Federal and California Emission Control Attainment and Future Engine Technology

for
Chevron Research and Technology Company

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16. Abstract

Chevron Research and Technology Company and The University of Michigan Office for the Study of Automotive Transportation undertook a delphi survey of chief powertrain engineers in order to better understand future product technology responses to governmental emission and fuel economy regulations. Seventeen respondents to the first round survey included representatives from major U.S. powertrain activities, one Japanese, and one European manufacturer.

The responses to this survey on federal and California emission control attainment and future engine technology clearly suggest an intense level of technical activity within each automotive company. All manufacturers have significant programs underway on alternative fuels, advanced engine systems, and advanced emission-control technologies. Given the number of uncertainties within the environmental arena, as well as other volatile areas, the reasonable consensus in this report is remarkable. However, realistically, the industry may have only a limited number of practical options available as it strives to meet future regulatory requirements.

Substantial concerns exist over the prospects of achieving the California standards while meeting consumer expectations and market realities. Panelists report little optimism toward lean-burn (including NO_X catalysts) and two-cycle engines in this decade even though both could lead to modest fuel economy improvements. Of the various alternative fuels, panelists view reformulated gasoline and compressed natural gas as the most favorable. Given forecast market volumes, other fuels may justify research and development attention.

The responses show the many trade-offs between fuel economy and emission controls. Panelists forecast lean-burn and two-cycle engine technologies, which provide fuel economy advantages, may not capture large market shares due to difficult emission control compliance. With 82% share, gasoline will remain the dominant light-duty vehicle fuel through the year 2010. Most panelists believe significant tax or other incentives must accompany alternative fuel acceptance.

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Executive Summary

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The automotive industry is experiencing enormous stress here in the United States and throughout the world. Shortages of profits, capital, time, and critical human skills individually and together characterize this stress-filled business environment. Furthermore, record levels of competitive pressure, aggressive regulatory pressures, and ever more demanding customers are forcing manufacturers and suppliers to reduce activities that do not add value. Collectively, these pressures represent an enormous competitive challenge for every industry participant.

Within this context, industry must address the particularly severe California environmental regulations. Furthermore, there are strong indications that other regions, including several east coast states, may adopt California emission requirements. Consequently, all major manufacturers are conducting good faith efforts to address environmental requirements while trying to meet broader customer expectations.

The responses to this survey on federal and California emission control attainment and future engine technology clearly suggest an intense level of technical activity within each automotive company. All manufacturers have significant programs underway on alternative fuels, advanced engine systems, and advanced emission-control technologies. Given the number of uncertainties within the environmental arena, as well as other volatile areas, the reasonable consensus in this report is remarkable. However, realistically, the industry may have only a limited number of practical options available as it strives to meet future regulatory requirements.

Substantial concerns exist over the prospects of achieving the California standards while meeting consumer expectations and market realities. Panelists report little optimism toward lean-burn (including NO_X catalysts) and two-cycle engines in this decade even though both could lead to modest fuel economy improvements. Of the various alternative fuels, panelists view reformulated gasoline and compressed natural gas as the most favorable. Given forecast market volumes, other fuels may justify research and development attention.

This survey considers many specific emission-control technologies. The following table presents technologies likely to achieve application, or at least serious attention, for future products. From a market perspective, the potential conflict between regulatory compliance and market success creates significant tension in a world of limited resources.

Significant California and Advanced-Federal Emission Control Technologies	
• Air-assist fuel injectors	• Advanced high-energy ignition systems
• Heated fuel injectors	• Low-crevice cylinder/piston design
• Close-coupled catalytic converters	• Improved engine-control software
• Heated catalytic converters	• Catalytic converter efficiency sensors
• Upgraded/lighter-weight valve trains	• High turbulence chamber design

The responses show the many trade-offs between fuel economy and emission controls. Panelists forecast lean-burn and two-cycle engine technologies, which provide fuel economy advantages, may not capture large market shares due to difficult emission control compliance. With 82% share, gasoline will remain the dominant light-duty vehicle fuel through the year 2010. Most panelists believe significant tax or other incentives must accompany alternative fuel acceptance.

