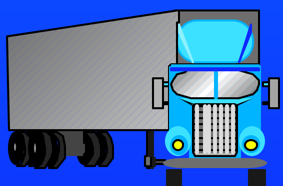
Current and Future Technology For Controlling Diesel Exhaust

Understanding Urban Air Pollution and the Role of Diesel Exhaust

Delhi, India November 6-11 2000



Overview

- Diesels Major Source of PM & NOx
- Serious Concerns Remain
  - PM Health Effects
  - PM Toxicity
  - Ozone Health Effects (NOx)
  - Secondary PM2.5 Formation (NOx)
- Major Regulatory Efforts Underway
- Fuel Sulfur Increasing Focus
- Retrofit of Existing Vehicles Growing

Features of Diesel Powered Vehicles & Their Emissions

- ***Higher Fuel Economy than SI Gasoline***
- ***Lower Emissions of CO_2 and Greenhouse Gas Contribution***
- ***Lower Emissions of Carbon Monoxide and Gas Phase HC's***
- ***Higher Emissions of NOx & Particulates***

Ozone

Soluble Organic Fraction (SOF)

VOC's

Insolubles

Carbon Soot, Sulfate

Total Diesel Hydrocarbon Emissions

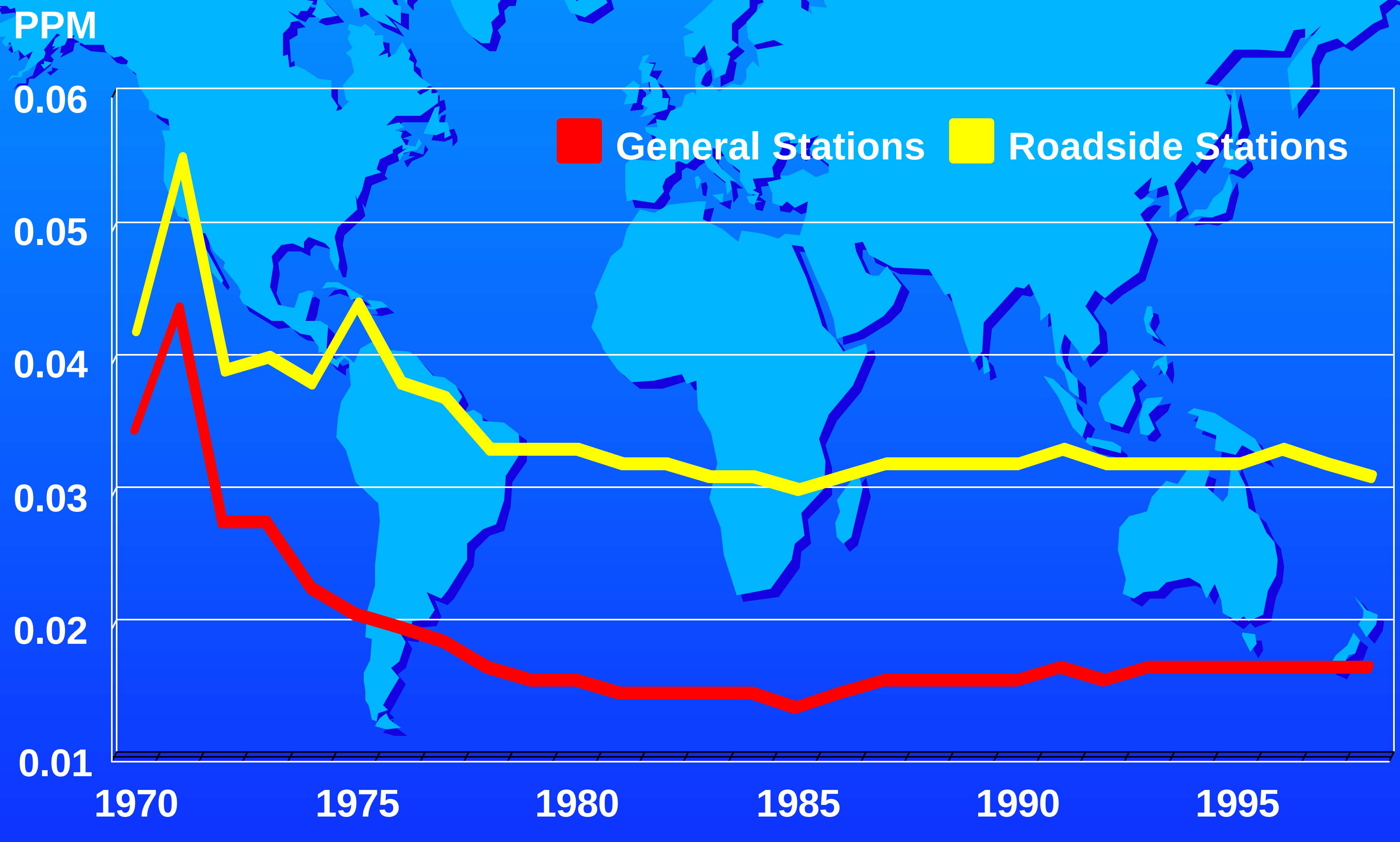
Serious Ozone Air Pollution Problems Remain in the US

- ~62 (1-hr) to 125 (8-hr) Million People Lived in Non-Attainment Areas in 1999
- EPA's Forecast For 2007
  - 28 Ozone Non-Attainment Areas
  - 80 Marginal Areas
  - 129 Million People Living in These Areas

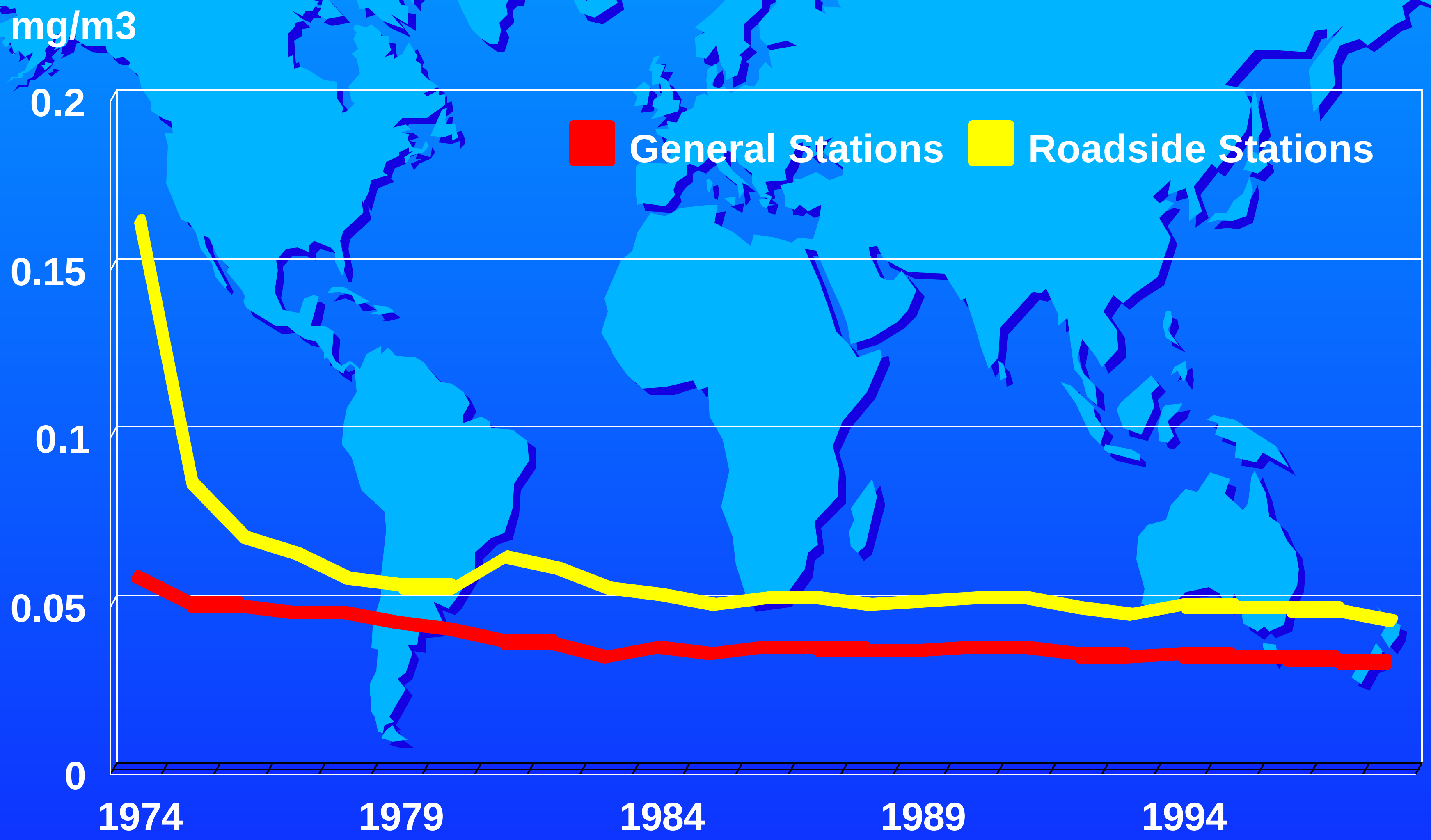
Ozone Problems in Europe in 1998
Number of Days over the Limits

	Indicative Ceiling	Danger Limit (360 ug/m3)
# of Days	10-60	8

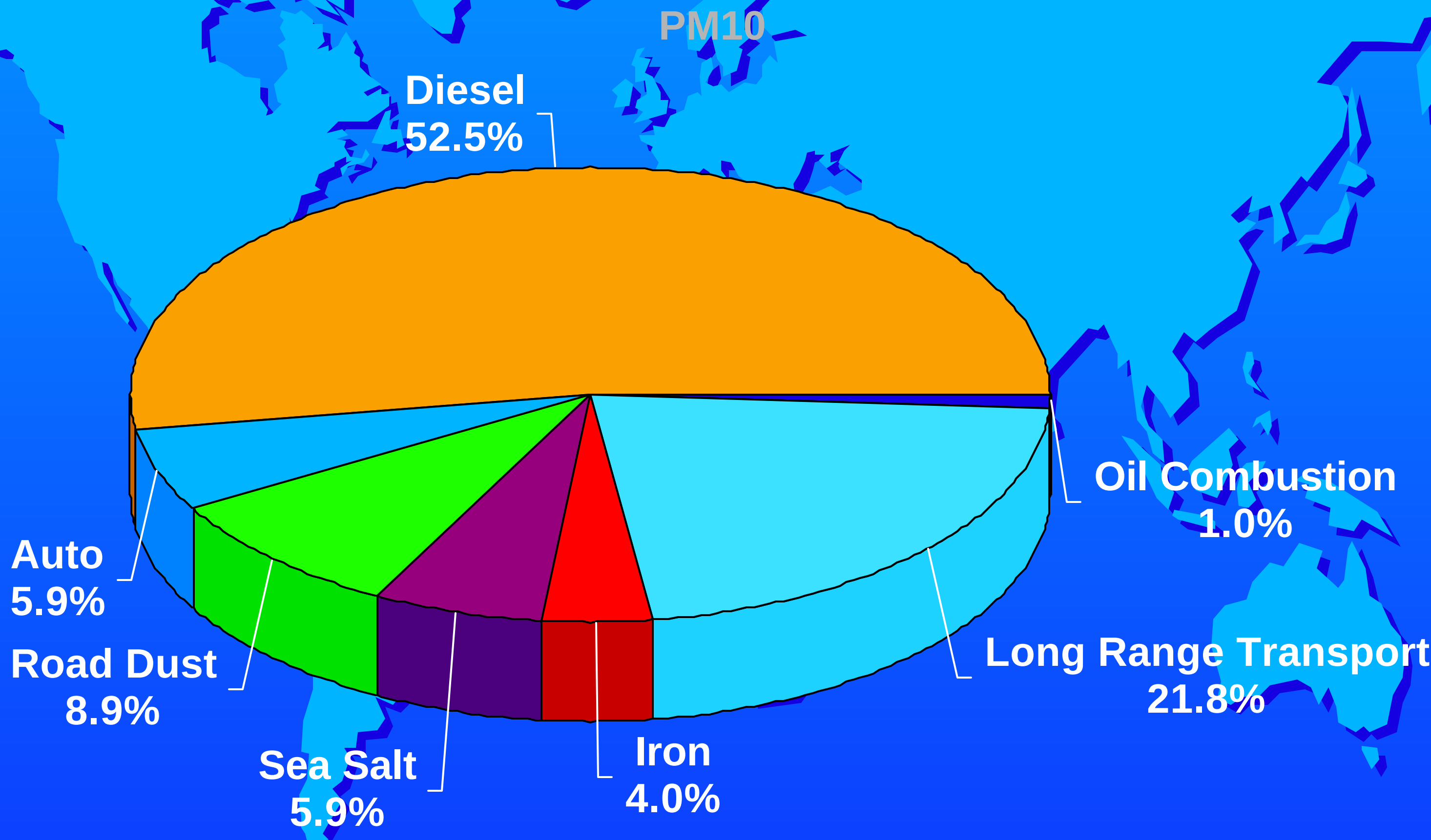
Nitrogen Dioxide Air Quality Trends In Japan



