets, regulations, and technology are all evolving quickly and in many ways unpredictably. Policymakers are becoming increasingly active in intervening to protect human health and safety. Technology options for vehicles are proliferating, to increase customer convenience as well as to serve societal goals of energy, environment, and safety. And markets for vehicles and vehicle products are becoming more difficult to forecast, for the simple reason that consumers have little or no experience with the new products – whether they be navigation devices or new propulsion technologies. While this report focuses on energy and environment challenges and technologies, it is important to note that there is a nexus between technology advances driven solely by market forces and those driven by social goals. Consider for instance that the replacement of the internal combustion engine by fuel cells will result in a high-power electricity infrastructure being installed on-board the vehicle. This new electricity infrastructure will enable the easy integration of a new array of in-vehicle products and services, from microwaves and hair dryers to pre-heating and pre-cooling to use of electrically powered products at remote recreational areas.

Automakers cannot afford to make serious financial commitments to the development and marketing of all promising technologies. They must make strategic choices. Key technology choices, with respect to energy and environmental concerns, include advanced diesel powerplants, direct injection gasoline engines, and various electric-drive technologies (including fuel cells, battery EVs, and hybrid-ICE technologies).

Diesel and Gasoline Direct Injection Engines

Diesel engines are widely used in cars in Europe, and gasoline-powered direct-injection (GDI) engines are widely used in Japan, but neither type of engine has been widely used in the US light duty vehicle market. Many companies would like to increase the use of these engines in the US, because both provide significant improvements in fuel economy. Mitsubishi for example, now manufactures 10 GDI models in Japan, which reportedly reduce fuel consumption by 20 percent, with a 10 percent increase in power output.[29] And new (direct injection) diesel engines are about 40 percent more fuel efficient, on a per gallon basis, than conventional gasoline engines[30] and therefor about 25 percent more efficient on the basis of

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[29] A. Demmler, "Smallest GDI Engine," *Automotive Engineering*, Vol 107, No 3, 1999, p. 40.

[30] U.S. Congress, Office of Technology Assessment (OTA), *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*, OTA-ETI-638, Washington, DC: U.S. Government Printing Office, 1995.

carbon emissions over the fuel cycle. The problem is that both engines tend to have significantly higher emissions than conventional (port injected) gasoline engines.

The potential for large reductions in fuel consumption is due to the ultra-lean operation of these two engines; unfortunately it is difficult to catalyze pollutants in the lean environment. Emissions of NOx and PM from both engine types are considerably higher than from conventional engines.[31] As of mid-1999, more than 300 different concepts of GDI engines had been analyzed, but none met strict LEV II and Tier 2 standards for NOx, HC, and PM.[32] To meet the standards, GDI (and diesel) engines will require major advances in engine design and aftertreatment, and will also require the use low sulfur fuels.

While both engine types face formidable emissions problems, the problem appears to be more severe for diesel engines. An independent review of the Partnership for a New Generation of Vehicles (PNGV) by the prestigious National Research Council, apparently reflecting the beliefs of the three automaker members, states that "GDI's potential for meeting California LEV II and US Tier 2 requirements is significantly better than that of the [diesel] engine."[33]

The most troublesome emissions problem is likely to be PM – and it is likely to prove even more severe than generally acknowledged. Both LEV II and Tier 2 emissions standards for PM deal with particle mass, not the size or number of particles. Evidence is mounting that the most severe health effects are from the very smallest particles (especially nanoparticles, those less than 50 nm in diameter). GDI and diesel engines produce large amounts of these very fine particles.[34] A study of a 1998 Mitsubishi Carisma with 1.8L Mitsubishi GDI engine found that at low speed conditions, a large fraction of particles were in the nanoparticle size range (though at higher speeds the particles were larger), and that the number of particles were one to three orders of magnitude higher than in modern conventional gasoline engines.[35] It is likely that particle size and number will soon be regulated, creating even greater difficulties for both GDI and diesel engines.

Lower levels of sulfur in fuel are an essential element of emissions reduction for both GDI and diesel engines. Indeed, this is a contentious issue. Regulators have been proposing lower sulfur levels for years, with strong support from automakers, but oil companies have

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[31] Japan Automobile Research Institute, *Environment and Energy Policies on Automobiles in Japan*. IOS Press and Ohmsha, Ltd, 1999.

[32] B.R.Graskow, D.B. Kittelson, M.R. Ahmadi, and J.E. Morris. "Exhaust Particulate Emissions from a Direct-Injection Spark-Injection Engine." *SAE 1999-01-1145*; Spicher, U., J. Reissing, J. M. Kech and J. Gindele. "Gasoline Direct Injection (GDI) Engines Development Potentialities." *SAE 1999-01-2938*; Cole, Roger L., Ramesh B. Poola and Raj Sekar. "Exhaust Emissions of a Vehicle with a Gasoline Direct-Injection Engine." *SAE* 982605.

[33] National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles: Fifth Report*. National Academy Press, 1999, p.70.

[34] Dickens, C.J., and D. E. Hall. "Measurement of the Number and Size Distribution of Particles Emitted from a Gasoline Direct Injection Vehicle." *SAE 1999-01-3530*, 1999.

[35] Graskow, B.R., D.B. Kittelson, M.R. Ahmadi, and J.E. Morris. "Exhaust Particulate Emissions from a Direct-Injection Spark-Injection Engine." *SAE 1999-01-1145,* 1999.

been resisting. Sulfur levels will continue to be reduced, though the timing is uncertain, and is likely to vary across regions.