Foreword

During the third quarter of 1992, the University of Michigan's Office for the Study of Automotive Transportation (OSAT) surveyed a select group of powertrain engineers, to gain insight into future strategies for attaining California and advanced federal emission certification along with increased Corporate Average Fuel Economy (CAFE) standards. Working with the Chevron Research and Technology Company, OSAT developed a series of questions focusing on internal combustion engine technologies likely to emerge to meet these challenges. A follow-up survey on one additional question in October 1992 supplemented this initial survey.

Respondents

The first round results (questions 1 through 7) compile the responses of 17 senior engineers. With increasingly centralized technical operations of the manufacturers' powertrain groups, the panel, while relatively small, provides a strong indication of collective industry viewpoints. The following table presents the first-round respondent profile.

Company	Number of Responses	Job Title	Number
General Motors	7	Vice President	1
Ford Motor	5	Chief/Executive Engineer	5
Chrysler	3	Department Manager	2
Foreign	2	Manager (including advanced powertrain technology, technology planning, engine research, product legislation and compliance, and other related activities)	9
Total	17		17

The second round (question eight) invoked responses from nine of the original panel. The following table presents the profile of second round responses.

Company	Number of Responses	Job Title	Number
General Motors	5	Vice President	0
Ford Motor	2	Chief/Executive Engineer	3
Chrysler	1	Department Manager	0
Foreign	1	Manager (including advanced powertrain technology, technology planning, engine research, product legislation and compliance, and other related activities)	6
Total	9		9

Presentation of Data

The tables following each question report the median value as well as the interquartile range (IQR) surrounding the median response. The median identifies the middle, or central tendency of the panelists' responses. The IQR bounds the median at the low end by the 25th percentile, and at the upper end by the 75th-percentile value. For example, in question one, the median of 4.5 for two-cycle engines shows that panelists are very pessimistic (on a 5-point scale) towards their use in meeting federal, tier-one, emission levels at 30-m.p.g. CAFE levels. The IQR shows that 25% of the panelists answered 4 or less (showing little optimism) and 25% answered 5 (unlikely). This narrow IQR shows close consensus among panelists.

Following each data table are edited comments. Often these comments add illustrations, exceptions, and amplification to the responses. The authors also present short discussions following each question, giving interpretation and supplier implications.

Definitions

The following tables present the definitions, timetables, and standards of the federal Clean Air Act and California automotive-emission regulations referred to in the text.

Clean Air Act Amendments of 1990

Passenger Car Standards

Standard	NMHC grams/mile	CO grams/mile	NO_X grams/mile
Current	0.41T	3.4	1.00
Tier I	0.25 [0.31]	3.4 [4.2]	0.4 [0.6]
Tier II	[0.125]	[1.7]	[0.2]

Notes: NMHC=nonmethane hydrocarbons; T=total hydrocarbons; CO=carbon monoxide; NO_X=oxides of nitrogen.

Standards are for 5 years/50,000 miles or 10 years/100,000 miles (shown in brackets) and for up to 3,750 pounds loaded vehicle weight.

Tier I standards must be achieved by MY 1996; Tier II, if imposed, would apply to MY 2004 and beyond.

Source: *Automotive Fuel Economy, How Far Should We Go?*, National Research Council, 1992, p. 73.

California Passenger Car Standards

Standard	NMOG grams/mile	CO grams/mile	NO_X grams/mile
1993 Base	0.25 [0.31]	3.4 [4.2]	0.4
TLEV	0.125 [0.166]	3.4 [4.2]	0.4 [0.6]
LEV	0.075 [0.090]	3.4 [4.2]	0.2 [0.3]
ULEV	0.040 [0.055]	1.7 [2.1]	0.2 [0.3]

Notes: NMOG=nonmethane organic gas; CO=carbon monoxide; NO_X=oxides of nitrogen.

TLEV=transitional low-emission vehicle; LEV=low-emission vehicle; ULEV=ultralow emission vehicle.

Standards are for 5 years/50,000 miles or 10 years/100,000 miles (shown in brackets) and for up to 3,750 pounds loaded vehicle weight.

For 1993 base, NMOG=nonmethane hydrocarbons only. In 1998, 2% of manufacturers' sales must be ZEV and in 2003, 10%.

Source: *Automotive Fuel Economy, How Far Should We Go?*, National Research Council, 1992, p. 74.

Survey Responses

1. What new internal combustion engine (ICE) technologies will be significantly used (10% or greater of total U.S. light-duty vehicle sales) in each of the given scenarios by the year 2000? For each engine technology and emission/CAFE scenario please indicate the likelihood of each technology's application (where 1=likely and 5=unlikely). Please use the blanks to indicate additional engine technologies. Please see page 4 for emission standards definitions.

