The 3-Way Catalytic Converter: a) Invention and Introduction into Commerce - Impacts and Results b) Barriers Negotiated

California Air Resources Board
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VEHICLE EXHAUST EMISSION REGULATIONS PROVIDED THE BASIS FOR THE INVENTION

- U.S. Clean Air Act Amendments of 1970
  - 90% Reduction of Exhaust Hydrocarbons (HC), Carbon Monoxide (CO) and Oxides of Nitrogen (NOx); Lead-free gasoline
  - Light-Duty Vehicle Emission in Terms of Grams per Mile:

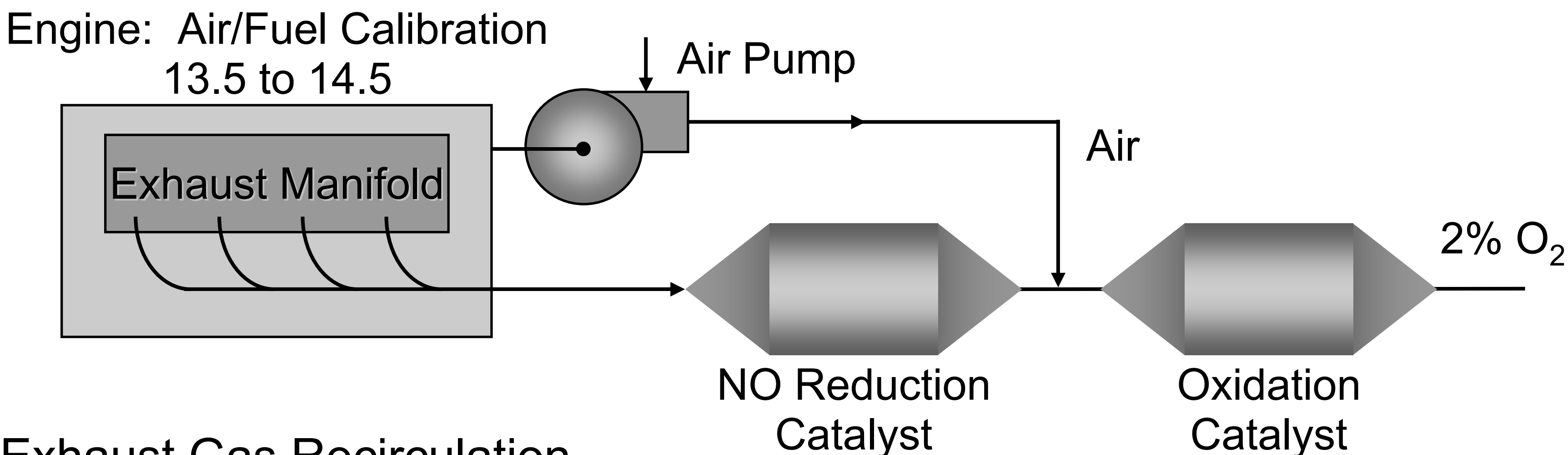
	HC	CO	NOx
Average	4.1	34.0	4.0
Statutory Standard	0.41	3.4	0.40

  - Oxidation Catalyst Was Proven for HC and CO Removal

But! How to Control NOx.

HC + CO OXIDATION AND NOx REDUCTION BY EXHAUST CATALYST REQUIRED SEPARATE REACTORS

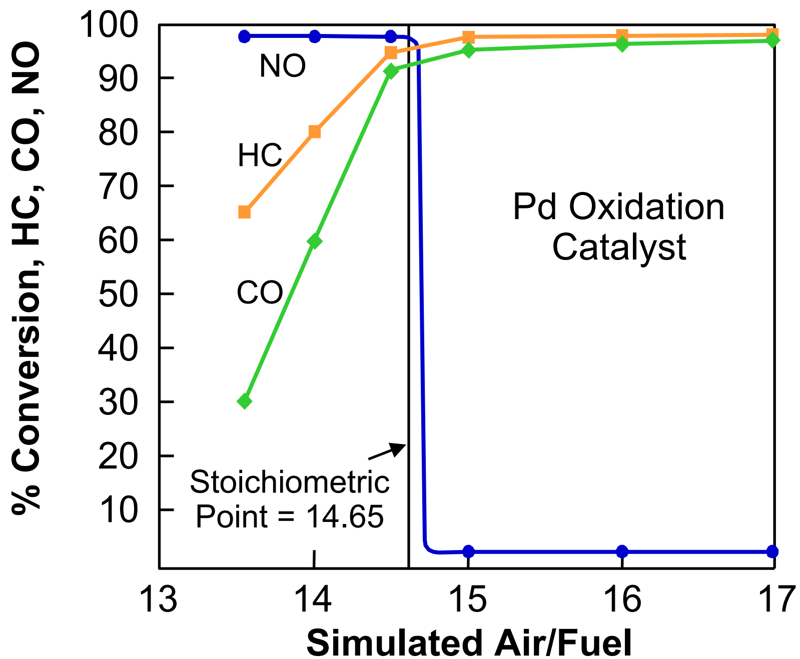
- Dual-Bed Catalytic Converter System:



- Exhaust Gas Recirculation
  - Could Decrease NOx by About 30%
  - Had a Negative Effect on Engine Performance

Carmakers and Catalyst Companies Were Working on the Second-Generation Catalytic Converter – the Dual-Bed System.

IN THE COURSE OF LABORATORY OXIDATION CATALYST EVALUATIONS, WE FOUND THAT OXIDATION AND REDUCTION REACTIONS OF SYNTHETIC EXHAUST WERE POSSIBLE AT THE PRECISE STOICHIOMETRIC MIXTURE



Not original data. Original data obtained by R. Kenson.

- Pd Was Better than Pt in the Laboratory Experiments
- Chemical Calculations and Thermodynamics Were Favorable
- Ford Science Laboratory Ran Vehicle Equipped With Engelhard PTX Catalysts and a Rich/Lean Carburetor Calibration - Obtained Oxidation of HC and CO and Some Reduction of NOx

1970 Clean Air Car Race: 43 Universities.
Wayne State University (Ford Engineers) With Engelhard Catalysts Won the Competition With Perfectly Calibrated Open-Loop Carburetor.

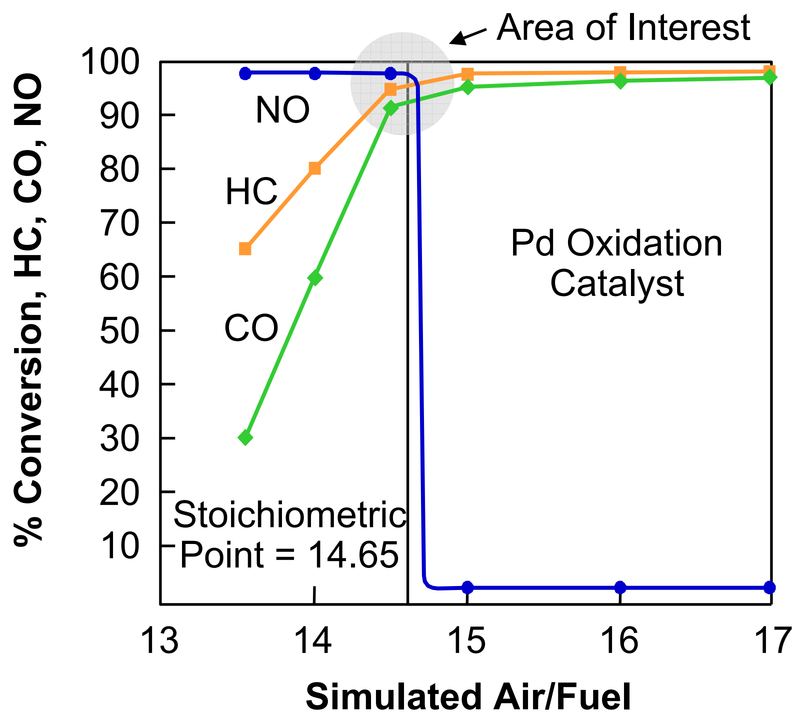
NO PRACTICAL SYSTEM CONCEPT TO CONTROL AIR OR FUEL TO STOICHIOMETRIC MIXTURE

Variables:

- Air Quality
  - Temperature
  - Barometric Pressure
  - Humidity
  - Altitude
- Fuel Quality
  - Winter/Summer Grade
  - Production Composition Variables
  - Oxygenates
- Engine
  - Wear, Durability
  - Idle, Accel/Decel, Full Throttle
  - Compression Ratio – Turbocharger; Air Filter

An Open-Loop System Could Not Work.