Suspended Particulate Matter Air Quality Trends In Japan

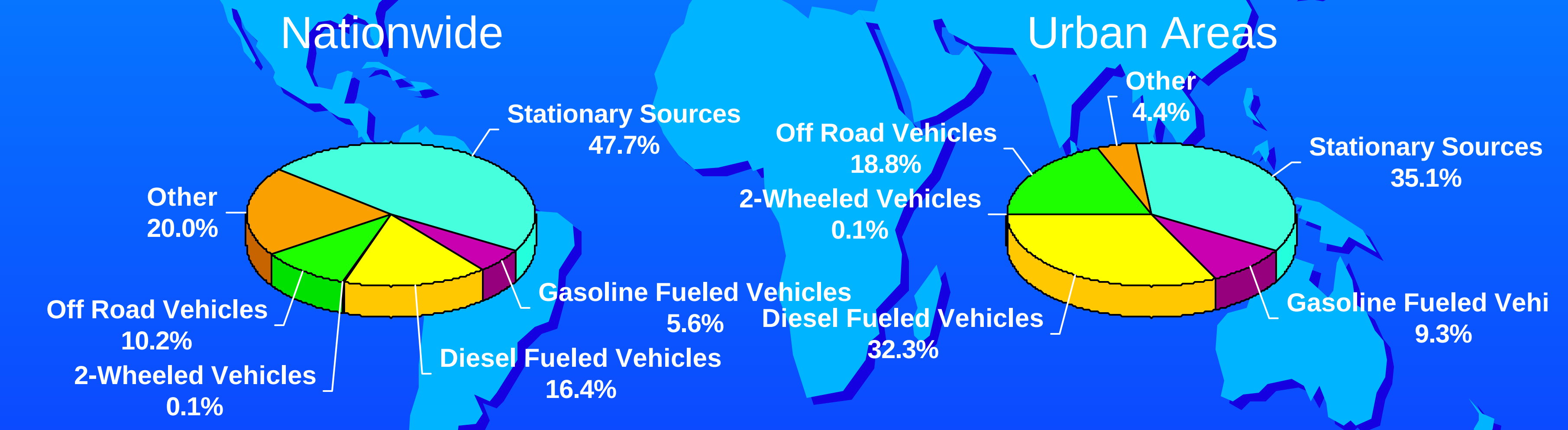


Average Source Contribution To Midtown Manhattan Site

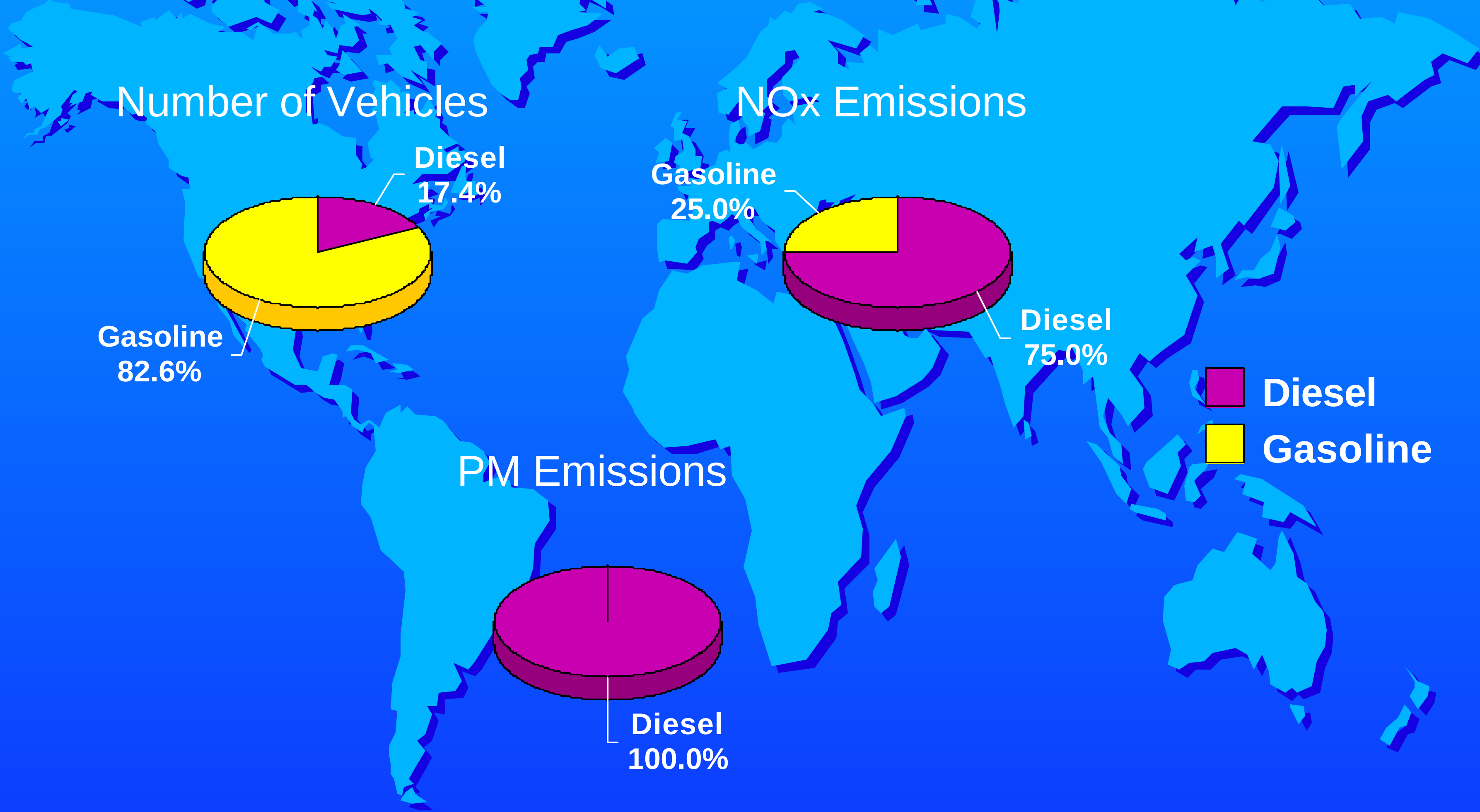


Chemical Mass Balance
AWMA 94-WP91.01

NOx Emissions From Various Sources in Japan (Tons/Year)



Emissions From Vehicles in Japan



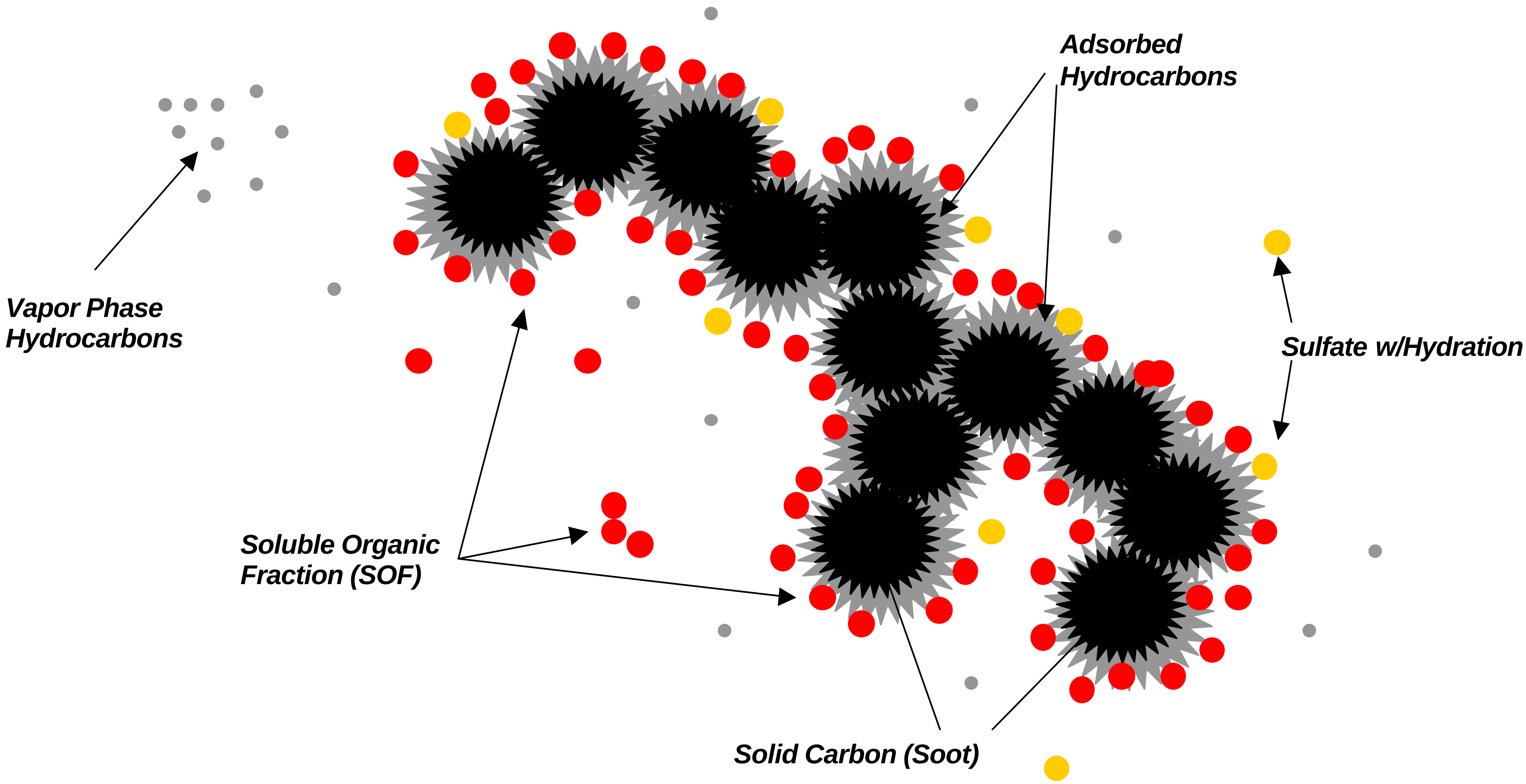
Source: Interim Review
July 28, 2000

PM10 Study Just Released in Europe (Lancet Medical Journal)

- ~6% of all deaths from PM10
- ~40,000 deaths per year in Austria, France, Switzerland; 2 times traffic fatalities
- Motor Vehicles responsible for ~50%
- People in Cities die about 18 months earlier than they would otherwise
- over 300,000 cases of chronic bronchitis; 500,000 asthma attacks; 16 million lost person days of activity
- Health costs from pollution from traffic ~1.7% of total GDP

Schematic of Diesel Particulate & Vapor Phase Species

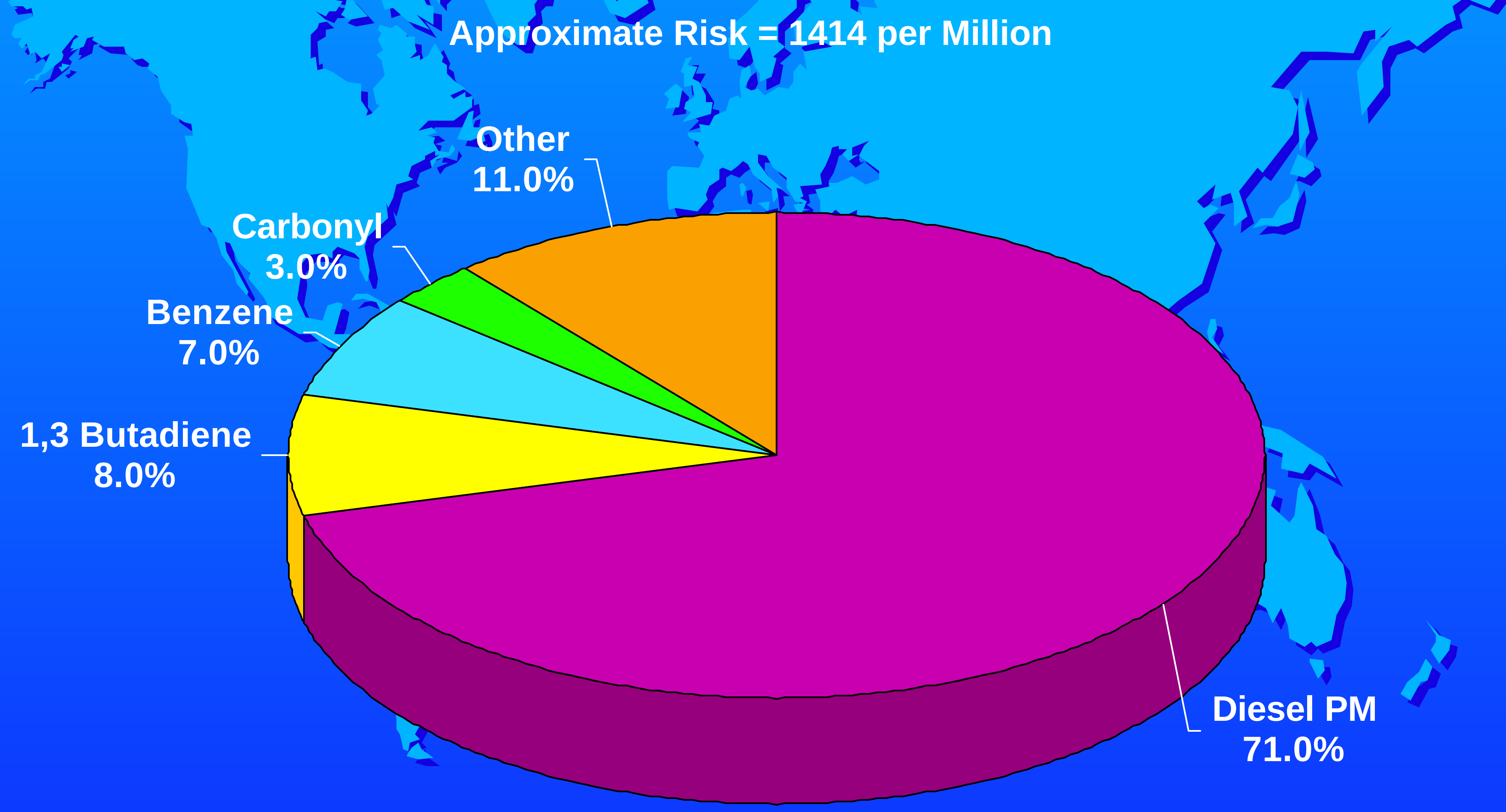
(from Sawyer & Johnson)