Likely ICE Technologies for Given Federal Scenarios								
Engine Technology	30 mpg CAFE				35 mpg CAFE			
	Federal Tier 1		Federal Tier 2		Federal Tier 1		Federal Tier 2	
	Median	IQR	Median	IQR	Median	IQR	Median	IQR
Two cycle	4.5	4/5	5	4/5	4	3/4	5	4/5
Lean burn	4	3/5	4.5	4/5	4	3/5	5	3/5
Lean NO_X catalyst	4	4/5	4.5	4/5	4	3/5	5	4/5

Single Responses—Likely ICE Technologies for Given Federal Scenarios				
	30 mpg CAFE		35 mpg CAFE	
Engine Technology	Federal Tier 1	Federal Tier 2	Federal Tier 1	Federal Tier 2
Air-assist injection	3	4	4	5
Today's fuel control and catalytic technology	2	—	—	—
Close coupled higher temperature catalysts	—	2	2	2
Today's fuel control and catalytic technology	—	—	2	2
Lean NO_X catalyst	2	2	2	2

Comments

Tighter emissions requirements will probably keep most auto makers from committing to two-cycle engines for fuel economy.

Strict emission standard degrades two-stroke fuel economy. The only benefit is inertia test weight (ITW) reduction, maybe one class. Lean NO_X catalysts have not met durability requirements yet.

Conventional engines using advanced control strategies and features such as variable valve timing are the most probable solution. This may influence vehicle weight and engine capacity reductions.

It is unlikely that these technologies will surpass 10% by 2000.

Two-cycle is incorrect terminology. The cycle still has four parts: intake, compression, expansion, and exhaust. The two-stroke requires two piston strokes; the four requires four.

Discussion

Panelists do not expect two-cycle, lean-burn, and lean NO_X catalysts to play a significant role in the attainment of future, federal, emission standards through 2000. However, commercialization of these technologies may occur over the next eight years in a number of individual applications. Our expert panel foresees these three technologies' implementation at a rate less than 10% of the total U.S. light-duty market (or approximately 1.3 to 1.5 million units). The tight interquartile ranges—showing consensus among the panelists—reinforce the unenthusiastic median responses of 4 and 5 (highly unlikely to achieve 10% application rates) across the given technologies for each scenario.

The format of this question highlights the tension between fuel economy improvements and emission control. While the comments emphasize the degradation of two-stroke fuel economy with increasing emission-control standards, the numerical responses show the two-stroke's appeal in the higher fuel-economy scenario (the interquartile range drops to 3/4 from 4/5). Lean burn, another technology delivering fuel economy with emission certification difficulty, receives lower expectations in both advanced emission-control scenarios.

"Other responses" indicate the technologies our panelists view as the likely responses to these scenarios. Air assist injection, advanced fuel control systems, and catalyst technology advancements; close coupled, higher temperature catalysts; higher power per liter displacement engines; and exhaust heat management suggest other opportunities being pursued.

California Regulations

Likely ICE Technologies for Given California Scenarios								
Engine Technology	30 mpg CAFE				35 mpg CAFE			
	CA LEV		CA ULEV		CA LEV		CA ULEV	
	Median	IQR	Median	IQR	Median	IQR	Median	IQR
2-cycle	5	4/5	5	5/5	4.5	3/5	5	4/5
Lean burn	5	4/5	5	4/5	5	4/5	5	4/5
Lean NO_X catalyst	5	4/5	5	4/5	4	4/5	5	4/5

Single Responses—Likely ICE Technologies for Given California Scenarios				
	30 mpg CAFE		35 mpg CAFE	
Engine Technologies	Federal Tier 1	Federal Tier 2	Federal Tier 1	Federal Tier 2
Air assist injection	5	5	5	5
Heated catalytic converter	2	3	4	5
Hybrid	—	—	—	3
Close coupled catalyst	2	—	2	—
Supercharged lower displacement 4-stroke	—	—	2	2
Exhaust heat management	2	3	2	3

Comments

Lean NO_X catalyst, if available, will give lean-burn technology a major push. The probability that it will be available by 2000 is low.

Three-way stoichiometric engine and catalyst systems should still offer the best emission and driveability through the year 2000.