PRESENTATION TO AUTO MAKERS – 1970 TO 1973 HIGHLIGHTED AND BROUGHT TO THEIR ATTENTION



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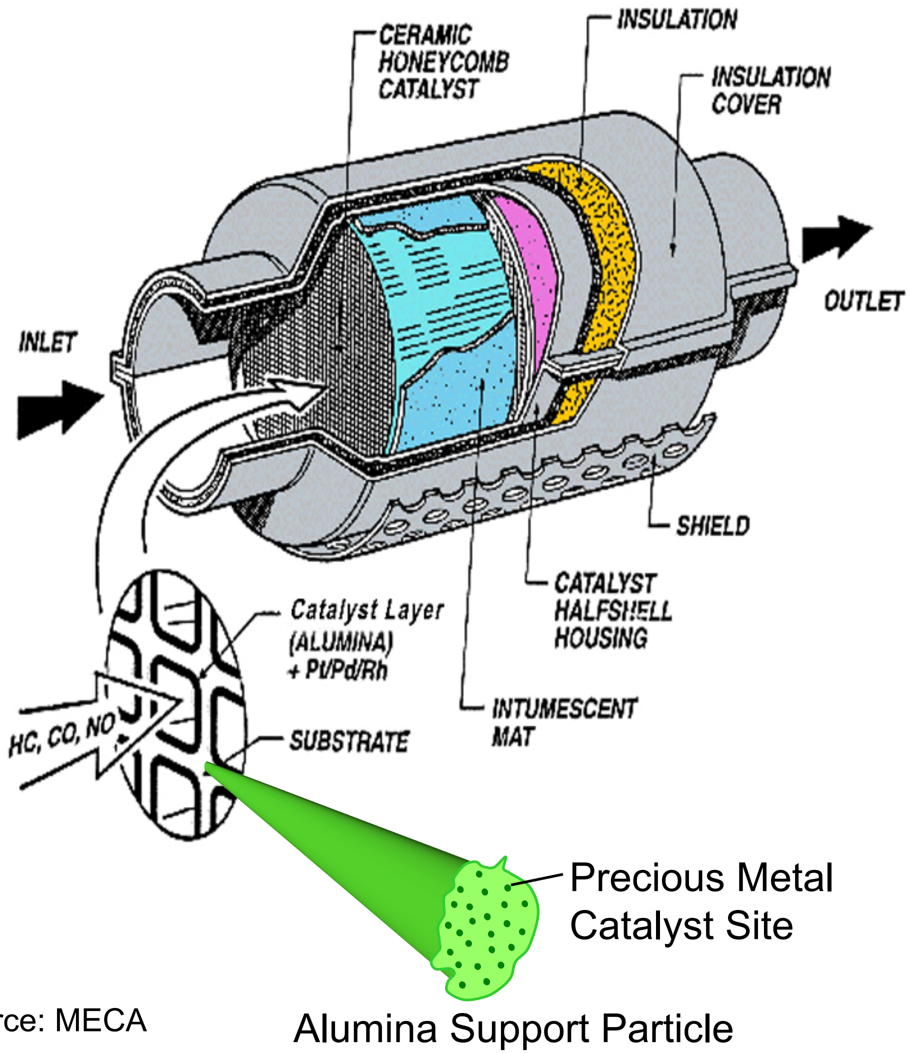
- If Stoichiometric Fuel Mixture Can Be Maintained, Then Engelhard Would Cooperate to Develop Catalyst
- Volvo Responded – 1974 Sent Volvo B21 Engine Equipped With R. Bosch K-Jetronic Fuel Injection System, Oxygen Sensor and Closed-Loop Feed Back Control

The Volvo/Bosch/Engelhard Team Was Formed.

LIGHT-DUTY EMISSION CONTROL SYSTEM

THE THREE-WAY CATALYST (TWC) SYSTEM
HOW IT FUNCTIONS

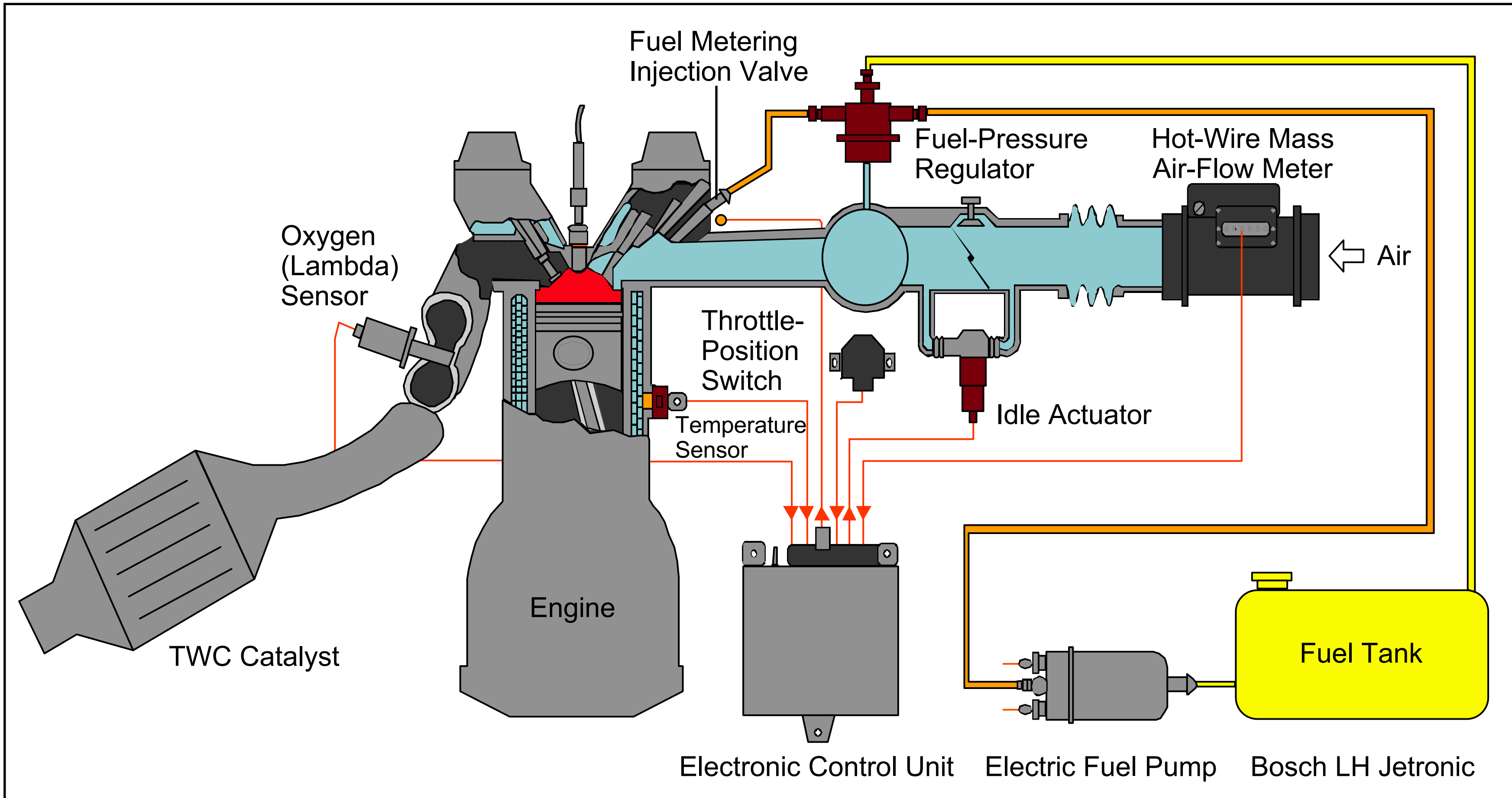
THE THREE-WAY CATALYTIC CONVERTER



Source: MECA

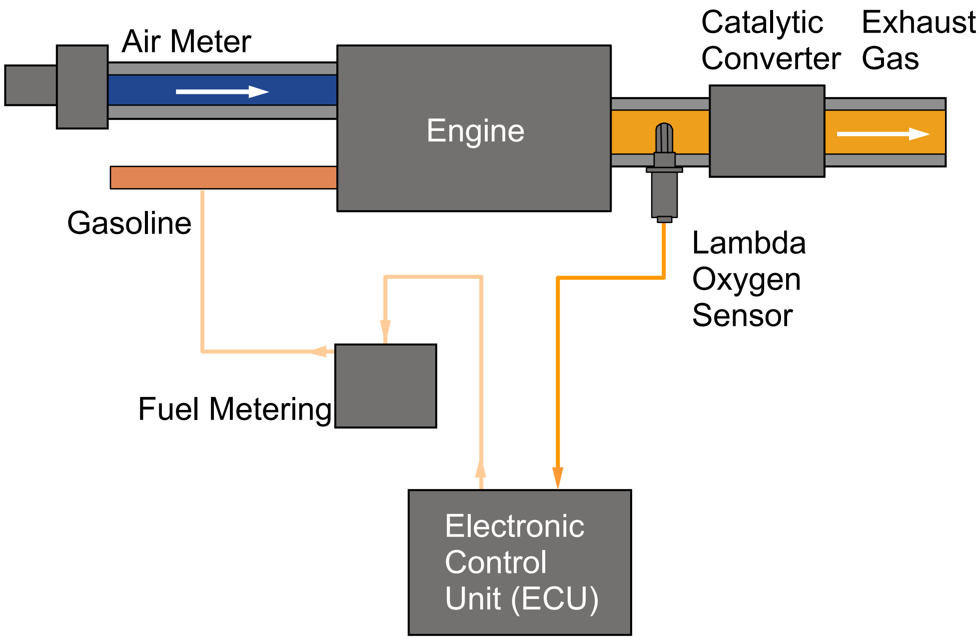
- Catalyst Layer Open Porous Structure With Support Materials of High Thermal Stability
- Mounting Materials With Improved Durability
- High Cell Density Ceramic or Metallic Substrates
- Insulation for Heat Management