1998 CARB Assessment of Diesel PM Toxicity

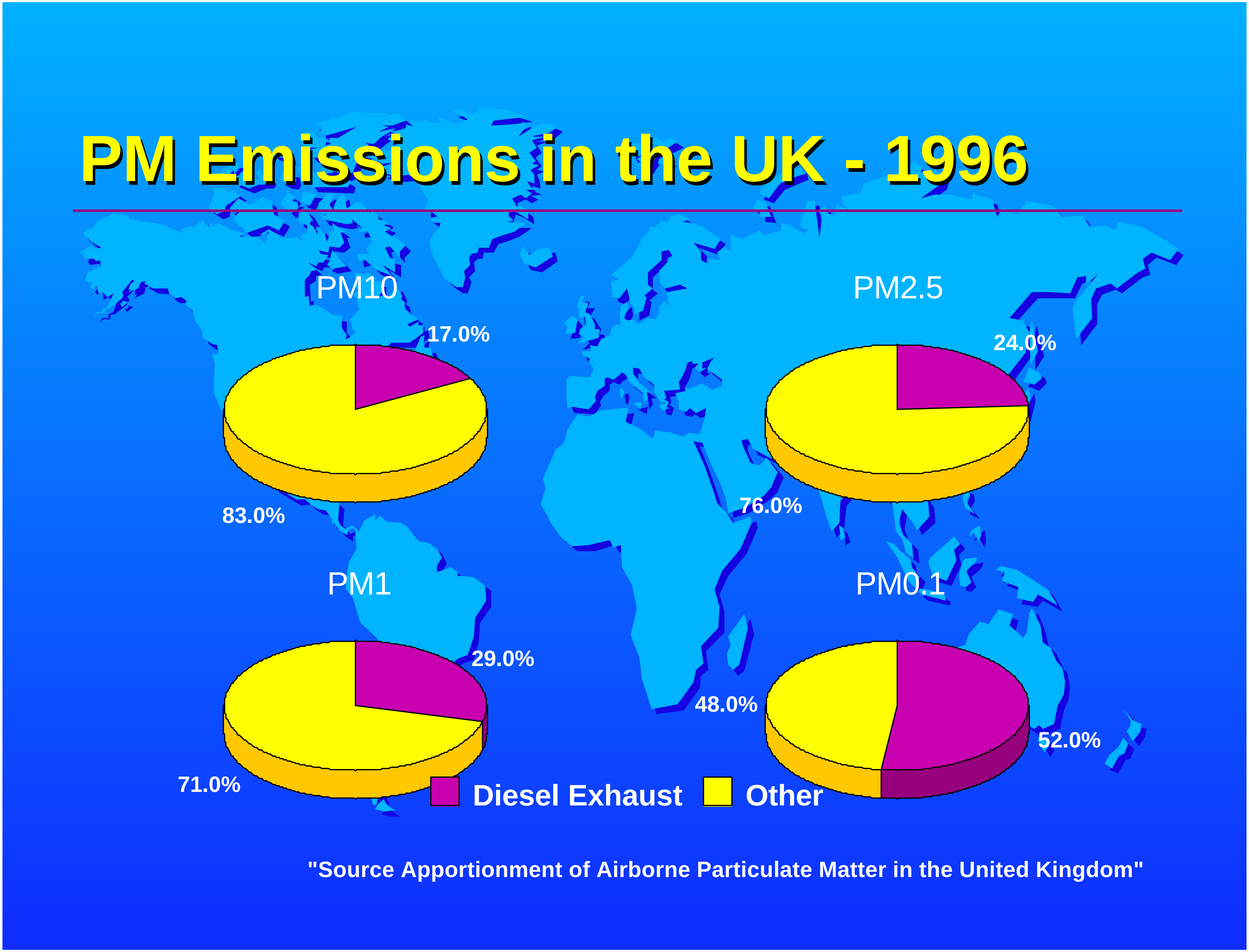
- 30 Human Epidemiological Studies Found Link Between Diesel PM & Lung Cancer
- Diesel PM Declared "Toxic"
- STAPPA/ALAPCO Report - ~125,000 Excess Cancers in US From Diesels

Average Los Angeles Basin Cancer Risk Apportionment



EPA Diesel Health Assessment Document - August 2000

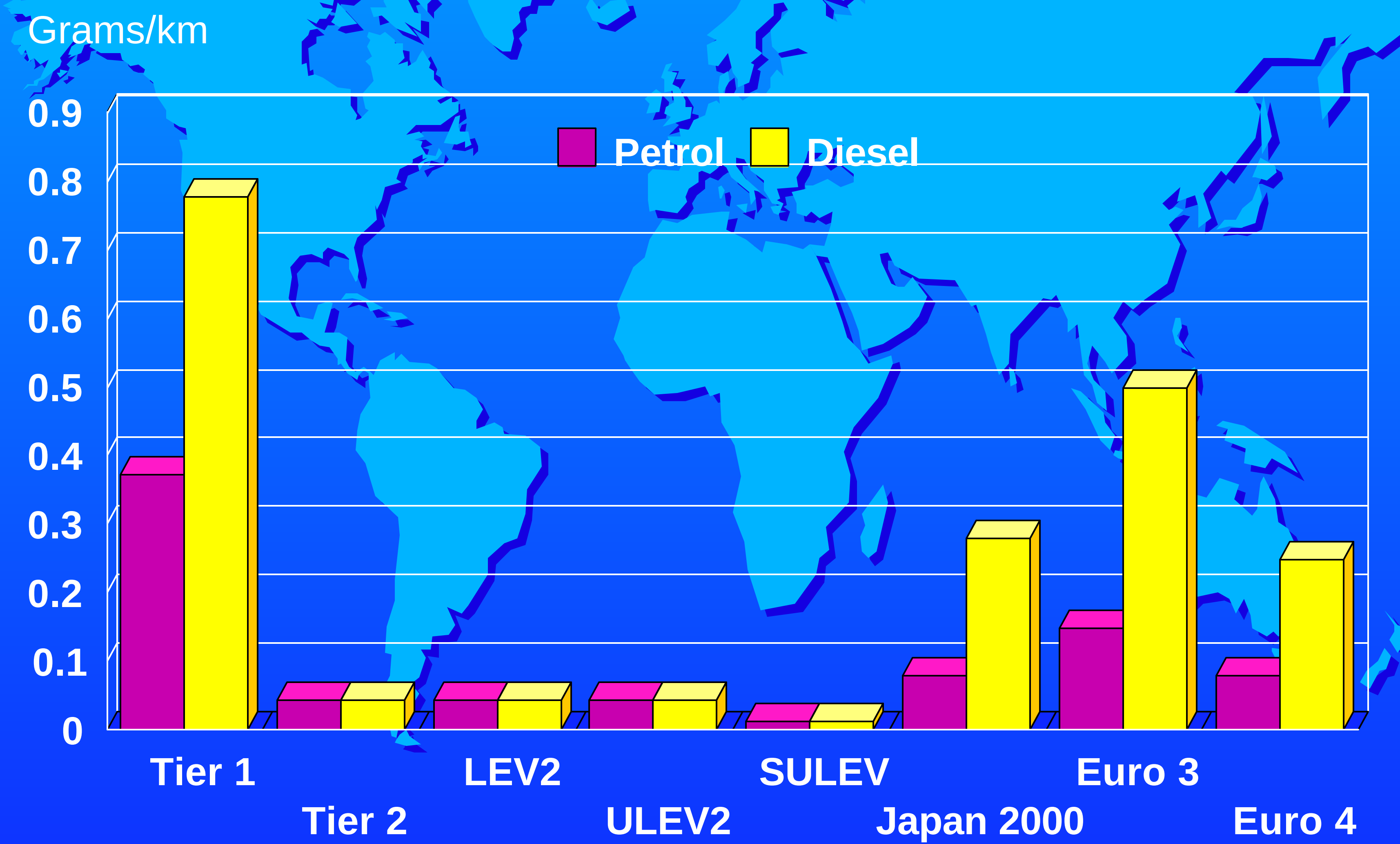
- Highly respirable with large surface area
- Excellent carrier for organic and inorganic compounds
- Toxicologically relevant organic compounds include PAHs, nitro PAHs and oxidized PAH derivatives
- Chemical composition & size vary with engine type, operating conditions & fuel
- Likely carcinogenic to humans by inhalation at any exposure condition


PM Emissions in the UK - 1996
PM10
17.0%
83.0%
PM2.5
24.0%
76.0%
PM1
29.0%
71.0%
PM0.1
48.0%
52.0%
Diesel Exhaust
Other
"Source Apportionment of Airborne Particulate Matter in the United Kingdom"

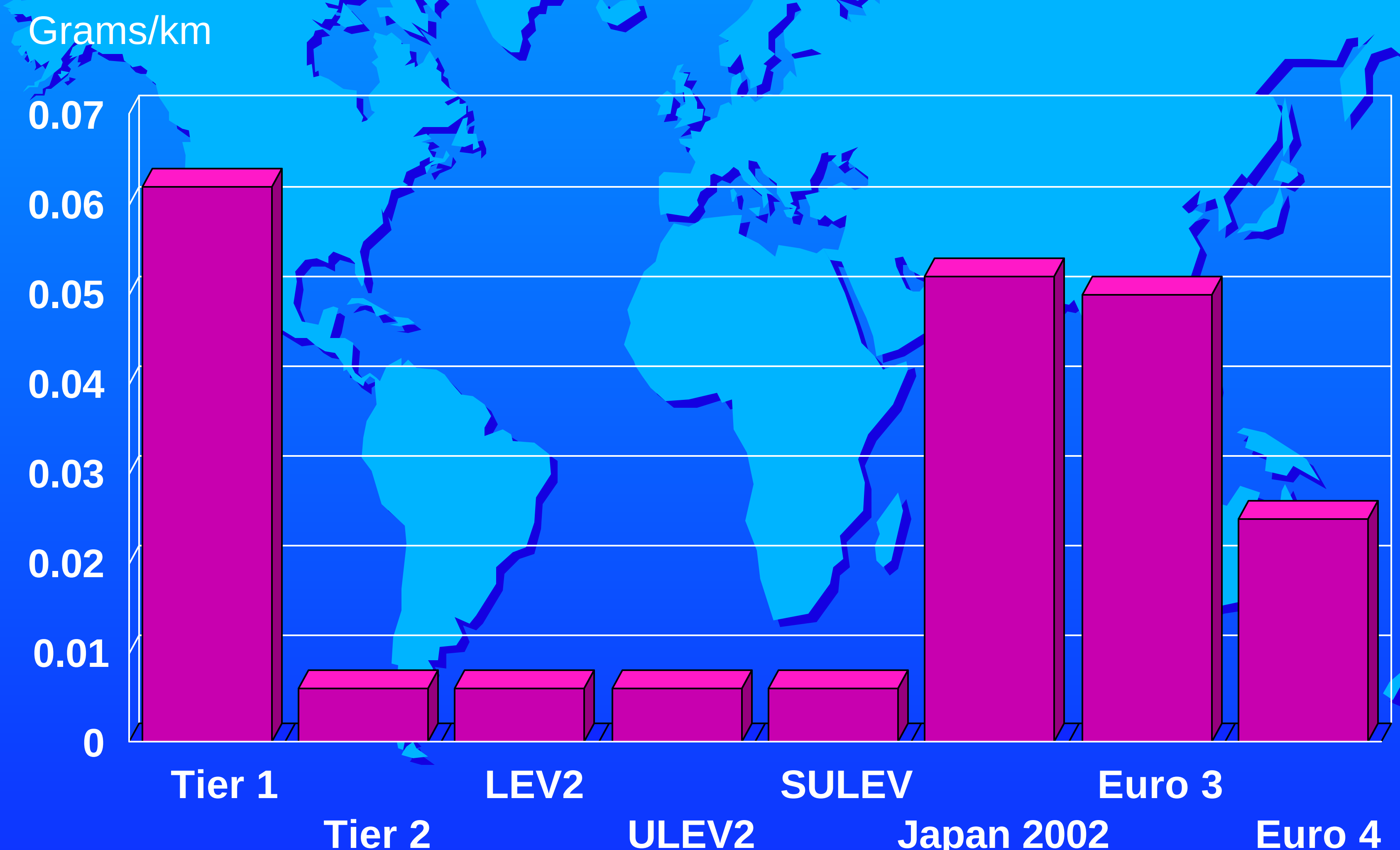
Diesel Challenges Around World

- Substantially Reduce PM
  - Mass
  - Number
  - Toxicity
- Substantially Reduce NOx
  - Ozone Control
  - Secondary PM
  - Acidification