Warm-up converters will probably be required for LEV and ULEV (with conventional engines and control systems).

At present, in research stages, only four-stroke stoichiometric technology can meet the emission standards. This statement assumes no loss in fuel efficiency.

Small cars are more likely than heavy vehicles to use two-cycle engines. Customer confidence needs to be obtained to allow increased diesel applications.

It is unlikely that these technologies will surpass 10% by 2000.

Discussion

Our panelists responded with more pessimism for these technologies in the California regulatory environment. The comments indicate two important elements that need constant monitoring. First, the comment regarding lean NO_X catalysts shows that technological breakthroughs may occur which could alter cost, performance, regulatory compliance, or other limits. Second, responses to this survey anticipate today's vehicle mix extending into the future. However, as one comment indicates, small cars are more likely than larger vehicles to use two-stroke engines. If affordability and other economic factors force the market toward smaller vehicles, two-stroke engines may become more commonly used.

The list of technologies with the greatest support is the same for California regulations as it is for federal emission regulations: air assist injection, improved fuel control, and catalyst technology advancements; close coupled, higher temperature catalysts; higher power per liter displacement engines; and exhaust heat management.

2. Please indicate the average passenger car fleet percentage gain in mpg each of the following technologies may provide. Please consider the technology's application to only the engine and the maximum possible gains in a vehicle that is optimized to take full advantage (aerodynamics, weight reduction, and others) of possible mpg gains.

Engine-Type	Engine Only Application		Complete Optimized Vehicle	
	Median	IQR	Median	IQR
Two cycle	**7.5%**	**2/10%**	**10%**	**3.5/15%**
Lean burn	**5%**	**5/10%**	**5%**	**4/10%**

Comments

Two-cycle improvements (0.5% and 1%) and lean burn (0.7% and 1%) assume 10% penetration rates.

Supercharged, smaller displacement, four-stroke engines may offer overall vehicle-mass reductions and improve fuel economy at better emission levels than the two-stroke engine.

Two-stroke requires combustion degradation and lower fuel economy to achieve emission levels. Lean burn below 1 gram per mile NO_X requires lean NO_X catalyst even at 2,375 pound class.

Lean-burn improvement (10%) assumes same engine size.

High variability of actual results—depends upon the specific technology used.

I assume that these technologies may achieve required emission levels.

Lean-burn is a subset of two-stroke; that is, all two-strokes are lean-burn. A four-stroke lean-burn would not confer size, weight, or cost reduction opportunities.

Discussion

Given the wide range of vehicles (considering weight classifications, styling, function, and other characteristics) this question may not capture precise percentage fuel economy improvements. However, this question presents two ideas: first, the two-cycle engine comparison with lean burn expectations, and second, the value of complete vehicle optimization when considering powertrain technologies.

Although the median responses indicate that panelists believe two-cycle engines provide greater future fuel economy potential, the lower quartile responses—the minimum expected gain—show a higher potential for the lean burn. The lean-burn upper quartile range—the maximum expected gain—equals the engine-only application forecast. With complete optimization, the upper quartile range of a two-cycle may be 50% greater than the lean burn. The large interquartile ranges in each category reflect the variation of panelists' interpretation of vehicles, powertrains, and optimization success. The variation, as the comments relate, may also result from emission-control concern with each technology and differing experiences within each company's engineering programs.

Panelists forecast a 33% increase in fuel economy gains for a two-cycle engine in an optimized vehicle over an engine-only application. However, lean burn in both a straight-engine application and an optimized-vehicle form may deliver approximately 5% fuel economy improvement. Respondents did not, as judged by the interquartile ranges, differentiate between an engine-only and a vehicle-optimized scenario for the lean burn. From these results, lean-burn applications may appear as an extension to an existing powertrain application for an existing vehicle program. Two-cycle engines, taking part of a completely optimized vehicle, may gain due to a two-cycle's lighter weight, higher performance density, and packaging advantages.

3. What is the probability (where 1=high and 5=low) by 2004 of each of the three major auto producing industries attaining California ultralow emission vehicle standards for 10% of their sales (across the three given segments)? Please consider this question from the aspect of marketing vehicles in a cost competitive manner with practical ICE technology.