In summary, significant advances in NOx and PM control technology will be needed for GDI and diesel engine technologies to be used in the US and California.[36] The question is how far and how fast emissions can be improved, and whether they will be subject to even more severe standards in the future. Industry is working very hard to improve emission control technologies. Indeed, in response to the 1990 Tier 1 and LEV I rules, industry has made extraordinarily rapid progress in reduce emissions from conventional gasoline engines, well beyond virtually everyone's expectations. With the new standards for PM and NOx, and growing interest in more fuel efficient technologies by the automotive industry (motivated in part by the desire to forestall investments in electric-drive technology), it would seem possible, even likely, that major advances are likely in reducing emissions from direct injection and diesel engines.

If regulators tighten the NOx and PM standards still further, though, the prospects for light duty diesel and direct injection engines will dim. That would not be in the interest of many vehicle suppliers and engine manufacturers and perhaps not in the interest of society as a whole. On the other hand, if regulators decide that the fuel economy benefits are of overriding importance and they develop more flexible regulatory mechanisms that allow automakers to trade improvements in fuel economy for somewhat higher PM or NOx emissions, then the commercial prospects for those two technologies will be enhanced.

Electric Drive Technology

Companies prefer to believe that the success of new products and technologies depends on market factors and consumer demand. Generally that is true, and in the long term the success of a product indeed does depend on pleasing the customer. But there are many products and technologies whose success depended on government support. Nuclear energy is a good example. Governments provided virtually all the R&D during the early years of the industry and created the institutions and technologies for storing wastes; in the US, government also adopted rules to limit liability and to spread the huge capital cost over a large base and long time frame. Nuclear reactors would not have been built in the US (or any other country) without those government initiatives.

The introduction of electric-drive technologies is not as extreme a case as nuclear energy, but government will play a large role in influencing their market development. This influence could be rather large for three reasons: huge uncertainty about consumer acceptance; the principal near term motivation for their introductions is non-market factors (i.e., the reduction of pollution and greenhouse gases); and it is possible that many of the electric-drive technology combinations will have similar costs.

Certainly, businesses are already making investment decisions about battery, hybrid, and fuel cell electric vehicles based on their perceptions of what types of vehicles are likely to be most successful in the marketplace. For instance, battery EVs are being downplayed, while

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[36] A forthcoming report from US Department of Energy now under review, known informally as the "5 Lab Study," explores the cost, energy, and emissions prospects of GDI and diesel technology under different scenarios.

fuel cells are gaining more attention and resources, for the simple reason that the industry believes fuel cells are lower risk and have greater market potential. Nonetheless, there is no question that California's ZEV mandate has greatly accelerated the development and commercialization of electric drive technology, and that the details of the new ZEV partial credit program will likely influence automaker decisions about when and what technologies to invest in. And that the details of government tax credits and other subsidies, and even the details of non-monetary subsidies, could play a huge role in directing industry investments in different directions. For instance, if methanol fuel cell vehicles receive relatively few partial ZEV credits (because methanol is not deemed a clean fuel), if rules are adopted that treat methanol as a toxic substance (or even banned as in the case of the more benign MTBE), and if methanol fuel cells do not receive the same access to carpool lanes and preferred parking as do other electric drive technologies, then industry investments will shift to other electric drive designs.

In summary, the design of rules and incentives to encourage the introduction of more benign vehicles and fuels will play a large role in influencing corporate investment strategies. At this point, some initial assessments can be made of which technologies are likely to gain greater market acceptance, but it is impossible to determine with confidence which set of technologies is likely to be most successful. Indeed, it is likely that future vehicles will be differentiated much more than they are at present, especially in the US market – with a greater mix of fuels, vehicle sizes, and propulsion technologies. Each company will need to determine what role and what products to pursue. To the extent these product offerings vary from the status quo, it will be important for companies to form partnerships with local governments, businesses, and non-governmental institutions. The future world will be far more complicated than today's.

Conclusions

Japanese automotive companies (as well as most other international automakers) face difficult investment and marketing decisions. They must determine how to respond to the many opportunities opened up by the proliferation of inexpensive information management and computing technologies and, as addressed in this report, which propulsion and pollution control technologies to pursue.

A key challenge is to anticipate future government efforts to reduce pollution and greenhouse gases, and forecast accurately cost trajectories and market demand for new technologies. An accurate assessment of these forces and factors will provide the basis for decisions to invest in light duty diesel and gasoline direct injection engines, and electric-drive technologies. The pressure to invest in cleaner and more efficient vehicle technology is growing, but the prospects for incremental technologies -- diesel and direct injection engines in light duty vehicles – are clouded by ever tightening restrictions on particulate and nitrogen oxide emissions. Leapfrog technologies – battery, hybrid and fuel cell propulsion systems – provide the potential for major energy and environmental benefits, but the risks are high and major organizational transformations will be needed for companies to launch them successfully.

How automakers respond to opportunities presented by leapfrog technologies, and the government rules and incentives supporting them, is very different now than it was three decades ago. At that time, the three major domestic automakers controlled a large share of the US market, often behaving as oligopolists.[37] The industry is now more competitive, resulting in a greater willingness to innovate and take risks in pursuing promising new designs and technologies. One manifestation is competition to earn the mantle of "environmental" automaker of the 21st century. In any case, all automakers face a series of difficult decisions. In the face of huge uncertainty and risk, they must strategically determine which technologies to develop and commercialize.

[37] William J Abernathy, *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry*, Baltimore: Johns Hopkins University Press, 1978.