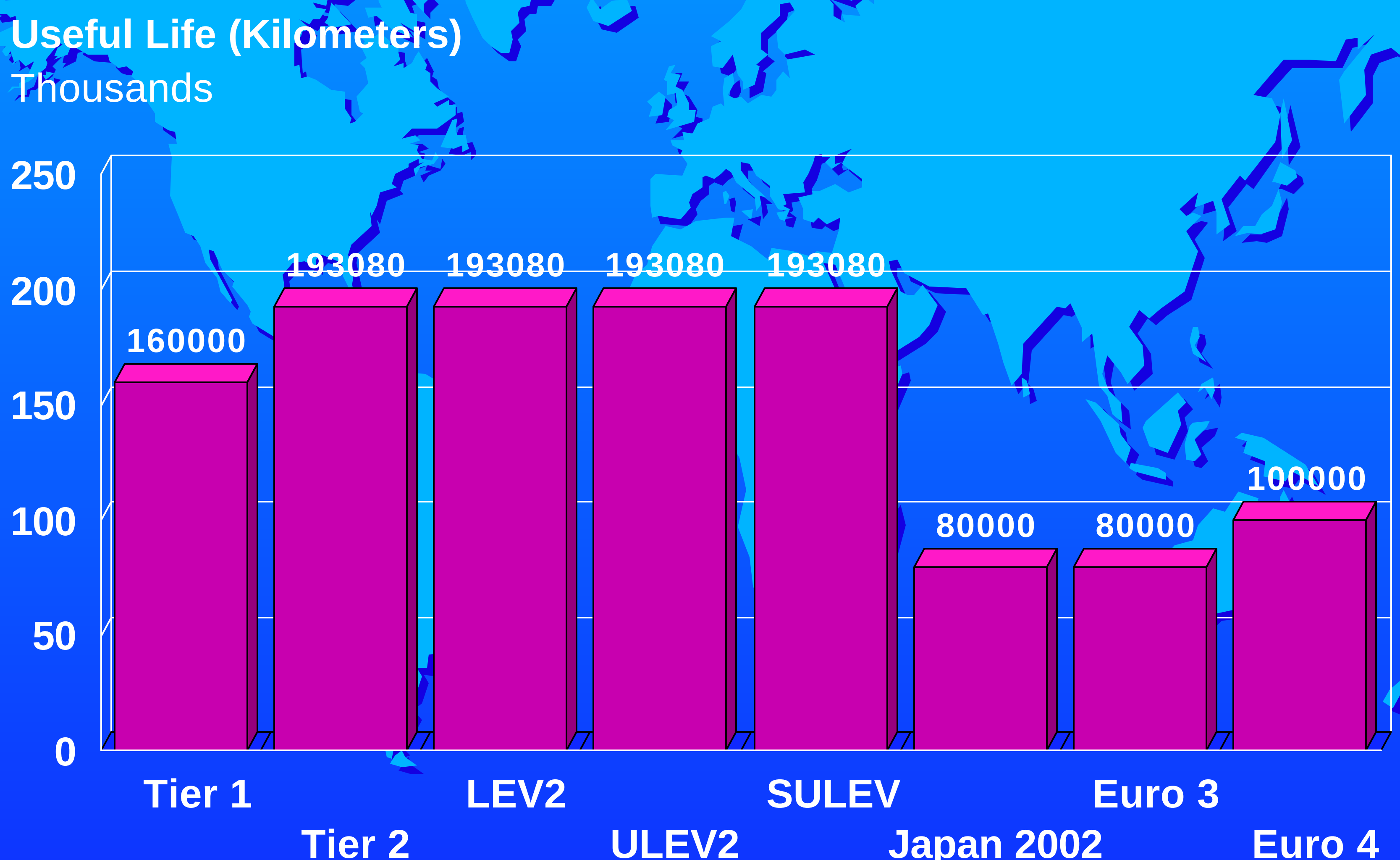
Global Trend in Light Duty NOx Control



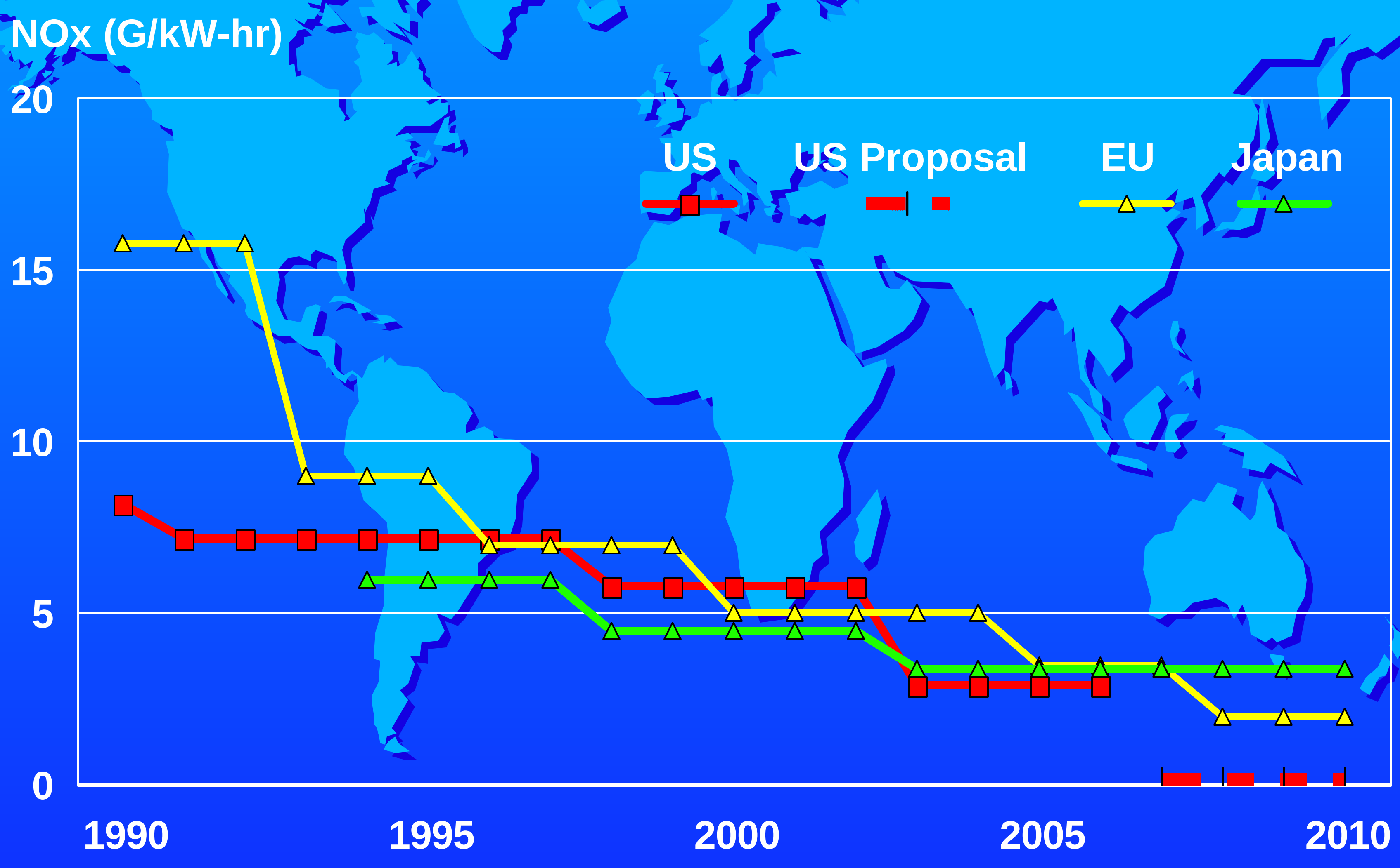
Global Trend in Light Duty Diesel PM Control



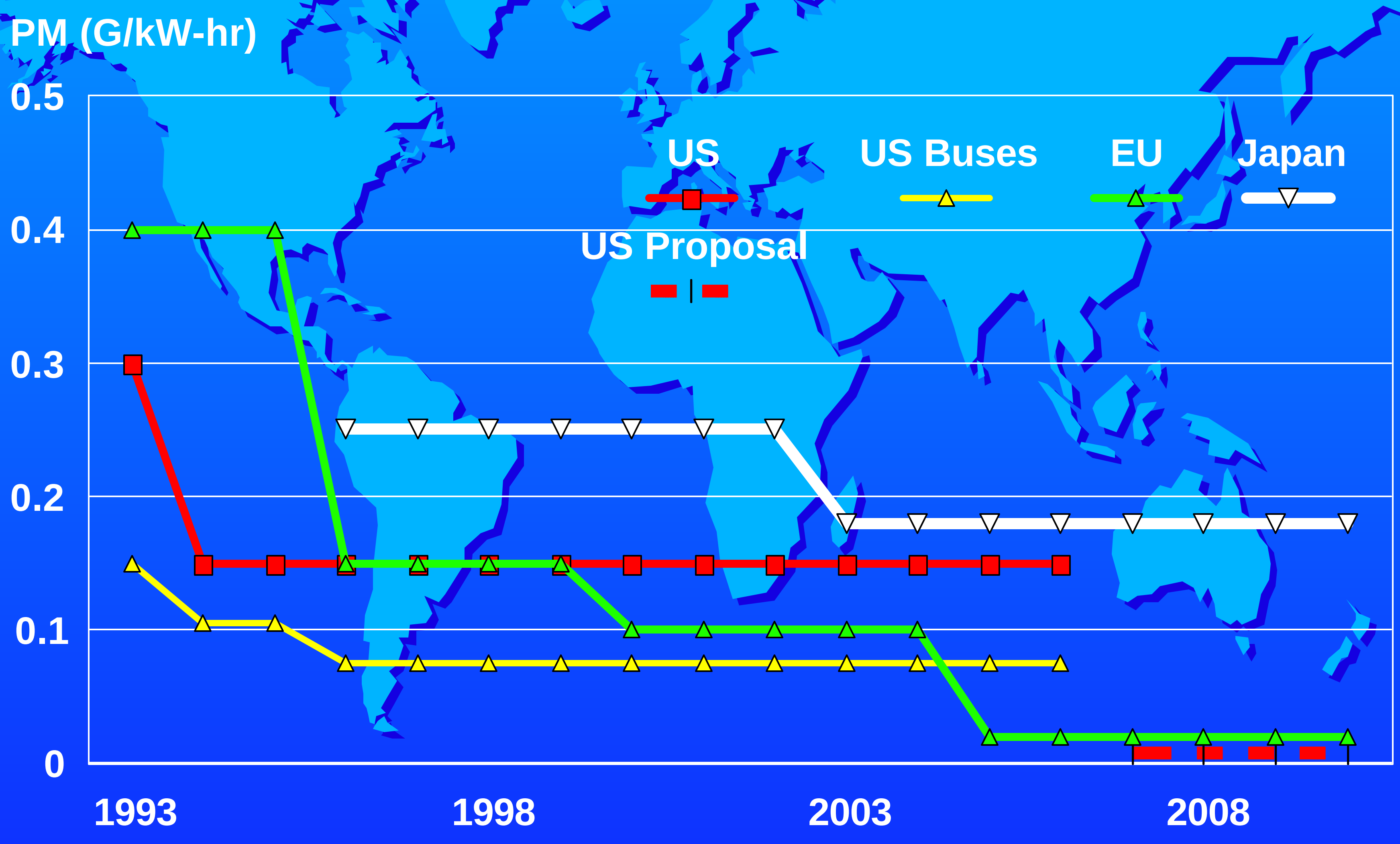
Global Trends in Car Durability Requirements



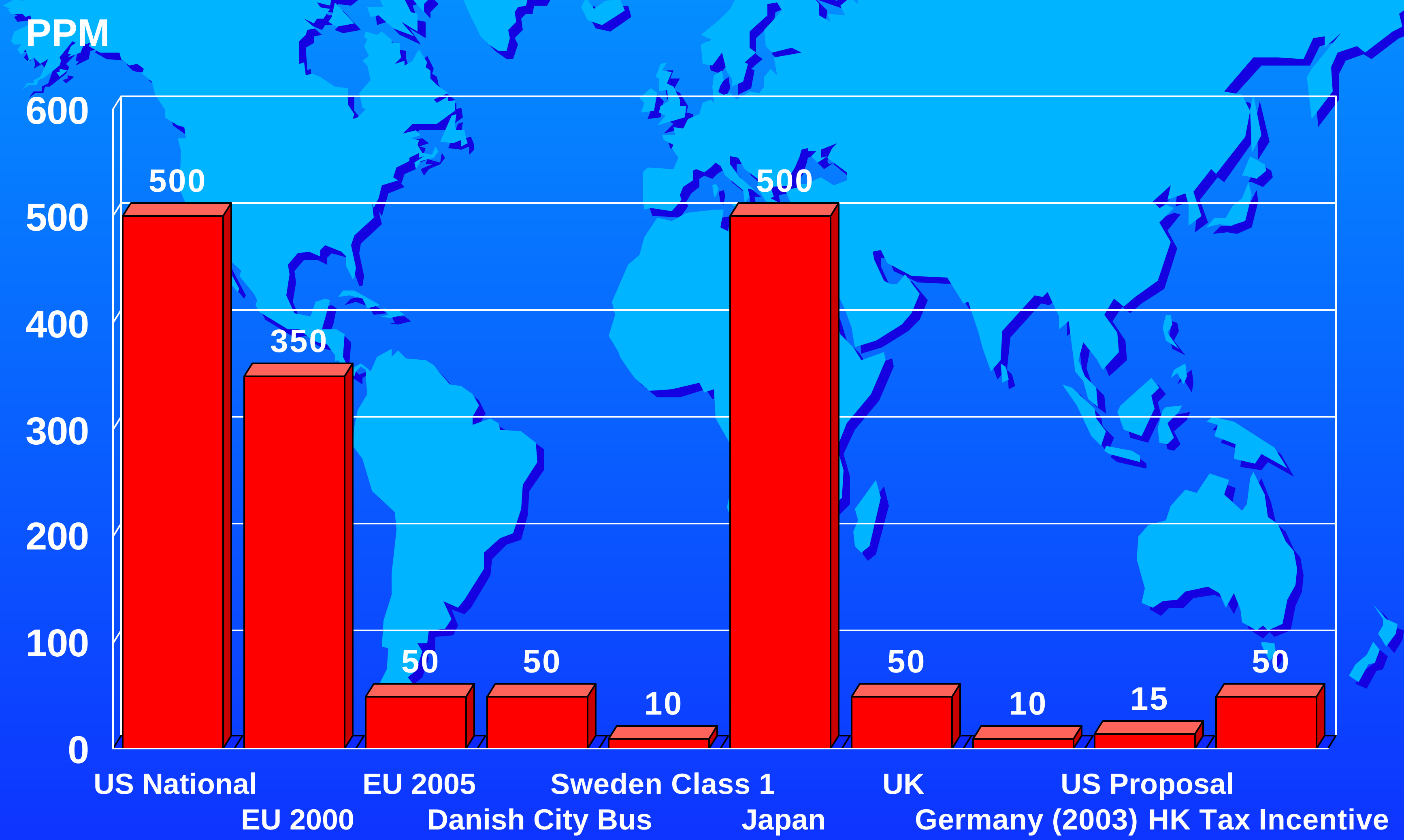
Global Trend in Heavy Duty Vehicle Emissions



Global Trend in Heavy Duty Vehicle Emissions



Diesel Fuel Sulfur Specifications



European Overview

- Low Sulfur Fuels Directive Adopted
- Tight Heavy Duty Standards Adopted; PM Filters, NOx Aftertreatment Likely But Mid Course Review Allowed
- Germany Pushing For Lower Sulfur in Diesel To Assure Feasibility of Tight Standards

European "Call For Evidence" On Very Low Sulfur Fuel

- Incremental Benefits
- Incremental Refining Costs
- Potential Linkage To Advanced Technologies
- Impact on Other Fuel Parameters
- Logistical & Investment Implications
- Overall Impact on Greenhouse Emissions (Well to Wheel)