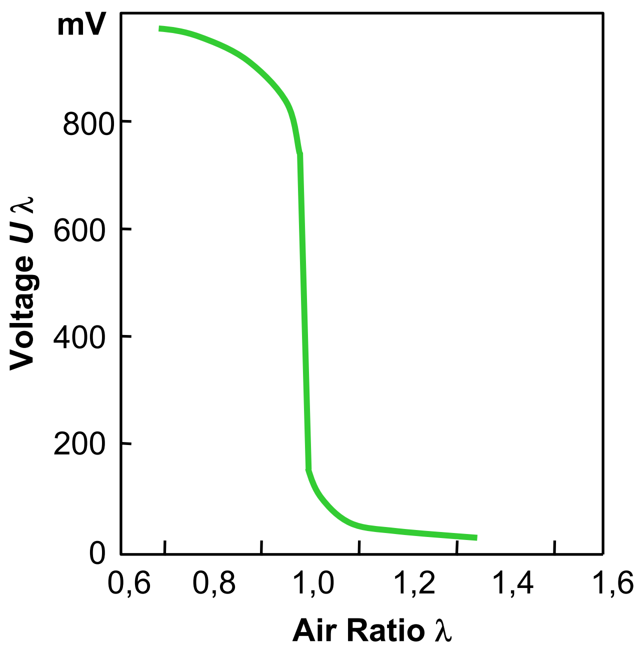
BASIC COMPONENTS OF THE TWC CLOSED-LOOP FUEL METERING SYSTEM



SCHEMATIC FOR THE LAMBDA CLOSED-LOOP CONTROL

THE AIR-FUEL INFLUENCES THE LAMBDA SENSORS VOLTAGE SIGNAL

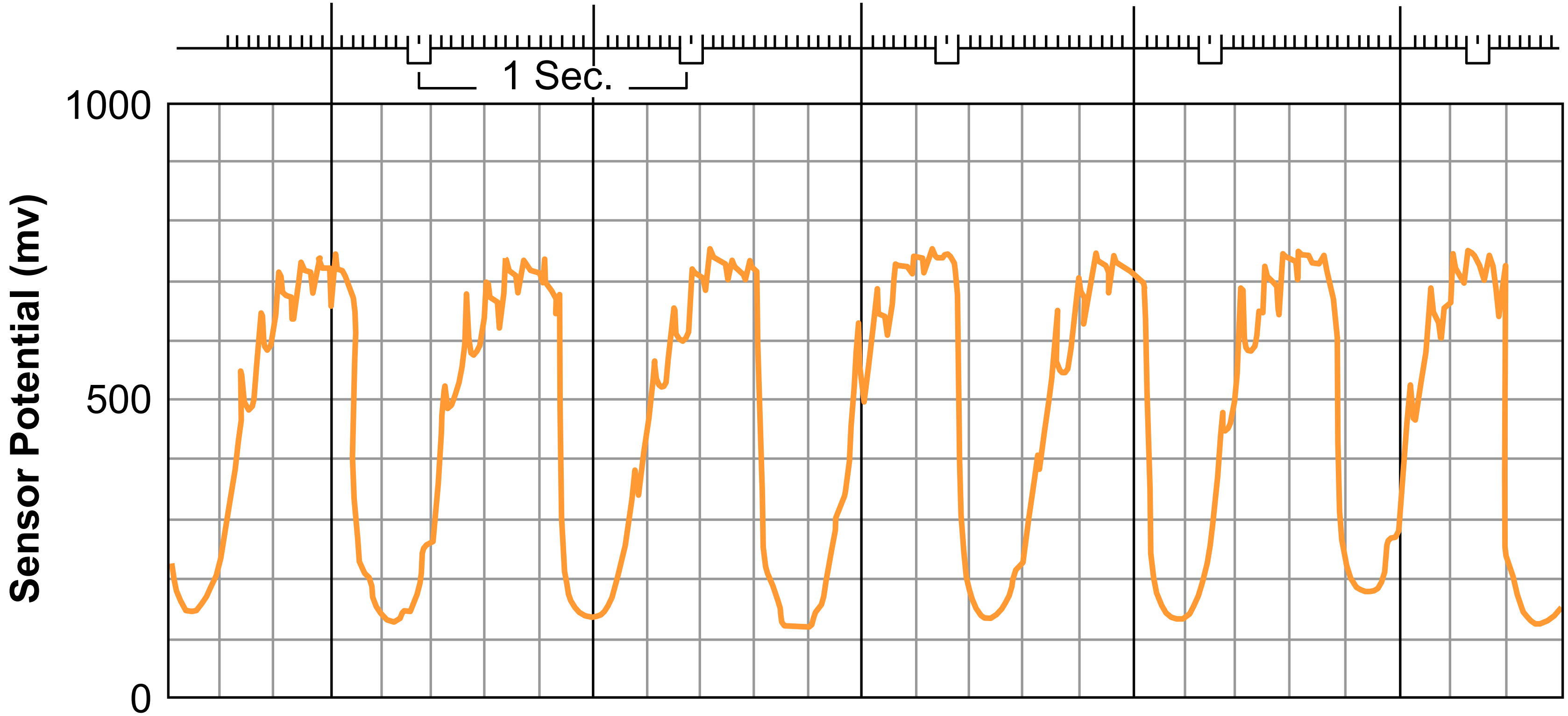




The Closed-Loop Fuel Metering System Maintains the Air/Fuel to the Stoichiometric Mixture

THE OXYGEN SENSOR CONTROLS THE AIR/FUEL MIXTURE TO AN *AVERAGE* MIXTURE

Sensor Voltage, 500 mv Set Point, 1600 RPM
Good Cylinder to Cylinder Fuel Distribution

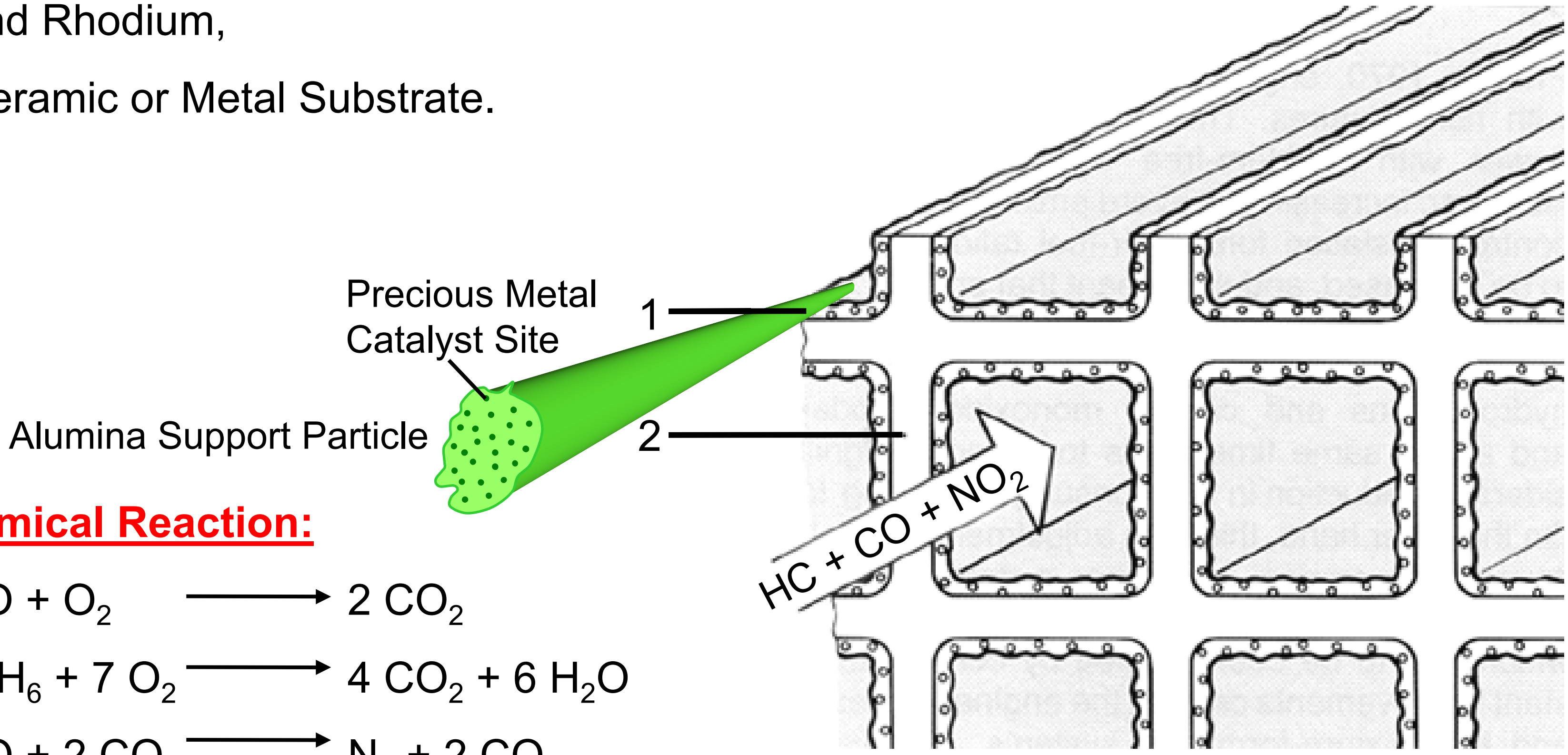


The Air/Fuel Mixture Is Not at Stoichiometric Very Long.