Probability of Meeting California ULEV Standards						
	Market Segment					
	Small Car		Large Car		Light Truck	
Industry	Median	IQR	Median	IQR	Median	IQR
U.S.	**1**	**1/3**	**3**	**2/4**	**3.5**	**2/4**
Japan	**1**	**1/2**	**3**	**3/4**	**3**	**2/5**
Europe	**2**	**1/4**	**3.5**	**3/5**	**4**	**3/5**

Comments

Expect that the capability of meeting ULEV standards for some vehicles by 2004 may be developed. However, cost competitiveness is still subject to great debate.

California is too large a market for the U.S. or Japanese manufacturers to walk away from.

Few European manufacturers market small cars in the U.S. Large car assumptions (U.S.=4, Japan=3, and Europe=2) reflect distribution of vehicle size.

Japan may be more likely to achieve ULEV by applying very high technology components while competing in total vehicle price due to their cost advantages.

Discussion

The comment "California is too large a market for the U.S. or Japanese manufacturers to walk away from" sets a strategic tone for the next ten years: environmental and safety regulations are increasingly a barrier to entry. While the California market is too large for the U.S. manufacturers and Japanese and European importers to ignore, it might become too expensive for the three or five competitors selling the fewest cars to maintain a market presence. Of course, regulatory compliance scales of economy shift dramatically if additional states—or the east coast region—adopt California standards.

Our panelists believe that small cars have the best chance of meeting the ULEV standards. While it is true that smaller-volume Japanese manufacturers tend to produce smaller cars, these manufacturers may not have the wherewithal—profits generated from a wide portfolio of products—to invest in regulatory compliance R&D. European manufacturers, it appears, may have trouble in that the more successful—relatively speaking—European firms tend to sell larger, performance-oriented vehicles. The difficulty expressed in the light-truck arena certainly indicates difficulty for the expansion plans of the Japanese (across all segments) and Europeans (into the mini van segment).

U.S. manufacturers will have a difficult time meeting the ULEV standards. First, many U.S. foreign affiliates produce American-nameplated small cars (GEOs, Festivas, Colts). Interesting competitive questions will arise if emission control technology transfers from American companies to foreign affiliates to maintain a marketing presence in small cars. Second, the market is now approximately 35% light-trucks with Ford and Chrysler selling as many light trucks as passenger cars. As noted, panelists forecast the light truck segment as the most difficult segment for U.S. manufacturers to achieve ULEV compliance in. This may force the reallocation of capital spending to truck powertrain programs.

4. Considering reformulated gasoline, methanol (M-85), and compressed natural gas (CNG) fuels, what additional technological factors (beyond 1991-1993 emission control technology) will be required to achieve ULEV emission standards (e.g., close coupled and/or heated catalytic converters)? Please identify specific technologies beneath each category area and the probability (where 1=high and 5=low) of each technology's application.

Likely Vehicle System Technology for California ULEV Standards						
	Type of Fuel					
Vehicle System	Reformulated Gasoline		M-85 Fuel		CNG Fuel	
Fuel Injector Systems	Median	IQR	Median	IQR	Median	IQR
• Air-assist injection	**1**	**1/3**	**1**	**1/5**	**3**	**1/5**
• Heated injectors	**2**	**2/2**	**1**	**1/2**	**5**	**5/5**
• High pressure	**2**	**2/3**	**2**	**2/3**	**—**	**5***
Catalytic Converters						
• Close coupled	**1**	**1/1**	**1**	**1/2**	**2**	**1/4**
• Preheated	**2**	**1/3**	**2**	**1/3**	**4**	**1/4**
• Heated	**1**	**2/5**	**1**	**1/5**	**4**	**1/5**
Ignition Systems						
• High energy	**1**	**1/3**	**1**	**1/3**	**3**	**1/3**
Valvetrain						
• Variable	**3**	**1/3**	**3**	**2/3**	**3**	**3/4**
• Upgrade/lightweight	**1 and 5***	**—**	**1 and 1***	**—**	**1 and 1***	**—**
• Direct acting mechanical	**1 and 2***	**—**	**2 and 2***	**—**	**2 and 2***	**—**
Cylinder/Piston Design						
• Low crevices	**1**	**1/1**	**1**	**1/2**	**2**	**1/3**
• HC benefit/reduction	**1 and 1***	**—**	**1 and 1***	**—**	**1 and 4***	**—**
• High turbulence chambers	**2 and 3**	**—**	**2 and 3***	**—**	**3 and 5***	**—**
Electronics/Sensors						
• Cylinder pressure/temp. control	**4**	**3/4**	**4**	**2/5**	**3**	**1/4**
• Catalyst temp./efficiency	**1 and 2***	**—**	**1 and 2***	**—**	**1 and 3**	**—**
• Fuel composition	**3 and 5***	**—**	**1***	**—**	**1***	**—**
Engine Control Software						
• Air/fuel control	**1 and 2**	**—**	**1 and 2**	**—**	**1 and 2**	**—**
• Improved	**1**	**1/1**	**1**	**1/1**	**1**	**1/1**
Other Single Responses:						
• Insulated exhaust system	**2**	**—**	**3**	**—**	**3**	**—**
• Improved oil control	**2**	**—**	**2**	**—**	**2**	**—**
• Improved thermal mgt.	**1**	**—**	**1**	**—**	**3**	**—**