Open Issues in Europe

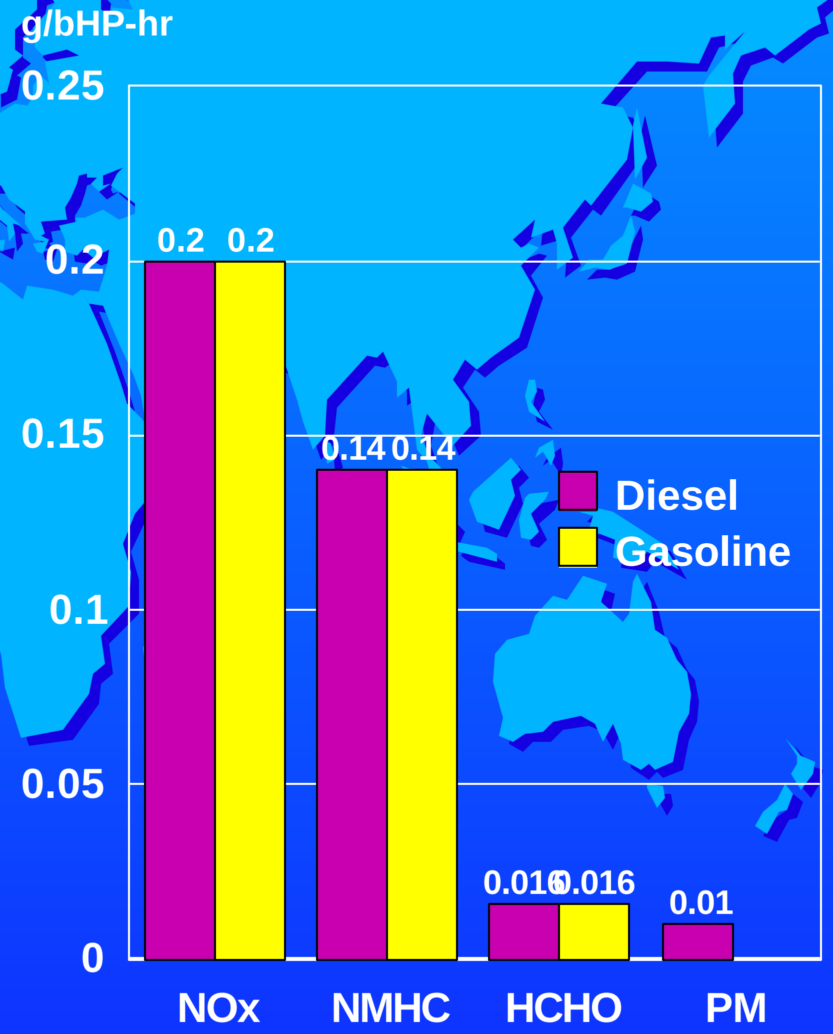
- Is 50 PPM Sulfur Low Enough?
- Will Filters or Traps Be Used Across the Board To Meet PM Standards?
- If Not, Implications
  - For Ultra Fine PM?
  - For Toxic Emissions?
- Should Light Trucks 2 & 3 Be Tightened to Car Standards?
- Should Light Duty Diesel NOx Be Tightened To Gasoline NOx Standards?

US Overview

- CA Adopted LEV2-2004; Diesel=Gasoline; SUV = Car
- Federal "Tier 2" Standards Adopted; Diesel=Gasoline; SUV = Car
- Massive Heavy Duty Diesel Enforcement Action Stimulating Program
- Tighter HD PM & NOx Standards Proposed
- Lower Sulfur in Diesel Fuel Proposed

EPA Proposed 2007 Requirements

- NOx - 4 year Phase-in
- 15 PPM Sulfur - July 2006
- No Crankcase Emissions
- Add Euro Test, OBD, Not To Exceed Provisions



Latest Developments in Japan

- Tokyo Government & Courts Pushing For Faster Action on PM
- Shift from NOx to PM Priority Control
- 2007 Diesel Standards Brought Forward; Likely New Heavy Duty Transient Test
- Low Sulfur Fuel (< 50 PPM) Before 2005
- Aggressive Retrofit Program Being Evaluated For Tokyo
  - Low Speed Driving Conditions
  - Low Sulfur Fuel
  - NO to NO2 Shift

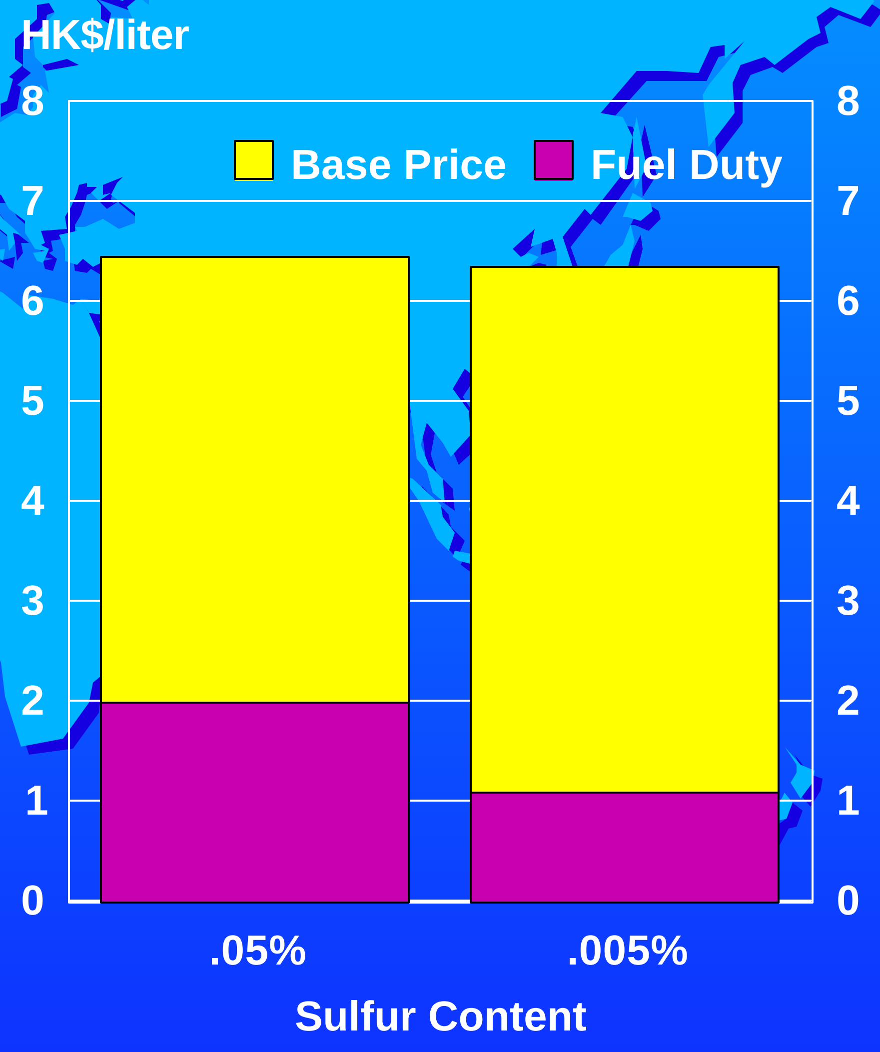

Tokyo Five Step "Diesel NO" Proposal
Ban on Sale and Use of Diesel Cars
Tighter New Vehicle Standards Brought Forward
Shift Tax Benefit Away From Diesel Fuel
Stimulate Advances in Technology To Control Existing Diesels and Require its Use
Diesel Commercial Vehicles Replaced By Gasoline Where Possible

Major Retrofit Effort Emerging

- Europe
  - Major Cities in Sweden
  - Germany
  - UK
- US
  - California
  - Northeast States (NESCAUM)
- Japan
  - Tokyo
- Other

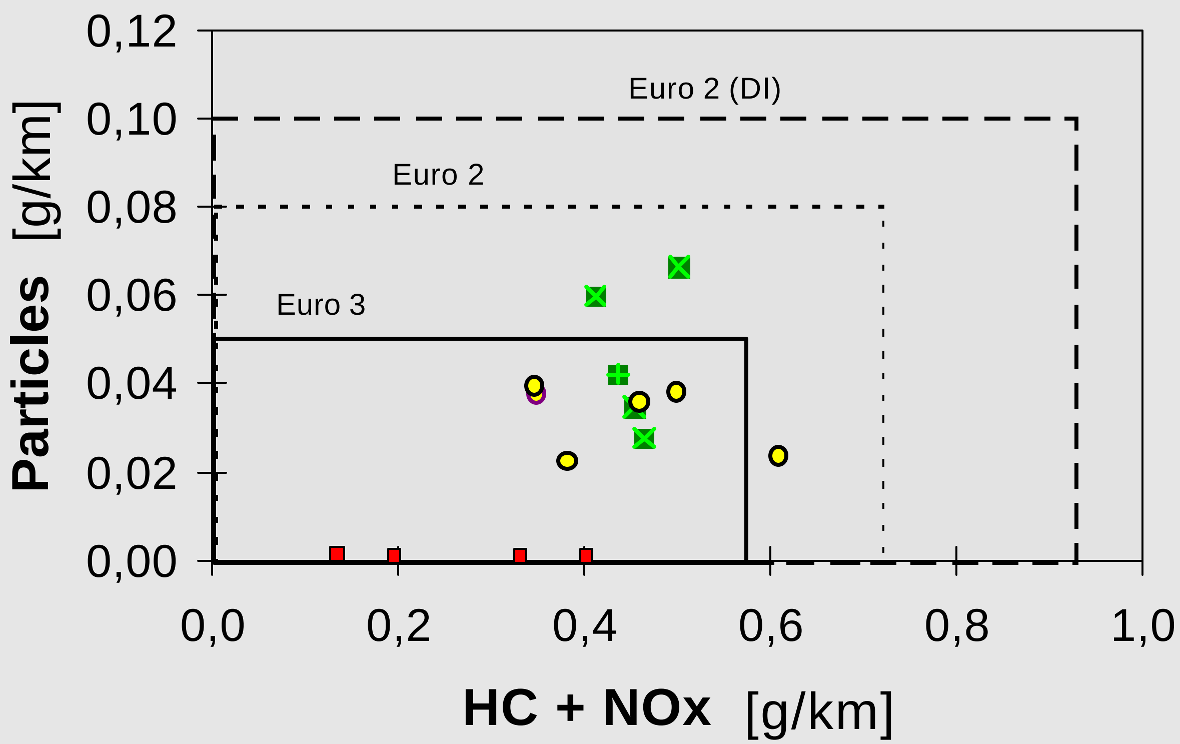
Recent Developments in Hong Kong

- Tax Incentive Offered For 50 PPM Fuel
- Likely Strong Retrofit Effort to Follow
- Taxi Fleet Shifting From Diesel to LPG



Regulated Exhaust Gas Emissions

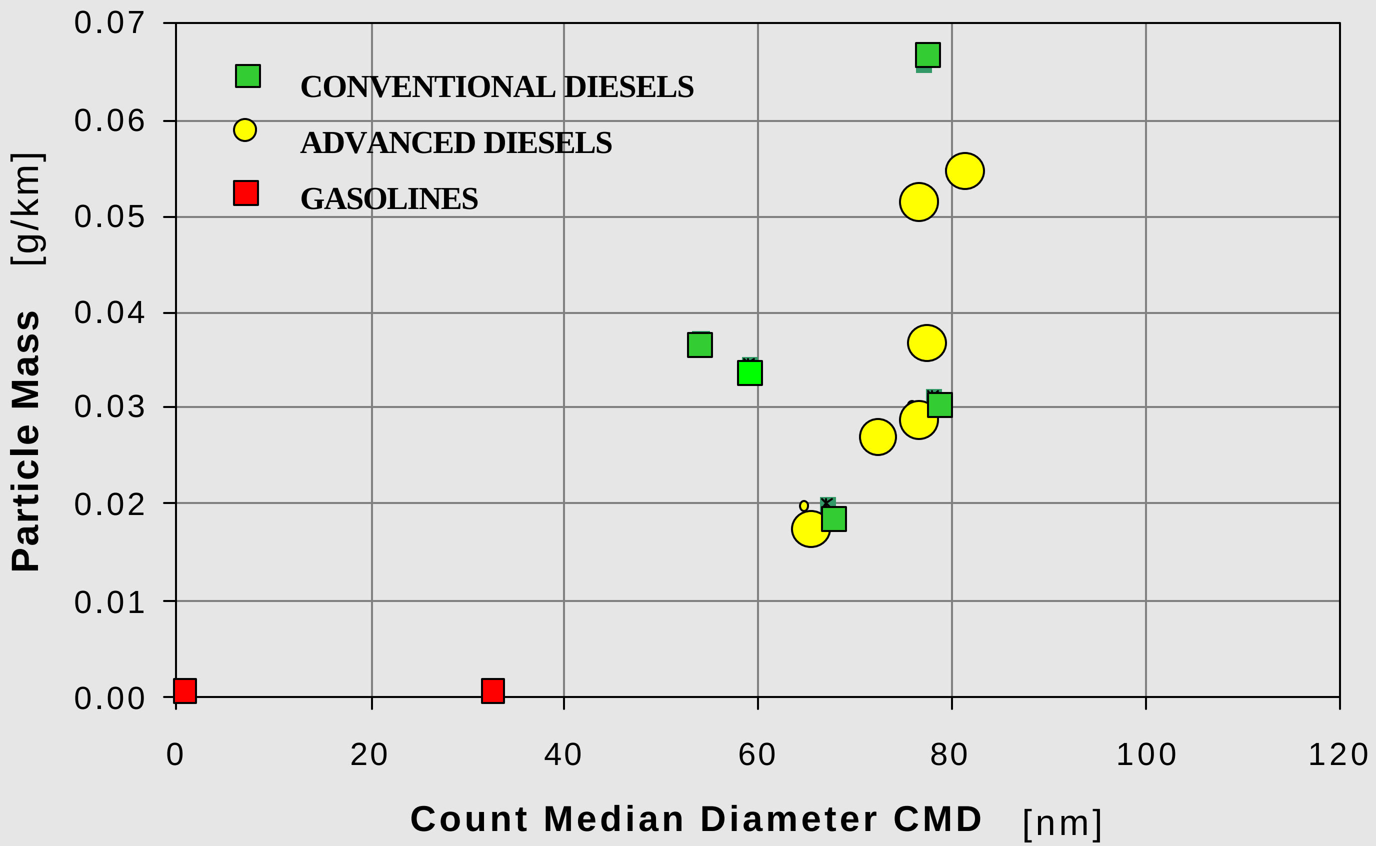
Conventional Diesel
Advanced Diesel
Gasoline