METHOD OF OPERATION OF THE THREE-WAY CATALYTIC CONVERTER

1 Catalyst Layer Containing Platinum and Rhodium,

2 Ceramic or Metal Substrate.



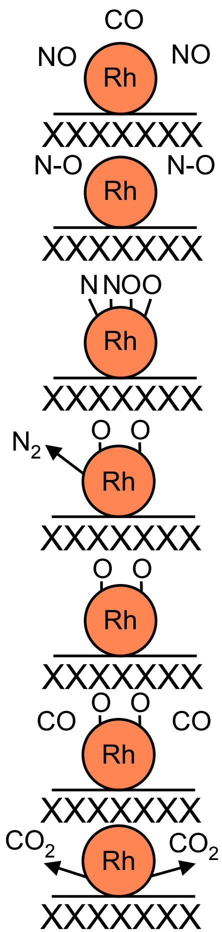
Chemical Reaction:

$2\ CO + O_2 \longrightarrow 2\ CO_2$

$2\ C_2H_6 + 7\ O_2 \longrightarrow 4\ CO_2 + 6\ H_2O$

$2\ NO + 2\ CO \longrightarrow N_2 + 2\ CO_2$

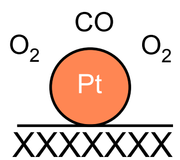
THREE-WAY CATALYST REACTION MECHANISM



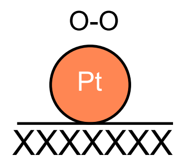
1. Clean Rh Surface
2. NO Molecules Attracted to Rh – Electron Bond Stretch
3. N Atoms and O Atoms Share Electron Bond With Rh
4. N Atoms Combine and Desorb as N_2 Molecules
5. Oxygen Atoms Remain
6. CO Molecules React With Oxygen Atoms to Form CO_2
7. CO_2 Desorbs Leaving a Clean Rh Surface

CO Is "Friend" and "Foe". Here "Friend" Reductant CO Removes the O That Is Stuck on Rh Surface.

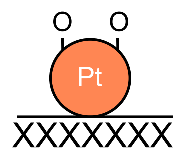
Pt SURFACE PROVIDES THE MEETING PLACE FOR OXIDATION REACTANTS

1. 

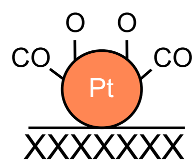
Clean Pt Surface

2. 

O_2 Molecule Attracted – Electron Bond Stretch

3. 

O Atoms Share Electron With Pt

4. 

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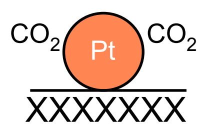
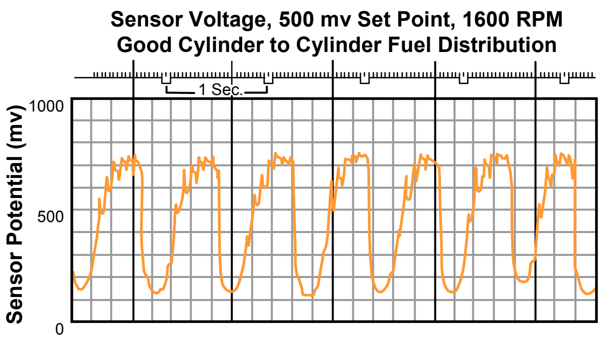
5. 

CO_2 Desorbs, Leaving a Clean Pt Surface

Excess "Foe" CO Is Oxidized to CO_2.

BASE METALS ASSIST BY STORING AND RELEASING OXYGEN

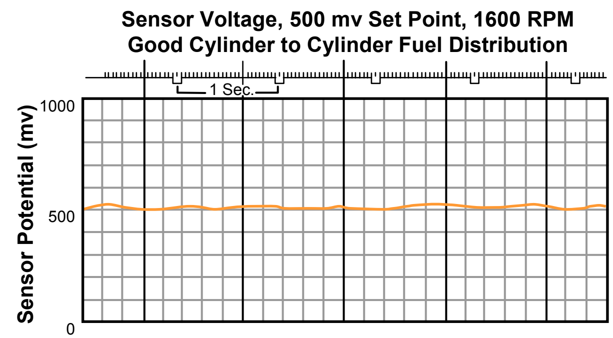


Catalyst Inlet

Lean – Too Much Oxygen

Rich – Insufficient Oxygen

Cerium Oxides (Ceria)



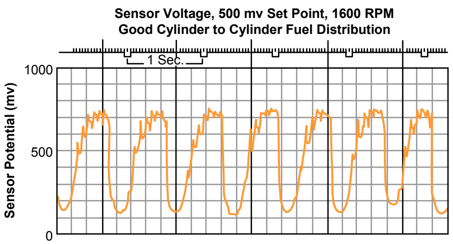
Catalyst Outlet

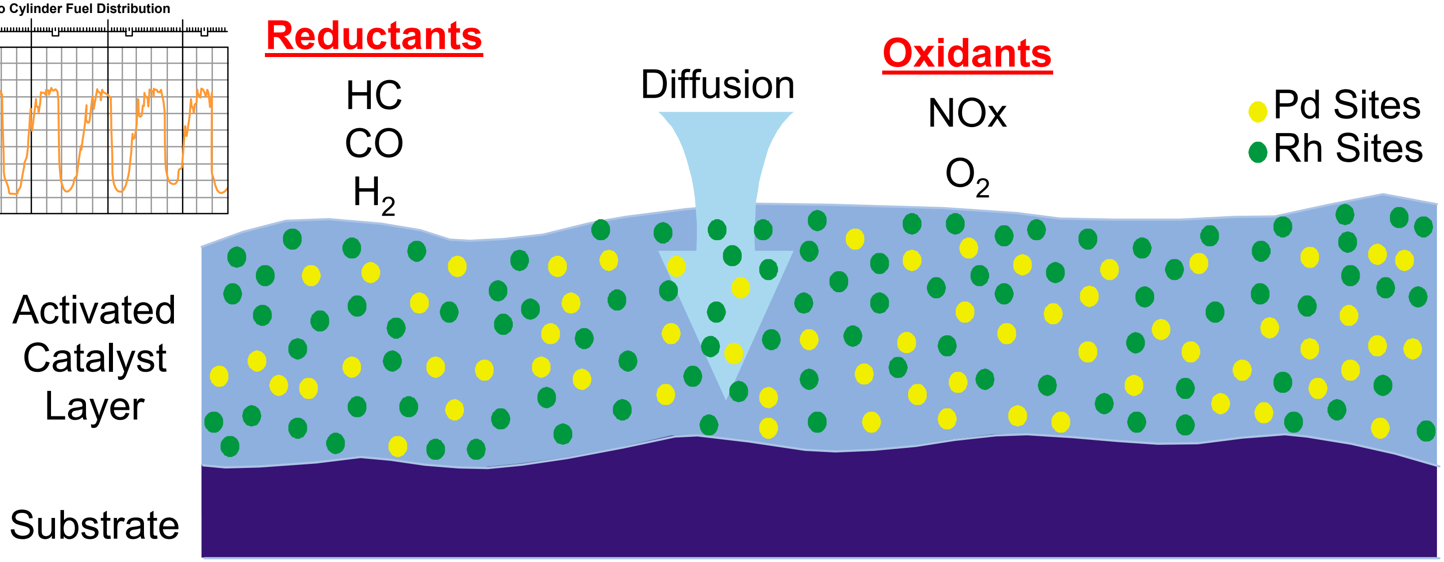
Lean $\overset{(+3)}{Ce_2O_3} + 1/2\ O_2 \longrightarrow (2)\ \overset{(+4)}{CeO_2}$

Rich $(2)\ \overset{(+4)}{CeO_2} + CO \longrightarrow CO_2 + \overset{(+3)}{Ce_2O_3}$

Ce_2O_3 Captures Excess O_2 That Would Escape the Tailpipe and Saves it for CO Oxidation When in Short Supply. The Act of O_2 Storage Enhances NO Reduction.