* Single or dual responses

Comments

Reformulated fuels together with CNG will be significant factors in achieving low emission vehicles in future years.

Discussion

The responses to this question indicate a wide range of activity being undertaken to achieve ULEV certification. As judged by the median and interquartile ranges, panelists view air-assist injection, heated injectors, close-coupled and heated catalytic converters, advanced high-energy ignition systems, low-crevice-volume pistons, and improved engine-control software as being particularly important. Reformulated gasoline and M-85 require the same emission control technology. The reader may compare these answers with question one, where air assist injection rates a neutral response. Please note that air assist injectors and close-coupled catalytic converters appear under the single response category in question one. This question reports a consensus of many panelists.

CNG fueled vehicles require innovation through upgrading valvetrains, improving piston design to reduce HC emissions, developing catalytic and fuel composition sensors, and improving engine control software. Generally CNG will probably require less sophisticated technology to achieve a given emission-performance level. The wide range of existing and future vehicles, powertrains, and corporate capabilities and strategies require a diverse range of solutions. As the road to ULEV compliance becomes better defined, this complexity may fade. For now, ample opportunities exist for suppliers to develop and source advanced powertrain systems and components. Question eight provides additional information on these specific powertrain technologies.

5. Assuming attainment of ULEV in California, what percentage of 1998 model year vehicles sales in California will use alternative fuels in 1998 other than reformulated gasoline?

1998 Fuel Application for California ULEV		
Alternative Fuel	Median	IQR
Ethanol	**1%**	**0/1%**
Methanol (M-85)	**2**	**1/10**
Propane	**1**	**1/1**
Compressed Natural Gas	**2**	**1/5**
Other Single Responses		
Hydrogen	**1%**	**—**
Electric vehicles	**2 and 2**	**—**

Comments

Reformulated gasoline will be the fuel of choice for most ULEV efforts.

Reformulated gasoline fuel should still play a leading role during this time frame.

Alternative fuels do not help ULEV except for CNG only because of NMOG law.

Alternative fuel vehicles not happen in large numbers until alternative fuel costs per mile are similar to gasoline and travel range improves for CNG.

Drawbacks of alternative fuels are so great (with the exception of some specialist fleet applications) that our belief is that no one will choose to use the alternatives.

Methanol (M-85) answer of 20% assumes 20% of the vehicles may be capable of using this fuel (flexible fuel vehicles). This could be as high as 50%. These forecasts are very uncertain.

Nonmethane standards strongly favor use of CNG.

Politics will be a major determinant of the future of methanol. CNG will be limited to truck applications.

Discussion

Through numerical responses and comments—particularly convincingly written comments—our panelists indicate for California in the 1998 model year a low probability of significant alternative-fuel vehicle sales. In total, panelists forecast 6% (8% including the single answers of hydrogen and electric vehicles) alternative-fuel use for California's 1998 new model year sales. Vehicle manufacturers will depend upon reformulated gasoline in their efforts to certify ULE vehicles.

This forecast raises two interesting issues. First, multiple fuel supply and, second, multiple fuel system service. It appears that fuel stations may need to supply a number of fuels as these multifueled vehicles increase in fleet operation. Handling multiple fuels greatly complicates the refining and distribution system. Service operations will also need to respond to this complexity through training, diagnostic and service tools, and part inventories.