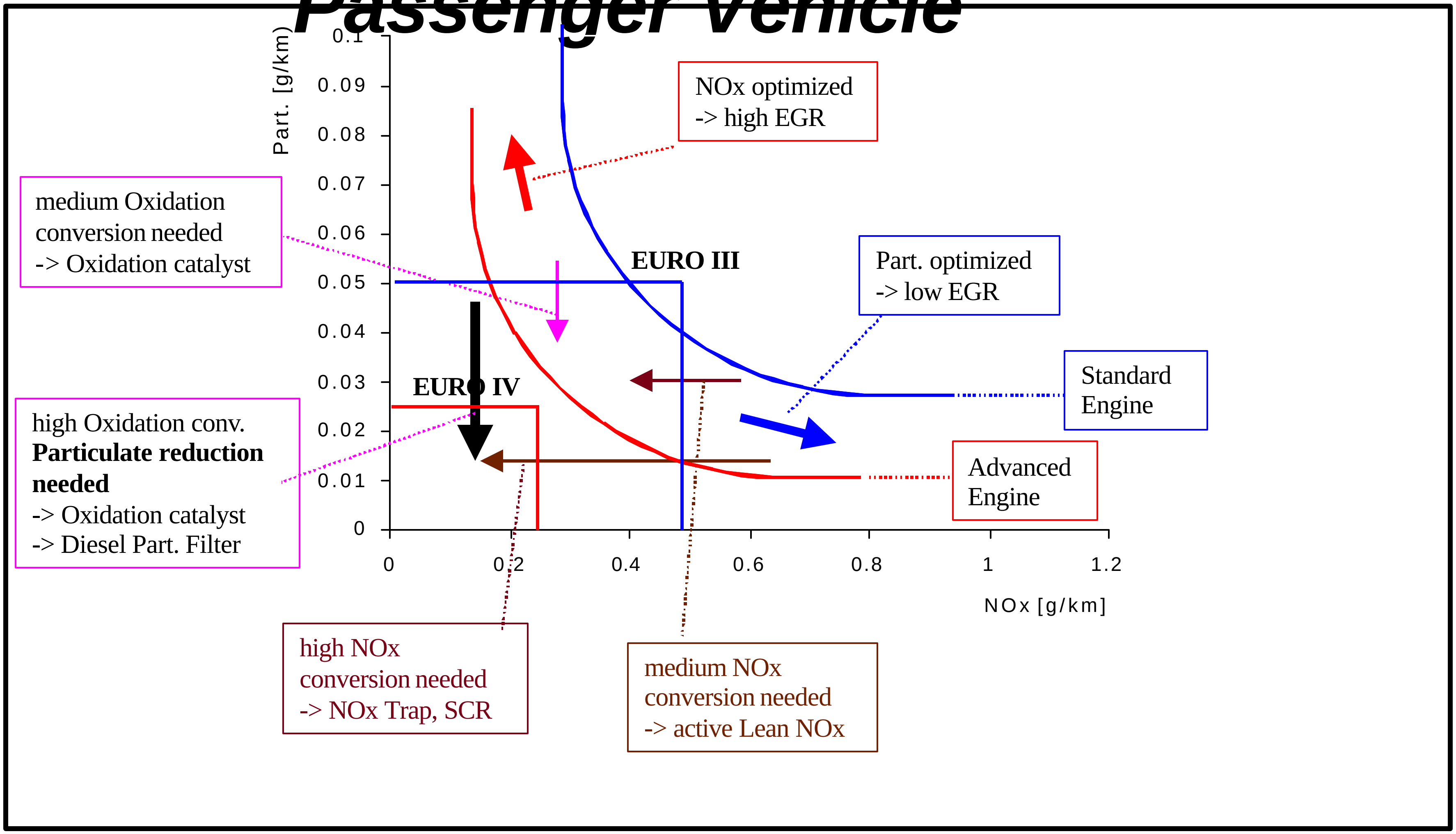
NEDC Drive Cycle

Median Particle Size

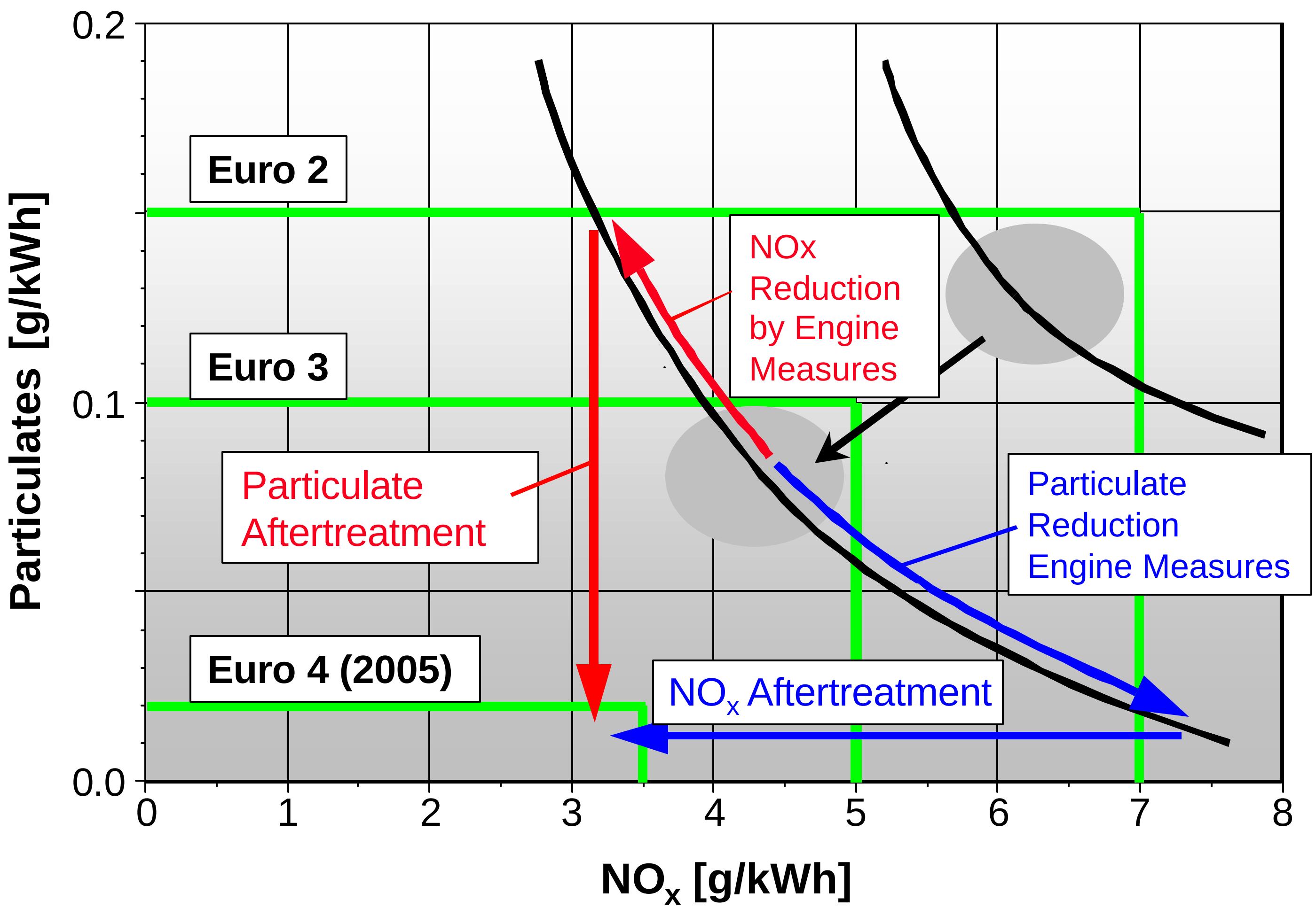
measured with SMPS at 100 km/h constant speed.



Particulate - NOx Trade Off Curves and Emissions Reduction Strategies for Diesel Passenger Vehicle



NOx/Particulate Trade-off Curve for Heavy Duty Vehicles



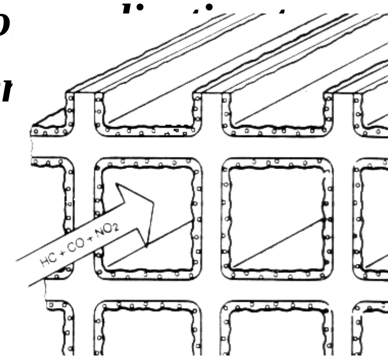
Modern Diesel Oxidation Catalyst

Design Features:

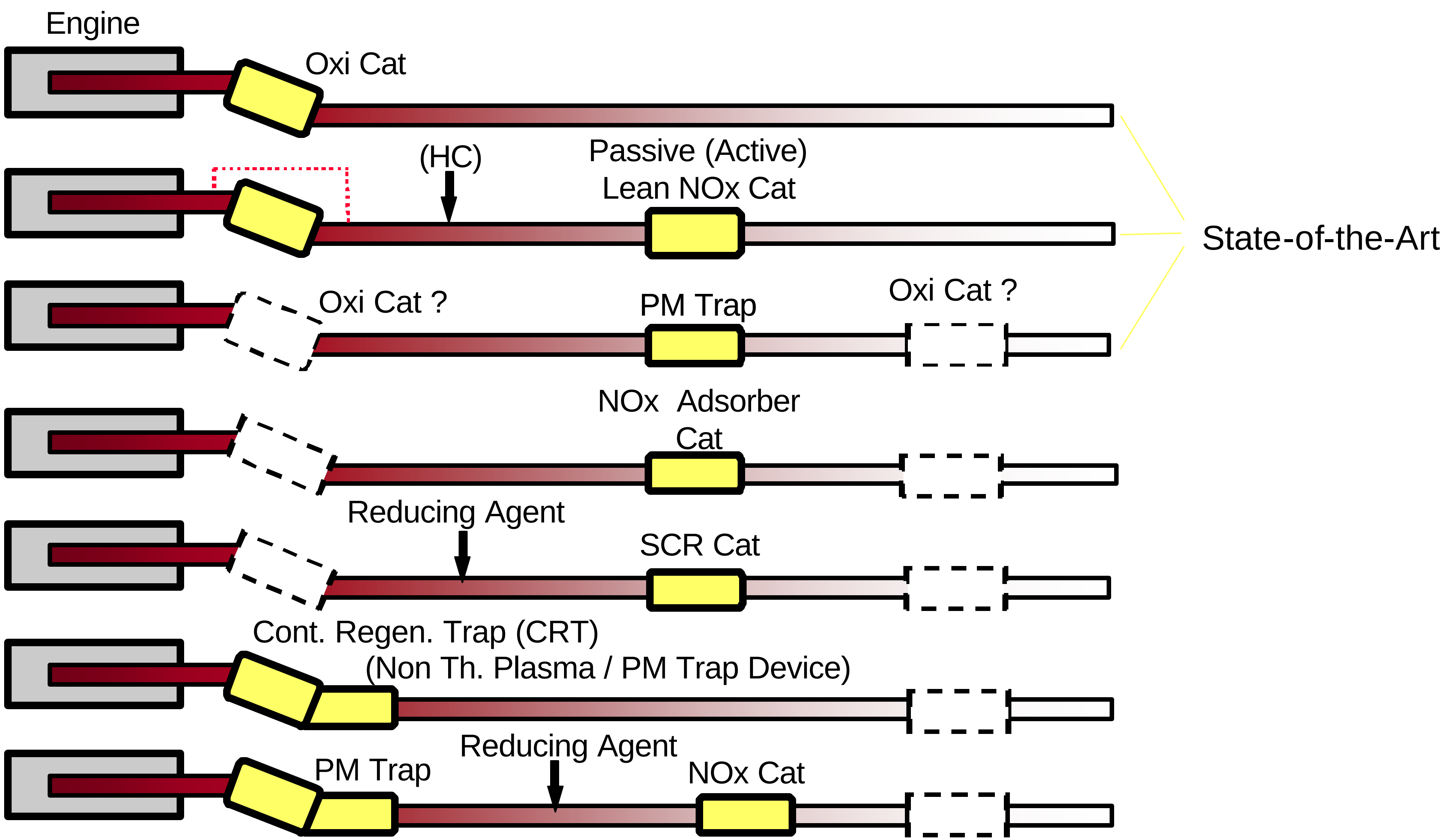
- *Low temperature activity + thermal stability*
- *Maximize oxidation of carbonaceous materials*
- *Minimize oxidation of sulfur and nitrogen species*
- *Resistant to plugging from oil and ash deposits*
- *HC trapping before light-off and release to active catalyst components*

Component Strategy:

- *Precious Metal loading dependent upo ... ratures*
- *Flow-through monolith having cell de ... cpsi*
- *Low sulfating washcoat components*
- *Zeolite for HC trapping*
- *BMO for oxidation of SOF*