PALLADIUM AND RHODIUM FUNCTIONS INTERACT IN SINGLE LAYERED TWC CATALYSTS





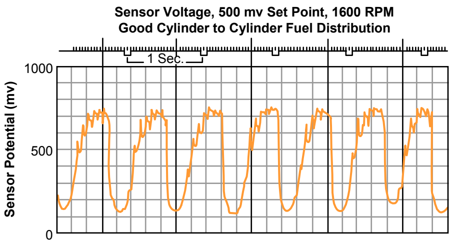
Competitive Reactions:

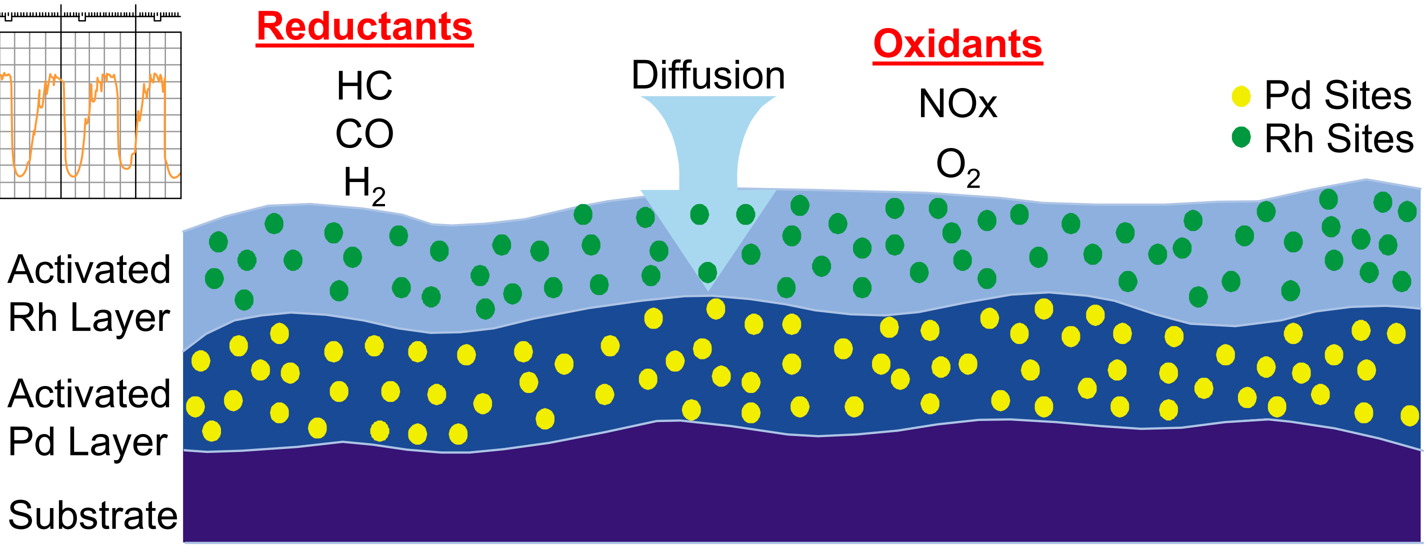
HC, CO, H_2 + O_2 $\longrightarrow$ CO_2 + H_2O

NO + Reductant $\longrightarrow$ N_2 + CO_2, H_2O

Reaction Rates Are Dissimilar. If Oxygen Consumes the Reductant, There Is Less Available for NO Reduction.

PALLADIUM AND RHODIUM FUNCTIONS SEPARATED IN DOUBLE LAYERED TWC CATALYSTS





Competitive Reactions:

$HC, CO, H_2 + O_2 \longrightarrow CO_2 + H_2O$

$NO + \text{Reductant} \longrightarrow N_2 + CO_2, H_2O$

A Separate Rh Layer Promotes the Interaction of NO With the Reductant.

CERTIFICATION TEST RESULTS – Outstanding Result for Volvo / Bosch / Engelhard Team and special Volvo calibration

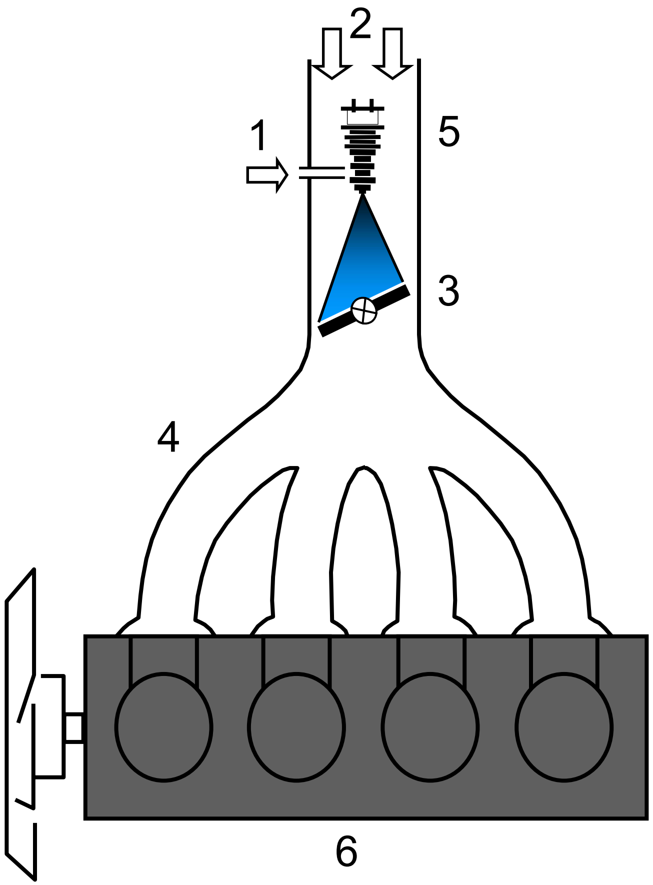
Volvo 4-Cyl MY 1977 California
April 27, 1976

		Emissions Grams/Mile Including Deterioration Factor		
		HC	CO	NOx
Regulation California 1977		0.41	9.0	1.5
Weight Class	Transmission			
3000	M5	0.205	2.72	0.207
3000	Aut	0.223	2.94	0.084
3500	M5	0.217	3.31	0.199
3500	Aut	0.169	2.38	0.168
Regulation U.S. Tier 1 1994		0.25	3.4	0.4

Conclusion: The Initial Volvo Equipped With Engelhard TWC Met the California 1977 Standards by Such a Large Margin That They Actually Meet the More Stringent Standards of 1994 and Later Years.

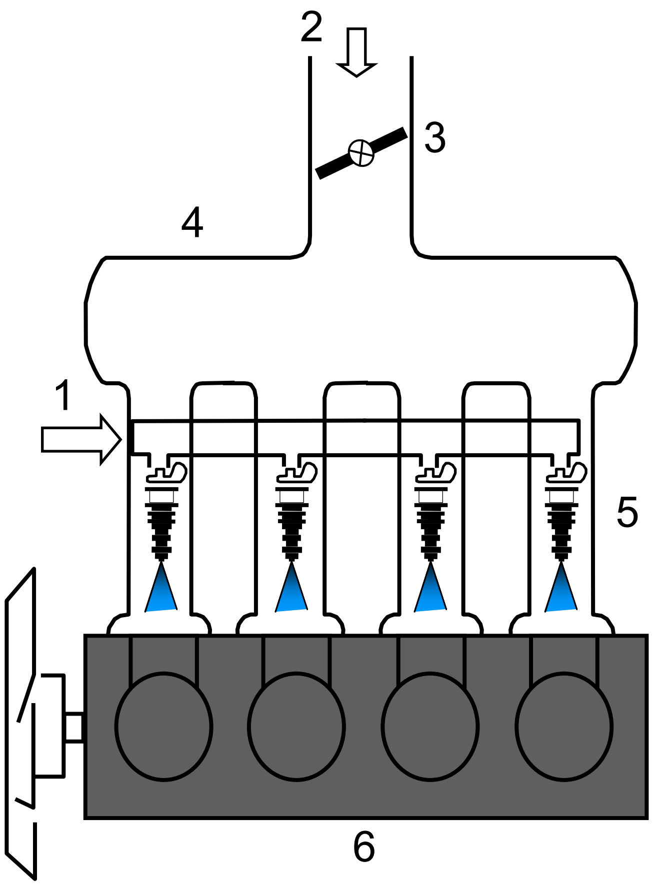
SINGLE-POINT FUEL INJECTION (TBI)