6. What fraction of total U.S. light-duty vehicle sales will be powered by the following methods in 2000 and 2010?

Light Duty Vehicle Fuel Application				
	2000		2010	
Vehicle Power Systems	Median	IQR	Median	IQR
Flexible/Variable	3%	2/5%	5%	1/10%
Natural Gas	2	1/5%	5	1/10%
Electric	1	1/2%	3	1/10%
Electric Hybrid	1	1/4%	2.5	1/10%
Dual response: Propane	1 and 1%	—	2 and 1%	—
One response: Hydrogen	2	—	5	—
Gasoline	92%	84/95%	82%	70/89%
Total	100%		100%	

Comments

Electric hybrids seem to offer the most potential for satisfying emission requirements, fuel economy, and customer performance and functional requirements. Electric vehicles will drive much of the needed technology, but their limitations as full-function transportation to meet typical American driving requirements will prevent them from being more than a small niche.

Popularity of electric or hybrid vehicles may grow quickly, but gasoline-fueled vehicles should be around for sometime to come—perhaps as a second vehicle for longer trips and heavy hauling.

The infrastructure won't exist by 2000 for large volumes of fuels other than gasoline.

Alternative fuels not happen without artificial market incentives (i.e., fuel and vehicle tax breaks).

Flexible-fueled vehicles could be quite high, especially in 2010. The forecast is very uncertain.

CAFE may affect alternative-fuel-vehicle applications. Higher CAFE may drive more auto makers to seek CAFE credits. Range of possibilities indicates the political and economic uncertainty surrounding alternative fuel technology.

Discussion

Gasoline will remain the dominant U.S. light-duty vehicle fuel in the short and medium term. While each of the given alternative fuels shows significant positive application rates, particularly given low use today, panelists forecast that 82% of the 2010 model-year vehicles will have gasoline engines (please note, the lower interquartile range shows a 2010 70% application rate). The comments highlight the major inhibitors to alternative-fuel usage: customer performance and functional requirements and infrastructure. These issues need addressing as does the possibility of initiating governmental incentives to help reduce the costs of switching away from gasoline-powered vehicles. Although gasoline's future appears reasonably secure, the forecast of 18% of the 2010 market indicates some 2.5 to 2.75 million alternative-fueled vehicles that may offer a significant market opportunity or a threat depending on the strategic perspective.

7. What are customer priorities at the given "fuel-equivalent" prices among each of the following factors? Please weight each factor so that the total adds to 100%.

Vehicle Purchasing Attributes				
	$1.15/gallon fuel		$3.00/gallon fuel	
Attribute	Median	IQR	Median	IQR
Vehicle acceleration from zero mph	**12%**	**8/20%**	**9%**	**2/15%**
Vehicle top speed	**2**	**0/5**	**1**	**0/2**
Vehicle passing acceleration	**12**	**9/20**	**10**	**5/14**
Fuel economy	**12**	**5/10**	**22**	**15/25**
Refueling convenience and speed	**10**	**2/15**	**4**	**2/14**
Fuel cost (dollars/refueling, cents/mile)	**6**	**2/12**	**18**	**8/25**
Driving range	**12**	**8/16**	**11**	**6/15**
Perceived fuel environmental desirability	**2**	**1/5**	**3**	**0/5**
Size and comfort of vehicle	**32**	**15/45**	**22**	**14/30**
Single response: Reliability	**30%**	**—**	**30%**	**—**
Single response: Safety	**10**	**—**	**—**	**—**
Total	100%			100%

Note: single responses not included in totals.

Comments

Fuel cost and fuel economy address the same issue. It is very difficult to assign percentages.

As fuel becomes more expensive, shopping for low fuel price will be more prevalent. Range becomes more important, and convenience of station less significant.

With higher fuel prices and the resultant effect of lower disposable income and toleration and interest in environmental issues are expected to decline.

This scale is not entirely appropriate as these dimensions exhibit thresholds implying that customer priorities change abruptly.

Discussion

This question provides an interesting check list for alternative-fuel-vehicle attributes. Our panelists responded as expected to this question: as fuel prices increase, vehicle-purchase attributes connected with fuel economy rise in importance. Fuel economy and fuel cost rise to the top of the customer's perceived priorities. Customers may partially forsake size and comfort of vehicles if fuel prices jump to $3.00 per gallon. For the alternative-fuel discussion, it is interesting that customers may give up refueling convenience and speed (important for electric and natural gas vehicles) but will not sacrifice driving range.

