Aircraft Particulate Matter Emissions

Past Practices:
What Was Available and How It Was Used

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Transportation Research Board

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A

Overview

- Why do we need to know about Aircraft PM?
- Available Measurements
- How Measurements Were Used
- What is Still Needed?

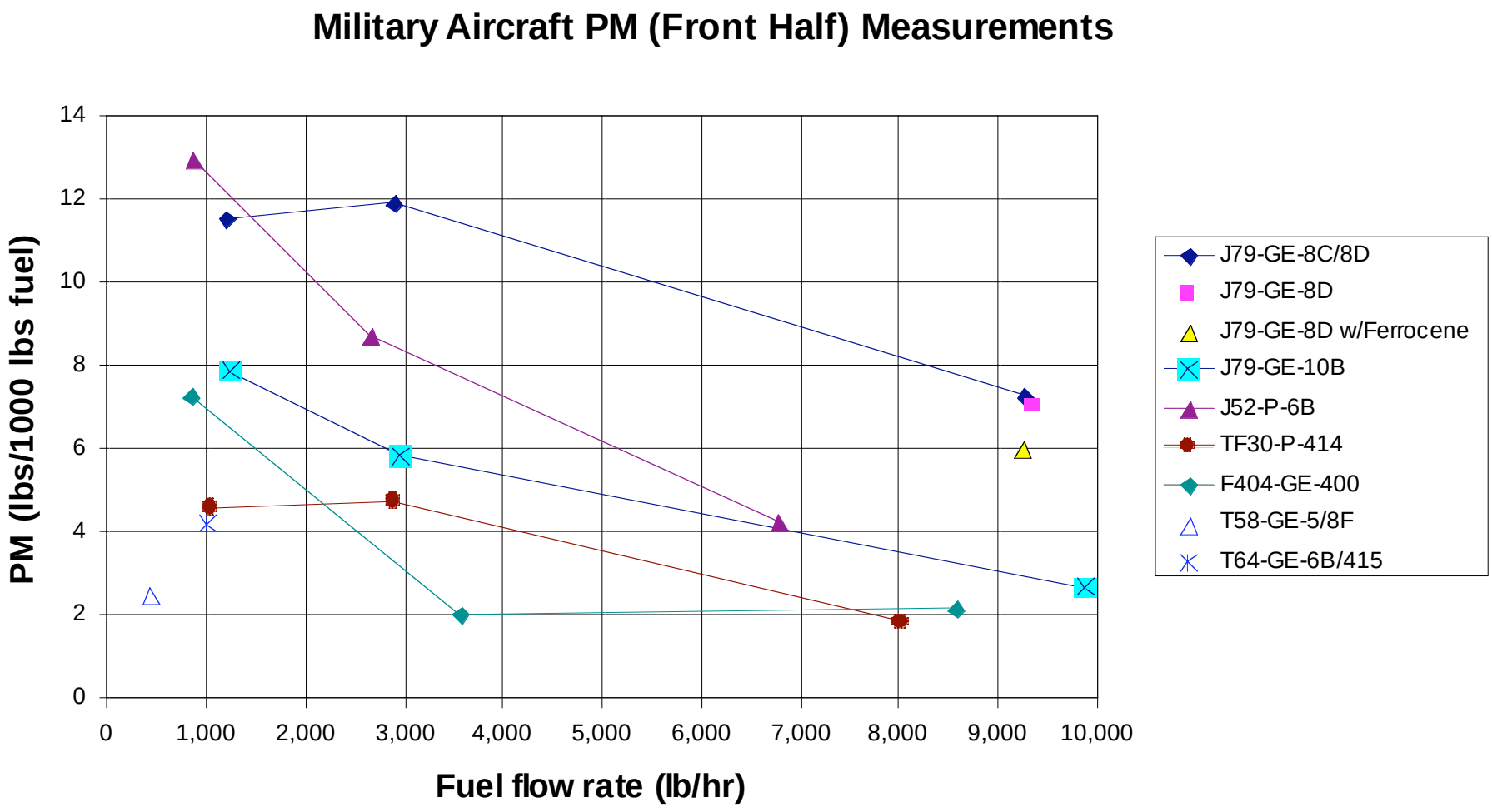
Why Do We Need to Know?