1 Fuel, 2 Air, 3 Throttle Valve, 4 Intake Manifold, 5 Injector, 6 Engine.

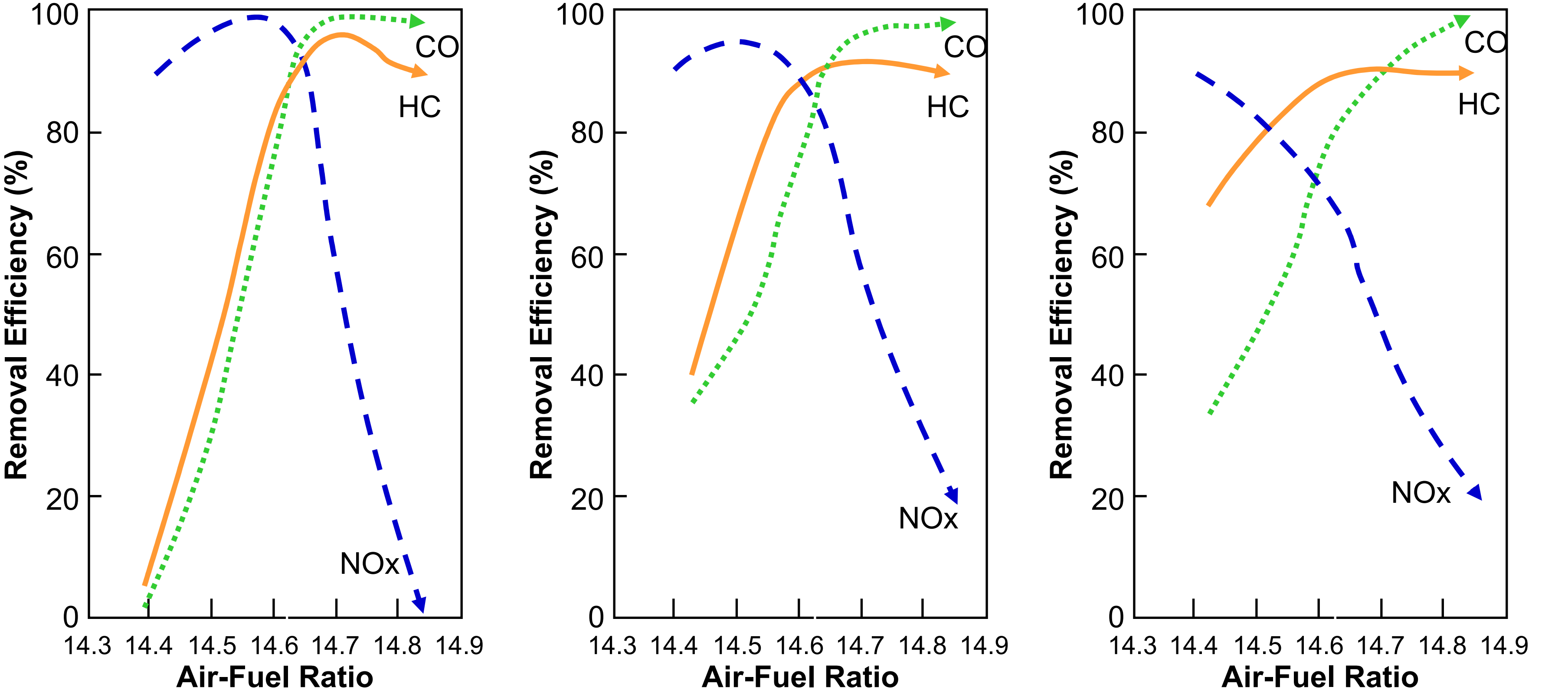


MULTIPOINT FUEL INJECTION

1 Fuel, 2 Air, 3 Throttle Valve, 4 Intake Manifold, 5 Injectors, 6 Engine.



THE QUALITY OF THE CLOSED-LOOP SYSTEM IS VERY IMPORTANT TO CATALYST FUNCTION



A. Closed Loop ±0.3 A/F @ 1.5 Hz (Multi-Point Fuel Injection)

B. Closed Loop ±0.5 A/F @ 1.0 Hz* (Single-Point Fuel Injection)

C. Closed Loop ±1.0 A/F @ 1.0 Hz* (Closed-Loop Carburetor)

*Simulated Utilizing Frequency Generator

Performance of Any TWC Catalyst Is Improved as a Function of Fuel Metering Control (±A/F and Frequency).

THREE-WAY CATALYTIC CONVERTER – RECOGNIZED AMONG THE TEN MOST IMPORTANT INVENTIONS IN THE HISTORY OF THE AUTOMOBILE

An Unique Success Story

- Minimized Environmental Impacts of the Automobile – Over 500 Million in Service
- Integrated Into Engine System – Other Forms of Emissions Control Would Not Be to One's Liking
- Healthier Lives for Billions of People – Literally Everyone
- Destruction Estimate –
  - 4 Billion Tons of Hydrocarbons
  - 4 Billion Tons of Oxides of Nitrogen
  - 40 Billion Tons of Carbon Monoxide
- Directly Associated With the Elimination of Atmospheric Lead (Pb)
  - Negatively Affects Children's Mental Health Development
  - Cause High Blood Pressure, Heart Disease and Organ Damage
  - A Pervasive Atmospheric Pollutant

SUCCESS STORY (Continued)

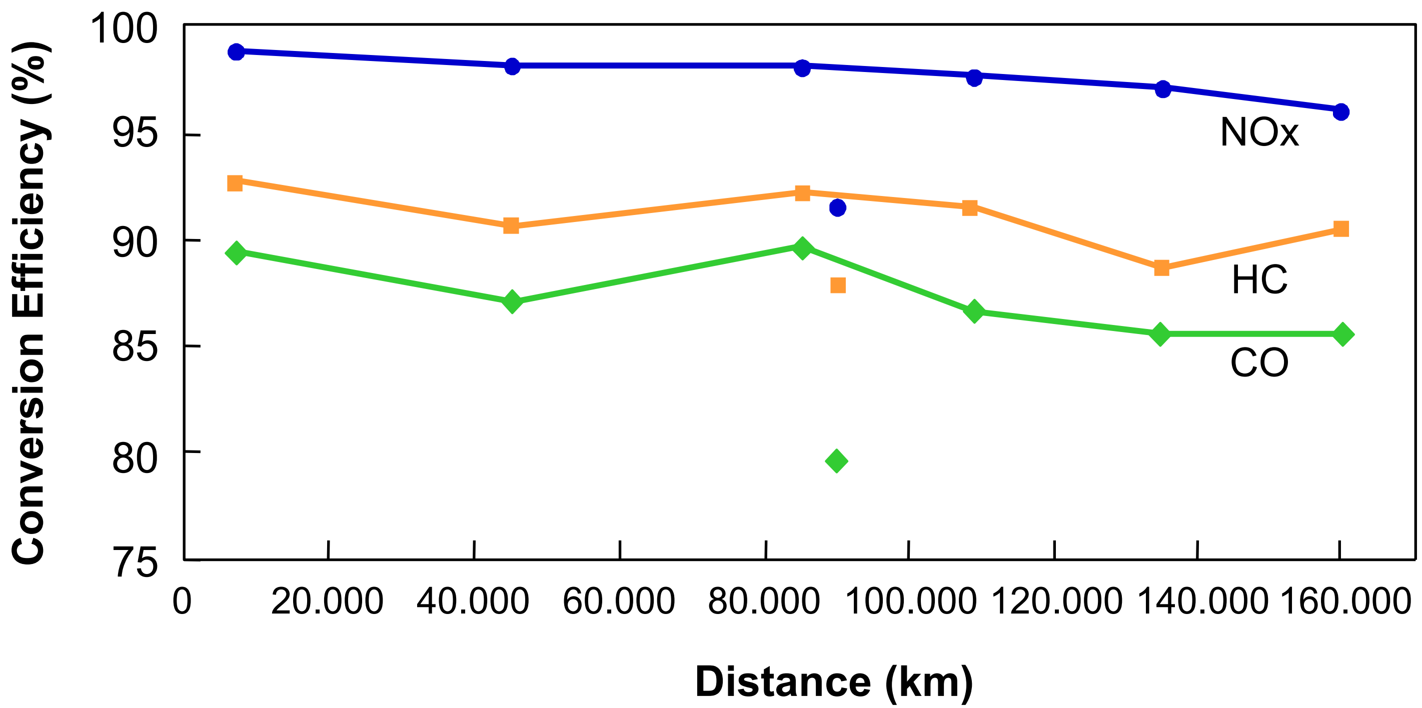
- Efficient and Durable (Mechanical and Function)
- Principle Means of Emissions Control – Without It, Ambient Pollution Would Be at Dangerous Levels
- Introduced On-Board Computers to the Automobile – Now Used for Many Other Functions Including Safety
- Passed secondary emissions scrutiny. No Sulfuric Acid mist or NO_2, no N_2O (only briefly with Pd TWC at start-up) or metal carbonyls. Whereas, in comparison, Oxidation Catalyst Formed 0.2 to 0.3 g/mile H_2SO_4 producing sulfuric acid mist. Also increased NO_2/NO ratio of total NOx

CONTINUED DEVELOPMENT HAS REACHED A HIGH LEVEL OF ACHIEVEMENT

- Proven, all types of driving, quick light-off
- Durable, Relatively Trouble Free. +30% performance with low S fuels
- U.S. EPA Standards
  - National Low Emissions Vehicle Standards
  - U.S. Tier 1 and 2
- California LEV 1, 2, 3, ULEV, SULEV, PZEV Standards – more can be achieved
- European Union Standards
  - Phase 2, 3, 4

World Countries Now Take Advantage of the Fully Developed Low Polluting Vehicles by Adopting Emission Standards and Unleaded Gasoline.

TWC CATALYSTS ARE DURABLE EVEN UNDER EXTREME USE CONDITIONS



Displacement: 4.2 L (290 hp)
Catalyst Specifications: Volume = 3.8 L
PM-Loading = 105 g/ft^3; PM Ratio = Pt/Pd/Rh 1/14/1
50 g/ft^3; PM-Ratio = Pt/Rh 5/1
EUROpean Testcycle Evaluation (MVEG-Cycle)

Thermal Resistance Improved
1000 to 1050 to 1100 to 1150^{o}C

Key Issues - 1

- Clean Air Act Amendments 1970. Technology forcing
- Clean Air Car Race: 43 University teams met Nixon proposed 1975 standard. Provided example for Congress and CAA Amendments of 1970. Statutory standards created ‘level playing field’ for all carmakers
- Unleaded gasoline: 1975 engines to operate on 91 RON (down from 96); no deliberate add of TEL; Average 0.016 g TEL/gal 1975 and 0.003 in 1976. But 0.050 g max standard retained too long!

Credit to Senator Muskie, Leon Billings, and Congress. Universities were a tremendous ally.

Key Issues - 2

- Negative Issues:
- Oil Industry scuttled UL/L pump price parity – UL pump price soared to $0.14 above L.
- EPA granted carmakers interim standards in 1973 – not ‘level playing field’.
- EPA scuttled automakers 1974 California trial of catalytic converter and unleaded gasoline. Required use leaded gasoline test fuel for certification!