8. **Regarding use with reformulated gasoline, please consider these advanced technologies that will be required to achieve California ULEV emission standards. First, please indicate the probability (where 1 = high and 5 = low) that these technologies will be in production by 1995. Second, please identify the calendar year you believe these technologies will be introduced. Third, please identify the type of engine where these technologies will be first introduced. Please circle more than one engine type if applicable.**

Vehicle System	Probability of Production Volumes by 1995 Median	IQR	Calendar Year Introduction		Expected Engine Application (percent of respondents) I4	V6	V8
Fuel Injector Systems							
• Air-assist injection	4	3/5	1997	1996/1998	56%	78%	44%
• Heated injectors	5	3/5	1997	1996/1998	11%	44%	11%
• High pressure/increased atomization	3	3/5	1997	1996/1997	56%	56%	44%
Catalytic Converters							
• Close coupled/light-off	4	1/4	1996	1995/1997	78%	78%	56%
• Heated	5	4/5	1998	1997/1998	11%	67%	67%
• Lean NO_X catalyst	4	4/5	1998	1998/2000	67%	11%	0%
Ignition Systems							
• High energy	2	2/3	1995	1993/1995	78%	78%	44%
Valve Train							
• Variable	4	2/5	1997	1995/1997	67%	56%	33%
• Upgrade/light weight	2	1/3	1995	1995/1996	78%	89%	33%
• Direct acting mechanical	2	1/4	1997	1995/1997	78%	56%	33%
Cylinder/Piston Design							
• Low-crevice-volume/HC reduction	3	1/4	1995	1995/1995	56%	89%	11%
• High turbulence chambers	2	1/4	1995	1992/1997	67%	67%	44%
Electronics/Sensors							
• Cylinder pressure/pressure volume optimization	4	4/5	1998	1998/1998	44%	33%	11%
• Catalyst temp./efficiency	2	2/3	1997	1995/1997	67%	89%	78%
• Fuel composition	4	3/5	1997	1997/1998	44%	44%	22%
Engine Control Software							
• Air/fuel control	1	1/1	1995	1993/1995	89%	78%	56%
• Optimized ignition timing	1	1/1	1995	1993/1995	78%	89%	67%
• Optimized EGR control	1	1/2	1995	1993/1995	78%	100%	78%

Other single responses:

Revised cooling systems	2	1998	V6
Exhaust system thermal mgt.	5	1994	I4, V6, V8
HC absorber	3	1999	V6, V8
Optimized cooling	4	1996	V6, V8

Comments

As we learn what species of organic gases are created or affected by various parameters, the above input will probably change quite dramatically.

Some low-crevice-volume pistons exist in production today. Ultralow-crevice-volume pistons will not be introduced until 1998.

A minimum of new, ULEV driver technologies will be in use in 1995 (only 1% volume required).

The first ULEVs will be 1) those select vehicles that are already very clean and require minor system changes and 2) vehicles with a variety of emission-system enhancements to allow companies to get production experience.

ULEV requirements will definitely drive the technologies in production in the late 1990s.

Many of the features noted are in existence today at some level. Many of the systems will continue to be developed and refined to enhance their performance.

Discussion

As the comments note, production exists in some version for many of the listed technologies. As many of the comments indicate, ULEV requirements will drive component and system innovation and evolution. Within the systems listing several innovations, panelists provide an indication of the technology with the greatest probability of introduction or likely improvements by 1995. These technologies are high-pressure and increased-atomization fuel injectors, high-energy ignition systems, upgraded and lighter weight valvetrains, high turbulence chambers, catalyst temperature and efficiency sensors, and improved engine-control software.

Readers should note the panelists' expectation of technology introduction dates. Those listed for 1996 and 1997 (air assist, heated, and higher pressure fuel injectors; close coupled catalytic converters; variable and direct acting valvetrains; and improved catalyst temperature and efficiency and fuel composition sensors) are likely to be currently consuming increasing research and development resources. The calendar year column presents an interesting timeline of product development expenditure as well as commercialization dates. Across all technologies there is reasonable consensus (most within two years).

The third column of data provides the reader the expected focus of research within a manufacturer's powertrain operations and, crudely, an estimation of possible production volumes (in all engine segments or selected markets). Some technologies, such as air-assist and heated injectors, lend themselves to specific engine families. Other technologies, such as close-coupled catalysts and catalytic temperature and efficiency sensors, will likely see application on all engine families.