Diesel Exhaust Gas Aftertreatment Systems



Overview and Efficiency of Diesel Particulate Filters

Ceramic Traps

Glass Ceramic Traps

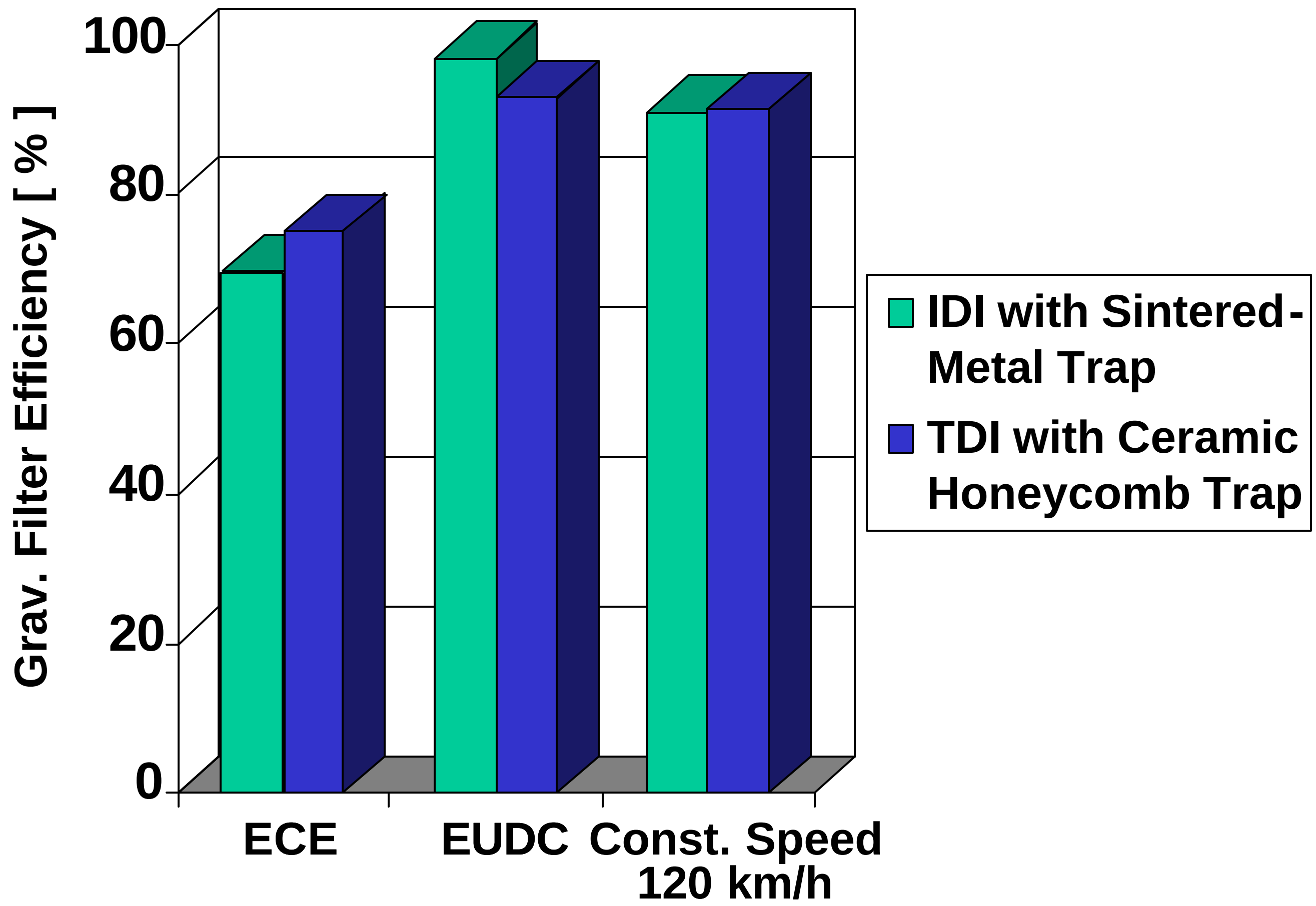
Silicon Carbide Traps

Glass or Metal Fiber
Worn Coils

Knit Fibers

Sintered Metal Traps

Structures Similar
to Wire Mesh



Diesel Particulate Filter Regeneration Strategies

- ***Active Measures***
  - ***Burner***
  - ***Electrical Heater***
  - ***Engine Process Modifications***
- ***Passive Measures***
  - ***Fuel Additives***
  - ***Filter Coating***
  - ***Reactive Species Generation***

“Combined Systems”

- **Catalytic effects**
- **Engine process modifications**

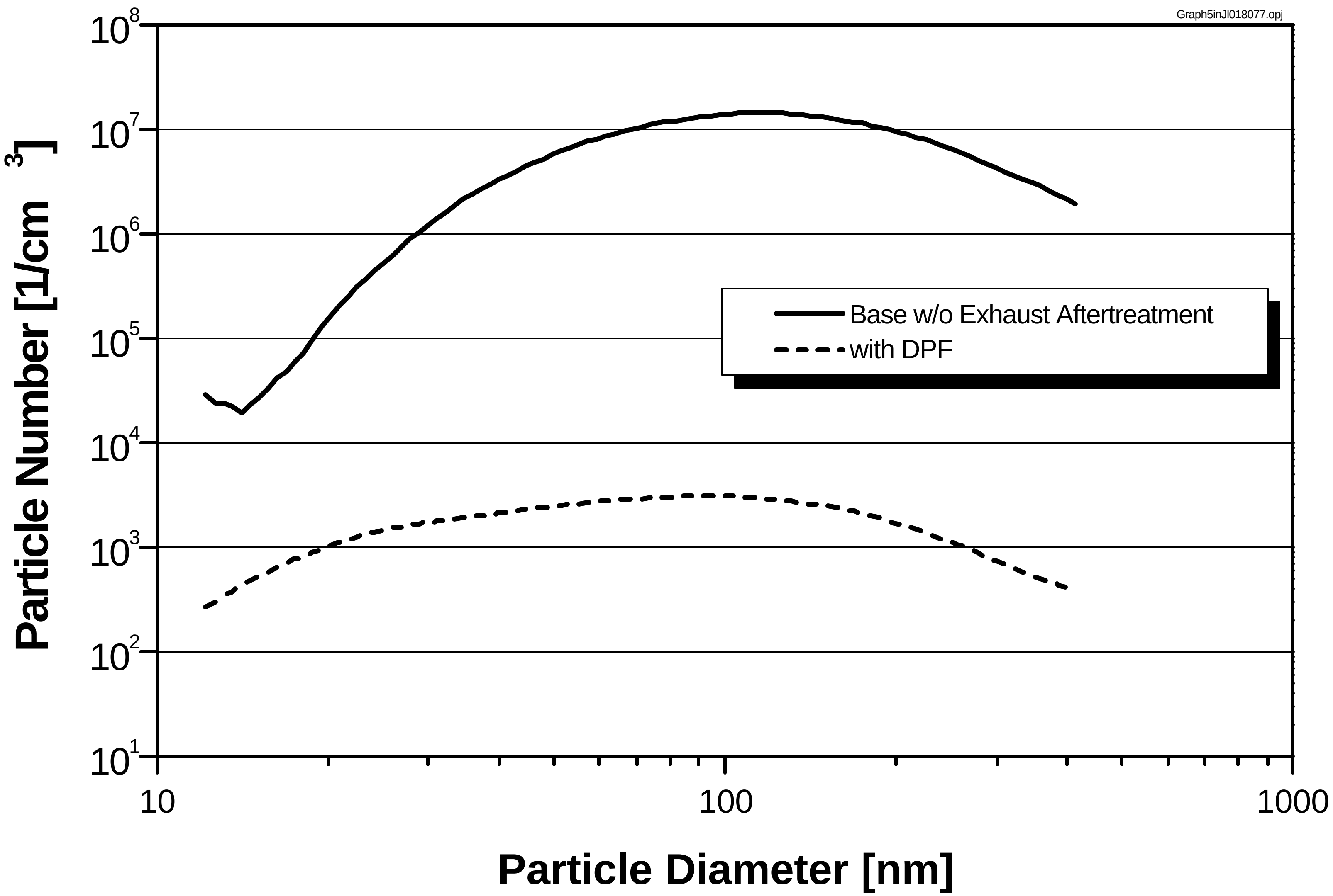
Diesel Particulate Filter - System Integration

Criteria for determining the necessity of DPF regeneration

- Maximum soot loading governed by:
  - filter properties
- Maximum backpressure governed by:
  - acceptable fuel penalty
  - acceptable loss in full load or acceleration performance

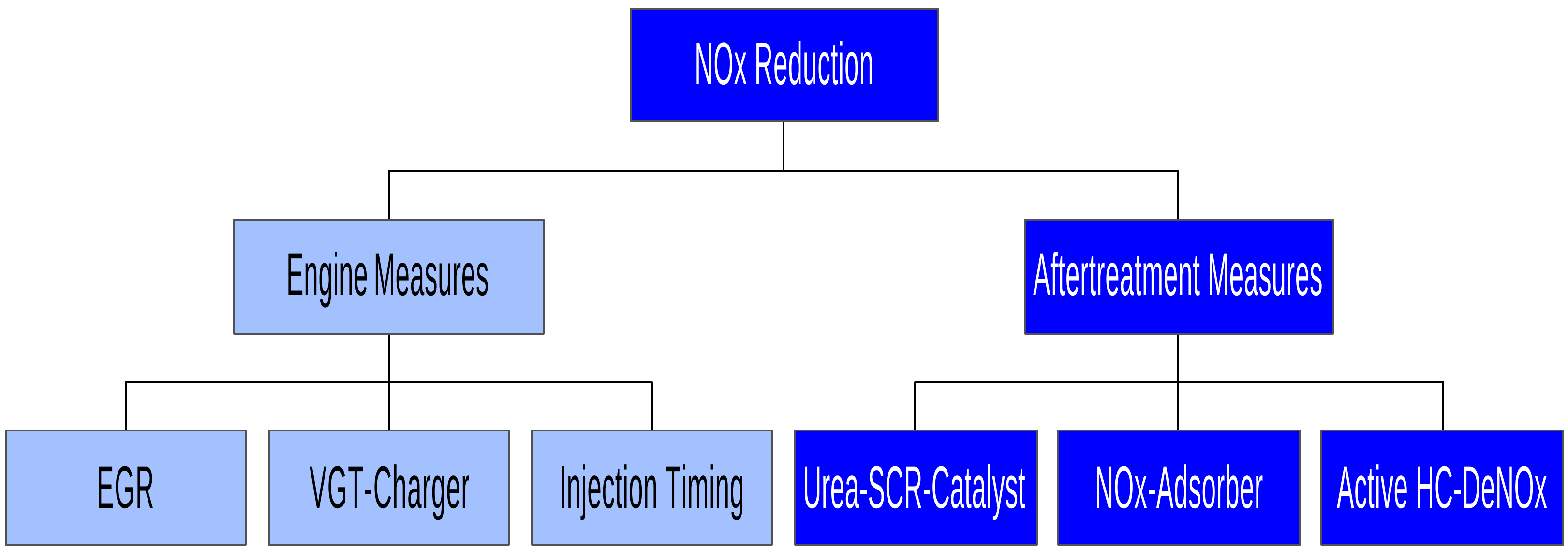
Required actions:

- Monitoring DPF Loading
- Start/Stop regeneration activity



Source: FEV 1997

Possible Measures for NOx Reduction in Diesel Vehicles

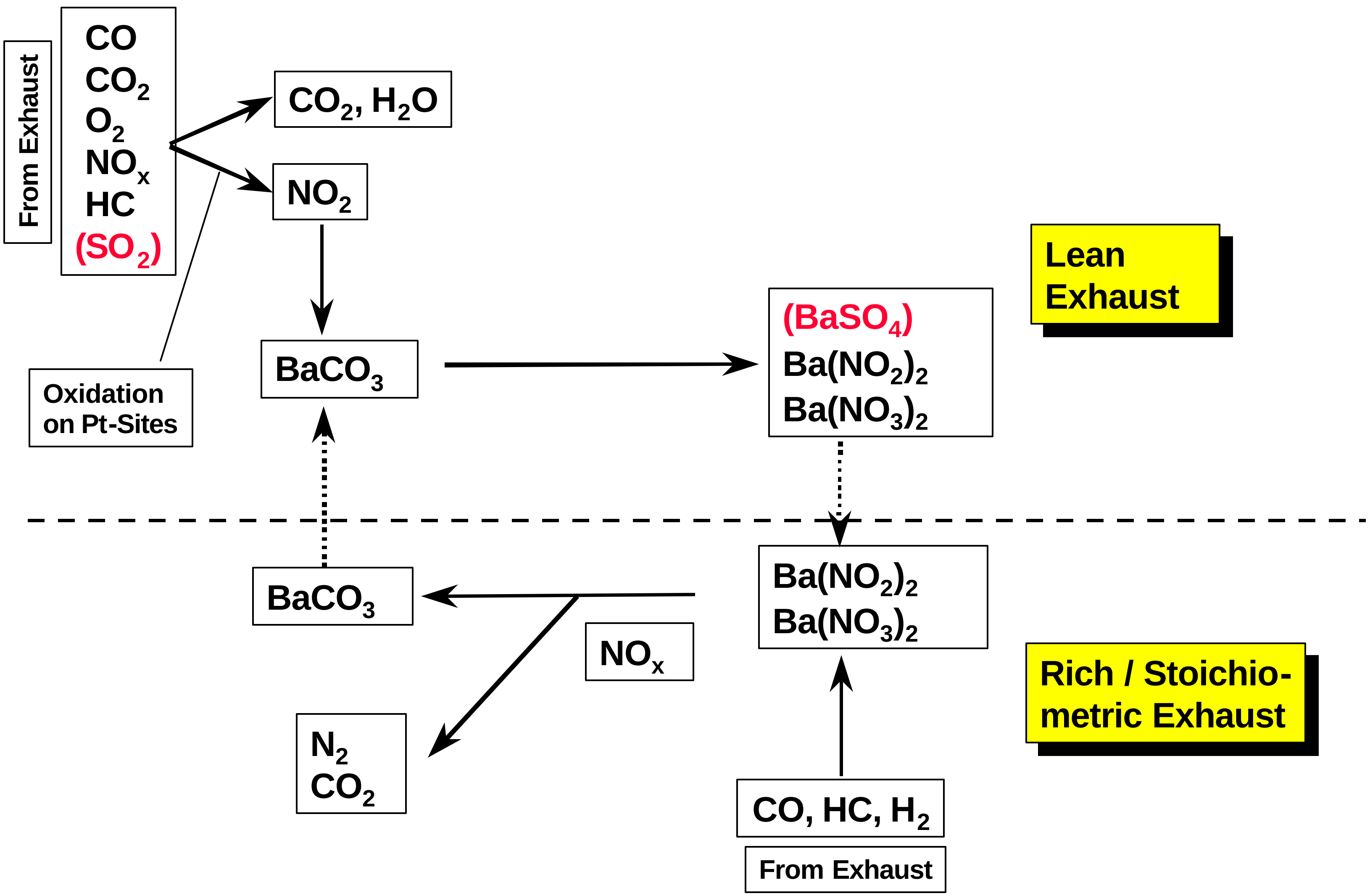


NO_x Adsorber Technology

NO_x Adsorber Catalysts

- Very high NO_x Conversion Rates
- NO_x Conversion Window Between ~ 200°C and more than 500°C
- Lowest Fuel Penalty at Comparable Conversion Rates
- Combination of Oxidation and NO_x Reduction Catalyst
- Single Injection System
- Low HC Concentrations in Exhaust Gas

Chemistry of NO_x Adsorber Catalysts



Diesel Engine Operation for NO_x Adsorber Sulfur Effects

Catalyst Characteristics and Issues:

- Oxidized Fuel Sulfur (SO_2) is Further Oxidized to $BaSO_4$
- $BaSO_4$ "Irreversibly" Occupies Catalyst Sites and Reduces NO_x Reduction Potential and is not Removed During "normal" Rich-Mode Operation
- Desulfurization Process of NO_x Adsorber Catalyst at High Temperatures and Rich Conditions Possible
- Desulfurization Results in SO_2 and/or H_2S Emissions

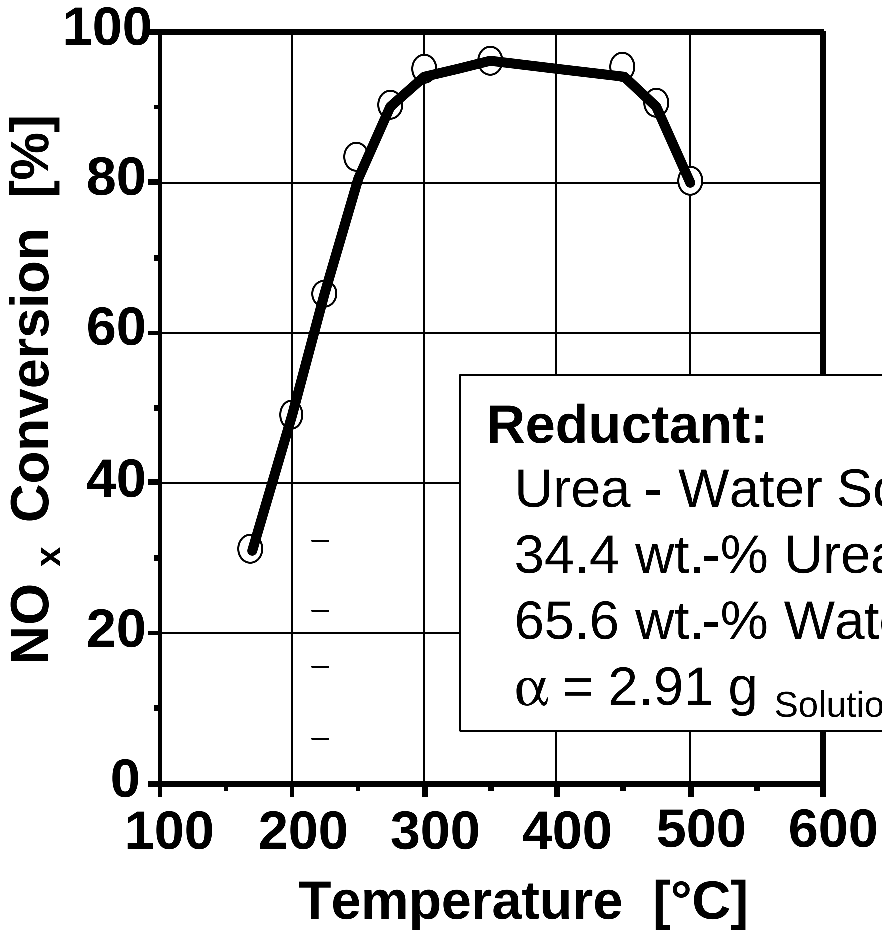
Urea-SCR Lean NO_x Catalyst

Urea-SCR

The technology is proven to yield high NOx conversion ratios with the following considerations for engine/vehicle integration:

- One significant advantage is that it can be considered a retrofit system
- Can be nearly self contained with no impact on the EMS
- The primary disadvantages include:
  - Storage volume of onboard urea-water solution for satisfactory refill intervals
  - Urea-water refill logistics (refill only urea-water solution or refill fuel and urea-water solution at each filling)

Fundamentals of Urea-SCR Lean NO_x Catalyst



Reductant:
Urea - Water Solution
34.4 wt.-% Urea
65.6 wt.-% Water
α = 2.91 g $_{Solution}$ / g $_{NOx}$

Catalyst:

Volume:	7.4 l
Substrate:	200 cpi
Active Compounds:	V_2O_5
	TiO_2
	WO_3

Boundary Conditions:

Speed:	2000 rpm
Load:	Variable

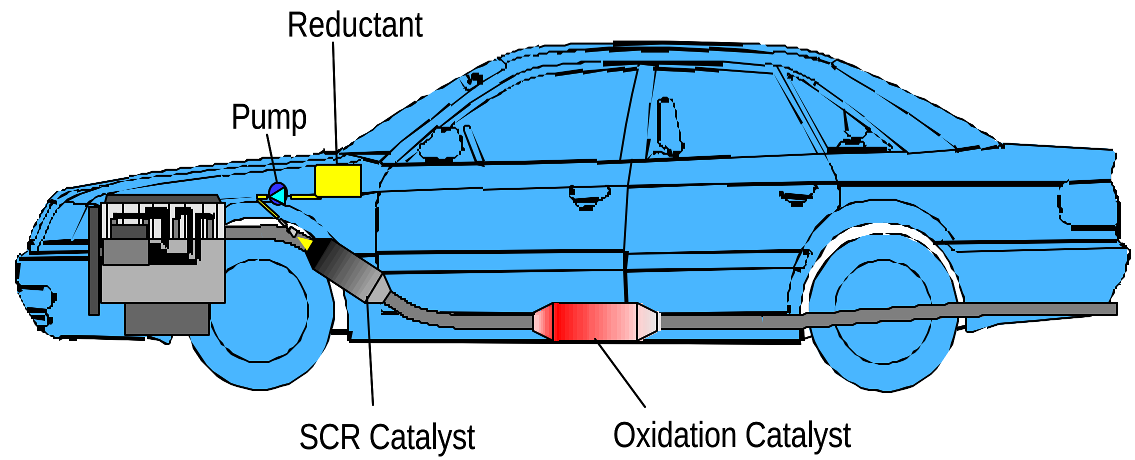
Potential of NO_x Reduction Measures

	Potential of NOx reduction		Change of fuel consumption compared to Euro II [%]		Valuation Euro IV potential
	Compared to Euro II [%]	Reachable NOx limit [g/kWh]	5 g/kWh NOx	3,5 g/kWh NOx	
Retarded injection	25	5,0	8 - 14	not possible	no potential
Retarded injection + pilot injection	33	4,5	6 - 12	not possible	no potential
EGR	50	3,3	2 - 4	4 - 8	potential, but ①
HC-DeNOx (HC:NOx = 3:1)	35	4,3	5 - 7	10 - 15	potential, but ①
Urea-SCR	75	1,7	at least uneffected	at least uneffected	potential, but ②
Water injection	50	3,3	at least uneffected	at least uneffected	potential, but ③

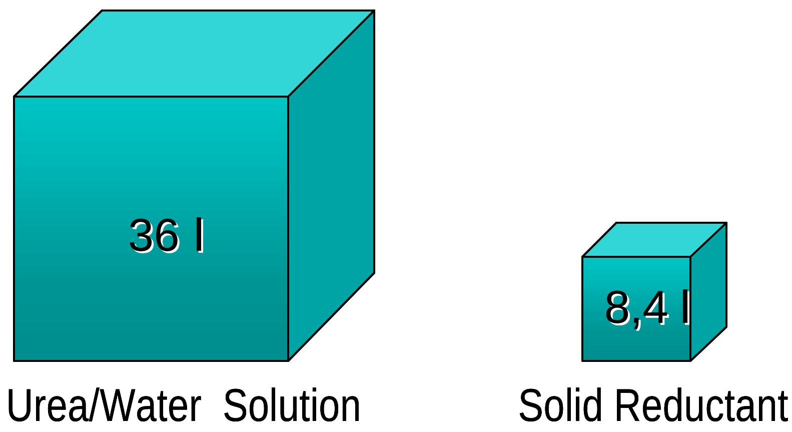
① Increase of fuel consumption; 2,0 g/kWh not reachable.
② additional 5 % urea referring to fuel capacity necessary
③ additional 30 % water referring to fuel capacity necessary, 2,0 g/kWh not reachable.

Reference: Ricardo, AVL (1996)

SCR with a Solid Reductant



Reductant required for 30.000 km Mileage(NOx Conversion approx.. 65 %):



Urea SCR

SCR Catalyst (S)

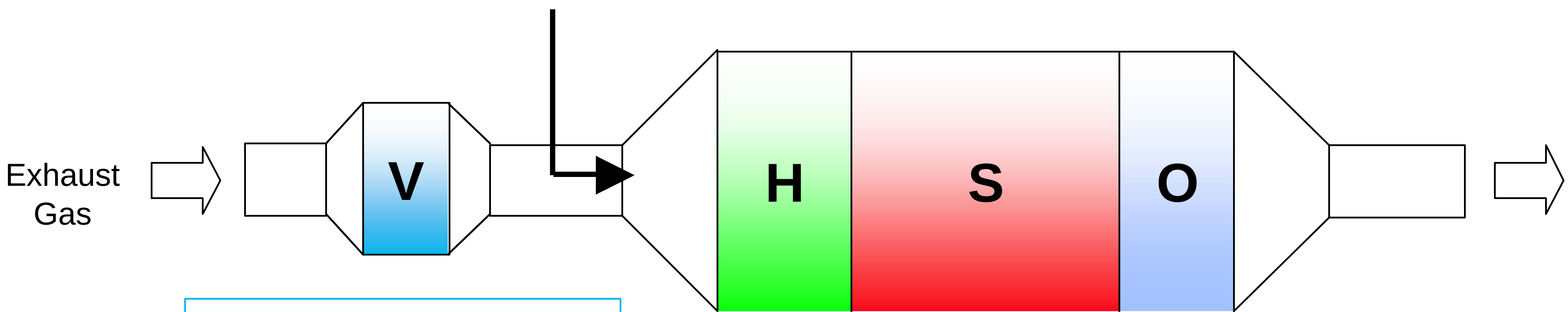
$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$

$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$

$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O$

Urea

$(NH_2)_2CO$



Oxidation Catalyst (V)

$2NO + O_2 \rightarrow 2NO_2$

$4HC + 3O_2 \rightarrow 2CO_2 + 2H_2O$

$2CO + O_2 \rightarrow 2CO_2$

Oxidation Catalyst (O)

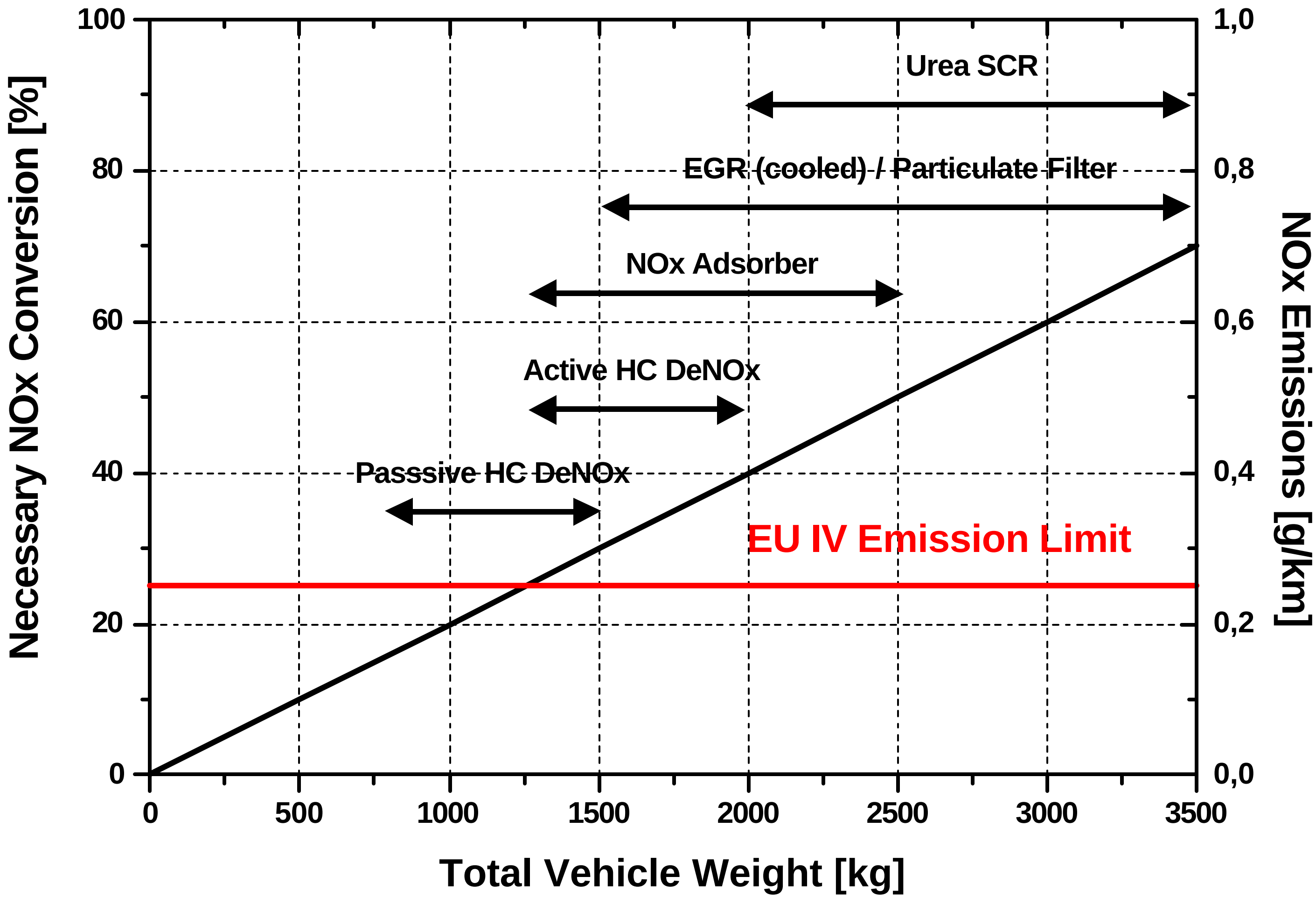
$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$

Hydrolysis Catalyst (H)

$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2$

Summary

Applicability of DeNOx Technologies for Passener Cars and Light Duty Vehicles



Conclusions

- Progress on New Vehicle Controls Occurring Worldwide
- Low Sulfur Fuel Spreading Rapidly
- Aggressive Retrofit Efforts Underway
- Remaining Questions:
  - Is Europe Finished or Will Tighter Fuels/Vehicle Standards Be Needed?
  - Will US EPA Proposal Prevail?
  - How Successful Will Global Retrofit Efforts Be?

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