Initially Cooperative auto industry lost focus.
EPA accommodation lacking.

Key Issues – 3. Post-Interim Standards

- 1975 GM adopted catalytic converter. Retuned engine gaining 28% FE and huge gain in engine performance
- Ford used catalyst on half of V8 and none on other half. But 1975 ½ adopted GM approach
- Chrysler used engine lean-burn adjustment with disastrous sales results

GM Ed Cole did the right thing – forever to his credit.
But! Interim Standards were an Auto Industry Mistake!

Key Issues – 4. Post-Interim Standards

- European carmakers generally adopted the catalytic converter
- Japanese carmakers (small vehicles, thus better FE) did not need catalytic converter to reach interim standards and used low pump price leaded gas. Major US sales penetration advantage during fuel shortages
- TWC penetrated slowly gaining uniform use with 1983 US Standards

Oxidation catalytic converter was easier to adopt than the TWC system

Key Issues – 5. Contender Technology

- Dual Bed Converter – NOx Reduction + Air + Oxidation Catalyst. Long heat-up time. Air pump cost + extra OC catalyst cost. Oxygen diffusion into NOx reduction catalyst
- Rich Thermal Reactor concepts. Air pump. Large volume. Thermal cycling degradation. Minus 30% fuel efficiency. Limited development path.
- Lean Thermal Reactor concepts. Required +1400 F – slow reactions. Negative engine performance
- EGR + Air and Oxidation Catalyst. Poor engine performance. Could not approach 90% reduction of NOx

TWC integrated into system. Not considered a 'hang-on' device

Barriers Overcome, Changes Required

Relevance to Global Warming
Planning now being faced

The Business Case
ENGELHARD HAD AN INVENTION

- 1963 Developed the PTX Monolithic Converter - Oxidation Catalyst
- Lead Poisoned the Catalyst

Potential Automotive Market Is Huge

Pave the Way Approach

- Put on Shelf? No!
- Select Proof Market - 1965
- Forklift Trucks and Mining Equipment
- LPG – and Unleaded Fuel
- Keep Eye on the Big One

Engaged Regulated Industry
AUTO INDUSTRY MOTIVATION BASED ON INCREASED AIR POLLUTION and GROWING PUBLIC CONCERN

- Ford Evaluated the PTX – Good Emission Results in Lab and Customer Test Car Fleets
- Low Volume and Weight, Any Orientation, and No Attrition
- Ford Decided to Approach Congress – Fall 1969.
  Reflecting Public and News Media Outcry for 'Detroit' Action
- GM President Ed Cole Became Industry Spokesman – Outstanding Engineer. Asked for Unleaded Gasoline and Strict Auto Emissions Regulations
- President Nixon (2/10/70) – Set 1975 (HC & CO) and 1980 (HC & CO & NOx) Auto Emission Standards Proposal

Tough Action by Congress –
CLEAN AIR ACT AMENDMENTS OF 1970

- Counter Political Force – Oil (TEL) – Wall St Jrl
- NAPCA – Conceive Clean Air Car Race of 1970
- 43 Universities Participate – MIT to EPA Ann Arbor to Cal Tech
- Unleaded Gasoline, LPG, NG, Diesel Fuels – SI Engines, Gas Turbine, Hybrid Electric, Diesel
- All Met the Nixon 1975 Emission Recommendations
- September 1970 – Class Winner Cars on Capitol Steps – College Kids Can Do it, Therefore…. All used a catalytic converter!
- 'Muskie' Standards Pass – 90% Lower HC, CO and NOx
- Emission Control Technology Needed – a Market Created

But Compromise Occurred
AUTO INDUSTRY REVERSAL – PETITION FOR SUSPENSION

- Engelhard Ran Ford Torino for 50K Miles – Met 1975 Standards
- Engelhard Took Strong Position That Catalytic Converter Was a Credible Candidate
- U.S. EPA Granted ‘Interim’ Standards
- After Hearings Were Over, GM Announced it Would Use the Catalytic Converter for 1975 MY – Obtained 28% Improvement in Fuel Economy. Others Followed – Ford, European, and Chrysler
- Japan Car Makers Did Not Use Catalytic Converter Until 1979 and Used Cheaper Leaded Gasoline
- Market postponed

NATIONAL ACADEMY OF SCIENCES CONSULTED

Is the Catalytic Converter Technology Viable?

- Not Unanimous in Favor
- Do Within Engine
- Too Fragile
- An Interim Solution
- The Engelhard 50K Mile Durability Run Provided Evidence to the Contrary. Still NAS View Was a Tough Hurdle

PUBLIC – Dim View

- Vehicles From 1970 Through 1974 Had Poor Performance
- EGR – Experience Was Very Bad
- Dieseling After Key-Off
- Fuel Economy Most Often Less Than 10 Miles/Gallon
- Therefore Viewed the Catalytic Converter as More of the Same

  \- - - -

- 1975 MY improved FE and performance – overcame some sentiment
- 1977-8 MY proved the TWC system
- But, we almost lost the Leaded Gasoline War in early Reagan years

INTERNAL COMPANY QUESTIONS

- A Three-Year Project – Auto Companies Will Engineer Out
- Heavy Investment
- Other Projects to Work on – This Delay Impedes Future Growth
- GM – <Over 5.0 Million Vehicles/Year. 40 candidate companies

TECHNOLOGY HURDLES

- In-Use Driving Scenarios for >100 Million Vehicles
  - Senior Citizen
  - Teenager
  - Trailer
  - Safety – Overheating and Fire Question
- Environmental Extremes
  - Minnesota
  - Death Valley
  - Sea Level to Continental Divide
  - Water Condensation – Freezing - Flood
  - Saltwater Marine
- Reliability
  - Engine Misfire
  - Ignition and Wiring
  - Lean/Rich A/F Mixture Extremes
  - Fuel Saturation

PRODUCT

- Ford and European Carmakers (marketing in US) Wanted PTX
- GM Wanted Pellet Catalyst
- Therefore, 2 Sample Shops, 2 Catalyst Development Efforts → Leading to 2 Plants

MANUFACTURING – Oxidation Catalyst

- Experience: Hand Prepared, White Gloves Approach in Units of 10 to 20 for Fork Lift Business
- Initial PTX Plant Capacity – 500K for California 1974 – Start-Up 1/73
- 2nd Huntsville PTX Plant – 2 MM for U.S. 1975 – Start-Up 1/74
- Bead Plant – 425K Cubic Feet for 1975 – Start-Up 1/74

THREE-WAY CATALYST IN 1977 INCORPORATED A HUGE CHANGE - Internal

- Entirely New Manufacturing Process. Replaced Initial Process
- Emissions Control Potential Beyond What Standards Required
- U.S. and Japan Auto Industry Only Used Carburetor Fuel Metering
- Worked With Carburetor Companies to Modify toward Closed-Loop Feed-Back System
- TWC Bead Product for General Motors

THREE-WAY CATALYST IN 1977 INCORPORATED A HUGE CHANGE – External Established Companies

- Threatened and eventually displaced the established automotive carburetor industry
  - But overcame traditional limitations:
    - Vertical height downdraft – visual, safety, hood streamline
    - Inlet manifold awash with gasoline
    - Fuel flow momentum and inertia during transients
    - Independent air and fuel flow measurement
- Electronic ignition displaced the traditional ignition distributor
  - Provided reliable ignition and overcame wet electrical shorts, contact wear, durability, calibration, high voltage limitations and saw-tooth fuel efficiency issues

SUPPLY

- Convince Industry of PM Supply
  - Proven Reserves
  - Sufficient Processing
  - Supply Train – Security
- Raw Materials Supply
  - 2nd Sources

ORGANIZATION AND MANAGEMENT SYSTEM

- Too Much to Do – Too Little Time
- Auto Industry Helpful – But!
- Company Not a Major Auto Industry Supplier
- Used Consultants Skilled in the Various Areas
  - Plant Location
  - Business Plan
  - Organization
  - Management System
  - Process
  - Process Control
  - Statistics and Statistical Process Control
  - Equipment Design and Specification
  - Employee Search
  - Supplier Quality Certification and SPC

WHAT WE KNEW THEN – 1977 THROUGH 1980's

- TWC durable but needed improved hydrothermal resistance for close coupling
- TWC System compatible with all SI fuels – maintained stoichiometric A/F. CH_4 a little tricky.
- Corrected for ambient temperature and pressure
- Compatible with T/C designs, EGR, decel fuel-cut
- Fuel injection response (deviation and frequency) improved TWC performance
  - Single-point
  - Multipoint
  - Multipoint Sequential
  - Learning capability
  - Potential for cylinder to cylinder A/F control

Clear Development Path Open for Continuous Development – Stringent Standards

TWC ADOPTION BY EUROPEAN COUNTRIES WAS DIFFICULT

- Embraced by Germany, Sweden, Denmark, Netherlands, Austria -
- UK considered it a US Mistake – favor Lean Burn
- Europe divided on leaded / unleaded. Myths prevailed
- German carmakers appreciated the technical advance. Provided TWC cars with unleaded gasoline along major routes to south
- UK Parliament switched in 2 days – children mental heath impaired by airborne Pb along highways (now known as TEL source, combustion engine generated, and inhaled Pb nanoparticles)
- EU organized Euro standards and timetable

Clear Development Path Open for Continuous Development – Stringent Standards

CONCLUSIONS and OPPORTUNITIES

The Three-Way Catalytic Converter Success Story

- Phenomenal Invention
- Destroyed:
  - 4.0 Billion Tons of Hydrocarbons
  - 4.0 Billion Tons of Oxides of Nitrogen
  - 40.0 Billion Tons of Carbon Monoxide
- Instrumental in Global Elimination of Atmospheric Lead
- Other Forms of Exhaust Emissions Control Were Sorely Lacking in Comparison
- Positive Impact: Societal, Political and Environmental
- Now Used Globally – Almost All Light-Duty Vehicles
- Additional 8 to 12% improvement in fuel efficiency
- Cleaner Air for Billions of People

The 3-Way Catalytic Converter Has Provided Direction - 1

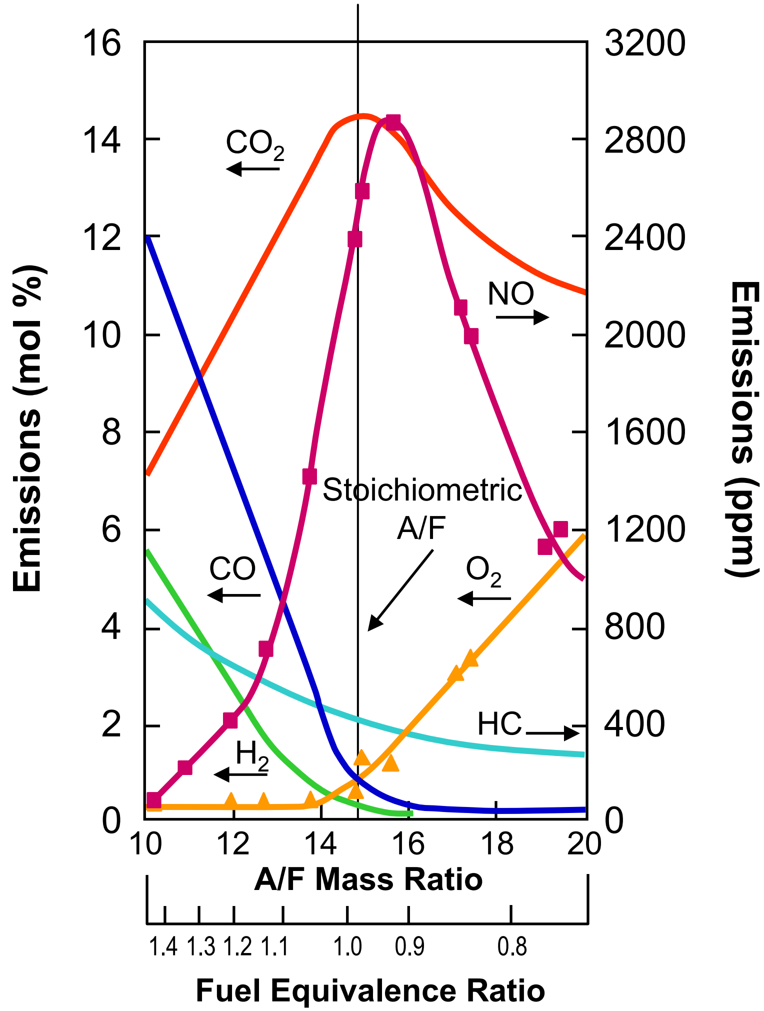
- Electronic engine management utilizing the systems approach: Calibration: a) power and performance; b) specific fuel consumption (CO_2); c) emissions control. [US opportunity missed past 12-15 years]
- Altitude and humidity compensation - impact on fuel consumption
- Fuel flexible from 100% gasoline to 100% alternate fuel
- Variation tolerant, i.e. oxidants - minimize regional fuel quality impacts
- Sulfur tolerant – no SO_3 produced – ULS improves performance ~ 30%
- Variable compression ratio: utilize octane effectively = smaller engine = low friction losses and less part throttle = fuel efficiency = while maintain emissions control
- O_2 sensor information – each cylinder A/F control

The 3-Way Catalytic Converter Has Provided Direction - 2

- Tough standards provide room and incentive for invention
- No current solution – R&D investment justified
- No 'wishy-washy' averaging, banking, trading to undermine business decisions. [Unproven method – serves to extend current situation]
- Clear business case
- Obstacle 'leaded gasoline' was dealt with. But rose again several times. Leaded gasoline myths still prevail
- Health issue #1. Catalyst poison #2.
- Clean sheet of paper. [Not 'group grope' with all stakeholders]
- Public interest be strongly & proportionately represented - ombudsman

THE AIR/FUEL MIXTURE HAS A PRIMARY EFFECT ON BASE ENGINE EMISSIONS

Recall this slide
Optimum:
Fuel
Power
Emissions



THREE-WAY CATALYST CLOSED-LOOP FEED-BACK SYSTEM ALLOWS ENGINE CALIBRATION TO OPTIMIZE POWER, FUEL ECONOMY AND EMISSIONS CONTROL – Opportunity #1

The Electronic Controlled Engine Systems Approach

- Maximum Power achieved with A/F ~ 13.5/1
- Minimum Fuel Consumption achieved with lean A/F approaching 20/1 lean limit
- Maximum HC, CO, NOx Emissions Control achieved stoichiometric ~ 14.65/1
- Engine calibrations optimize each depending on engine mode of operation
- Engine improvements of various types provide further optimization opportunity
- Somehow ‘fuel economy’ improvement became untouchable by ban of CAFÉ changes each year, for over ten years, in the Federal budget
- During that period of time, no improvement in fuel efficiency fell out of engine improvements

Return to the Systems Approach is Justified.
CAFÉ Standards or equivalent

Relevance to Global Warming Gases (CO_2) and Fuel Consumption Opportunity #2

Fuel flexibility would provide US national advantage

- Anticipate future fuels. Associated engine control / fuel metering to optimize: power, emissions and specific fuel consumption
- Design future engines be fuel flexible while retaining stoichiometric A/F
  - For various fuels and fuel mixes
  - Via incorporation of electronic engine control maps for each fuel; or via continuous engine / fuel / fuel metering control sensors
  - Materials compatibility: gaskets, lines and wetted surfaces
- Study retrofit of existing current engines to maximize fuel flexible capability and fuel efficiency. Establish a whole new industry for this purpose

EXHAUST THERMAL ENERGY CURRENTLY WASTED
Opportunity #3

Exhaust Thermal Energy can Generate Electric Power

- Engine generation of electrical power is relatively inefficient
- Sufficient exhaust thermal energy exists to generate electrical power more efficiently – turbo-alternator or other
- Result smaller engine calibrated for drive train only = lower friction and less part throttle = improved fuel economy
- Must be compatible with T/C and EGR requirements
- Reference: BMW think tank – Atlanta, GA

Clean, Low Global Warming Diesel Engine. Opportunity #4-1
But First, Diesel Engine Emission Standard Needs Correction.

Fuel Efficient Diesel Engine PM soot and NOx emissions have negative health and global warming issues.

- Current PM mass emission metric is insufficient to assure clean diesel engine
- Must add particle count limit to <u>assure</u> elimination of toxic solid insoluble lung alveoli penetrating nanoparticles – the most serious health issue.
- PM mass by gravimetric system cannot distinguish particle size fractions. Ref: EU PMP study
- Black soot particles implicated in global warming – size fraction impact?

Clean Diesel Engine - 2

Proven Solution for Filtration of PM and Disposal by Regeneration

- Diesel particle filters rated Best Available Control Technology (BAT) for all solid PM fractions – also remove liquid PM (lube oil) fractions
- BAT DPF removes solid particles (large and ultrafine) under all filter conditions and engine operating conditions – efficiency 99.9+% solid nanoparticles and 95% elemental carbon mass concentration.
- BAT DPF proven durable without any deterioration in filtration efficiency. Proven long life.
- BAT DPF eliminates both health and global warming issues

Clean Diesel Engine - 3

DPF PM Filtration is a Unit Operation quite different from the TWC Catalytic Converter

- BAT technology must be used for toxics / carcinogens
- Filtration performance assured with measurements under extreme filtration conditions. No in-use deterioration permitted. Note: Unlike TWC where DF is permitted.
- BAT DPF removes solid particles (large and ultrafine) under all filter conditions and engine operating conditions – efficiency 99.9+% solid nanoparticles and >93% elemental carbon mass concentration
- Proven long life. Easy to assess in-field use
- Cannot permit Non-BAT stochastic ‘open filters’ (sic)

Clean Diesel Engine - 4

Regeneration of DPF is Distinct and Separate Unit Operation

- Many ‘Regeneration’ techniques have been developed
- OEM designed active techniques assure regeneration under all conditions of engine use
- Peugeot example < over 3 million vehicles with fuel borne catalyst and internal active regeneration

Clean Diesel Engine - 5

NOx Emission Control Under Intense Development

- Selective catalytic reduction (SCR) of NOx with NH_3 (urea source)
- NOx Adsorber system
- Exhaust gas recirculation
- Combinations of DPF, DOC, and SCR

THANK YOU

John J. Mooney

Discussion

Questions and interactive comments