- Impacts on the Environment
  - Health Impacts (Ambient AQ Standards)
    - PM10
    - PM2.5
  - Global Impacts (Global Warming)
  - Emissions Limits
    - Smoke Number Only (so far)
- Impacts on the Engine
  - Incomplete Combustion
  - Impurities in Fuel
  - Engine Wear

Available Measurements

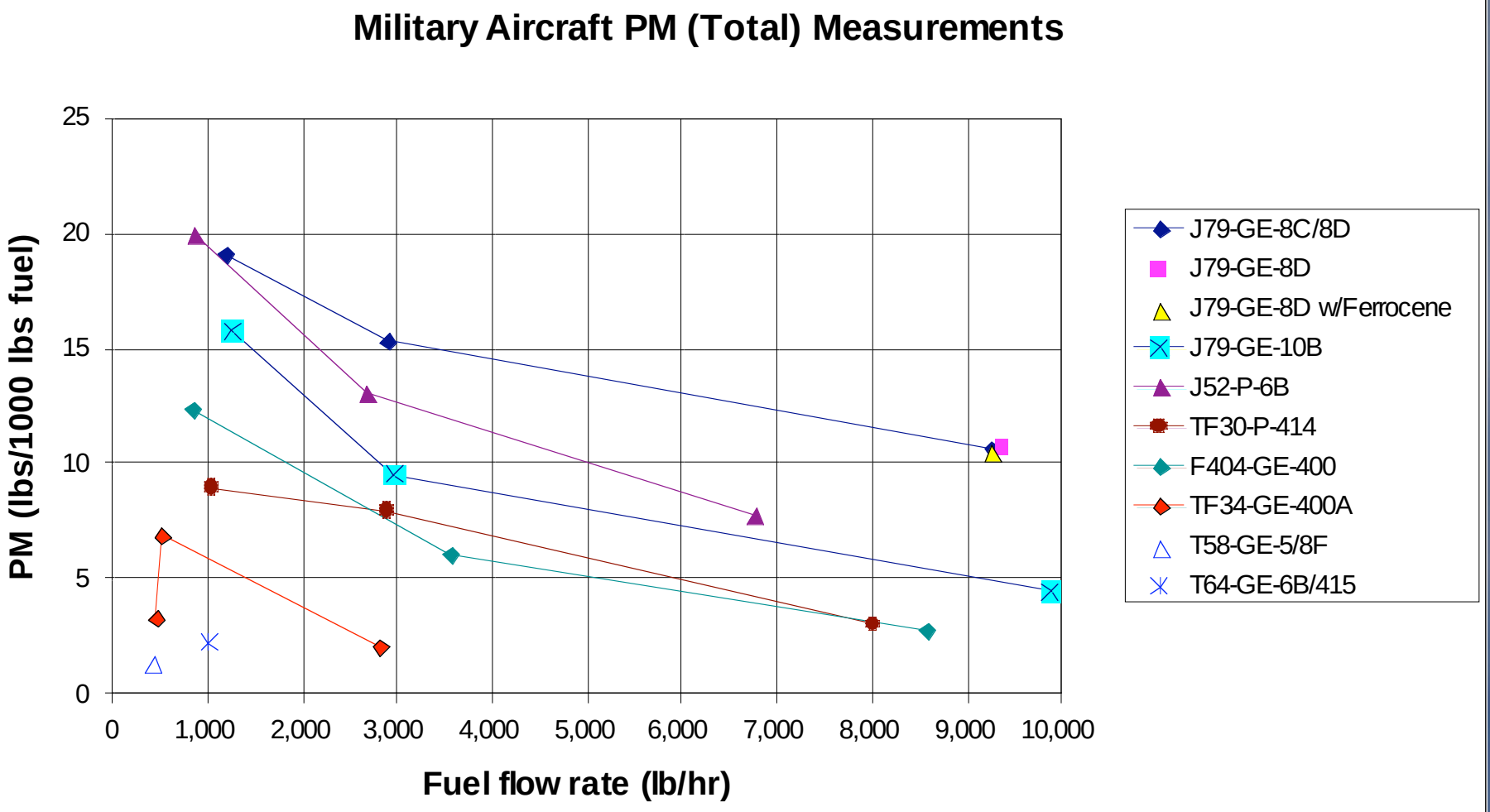
- Military Aircraft Studies
  - Navy and Air Force
  - Modified EPA Method 5
  - Aircraft Engine Test Cells (Ground Level)
- Commercial Aircraft Studies
  - Global Impacts
    - Conducted at Cruise Altitude
  - Local / Airport Vicinity
    - Ground Level

U.S. Navy Data



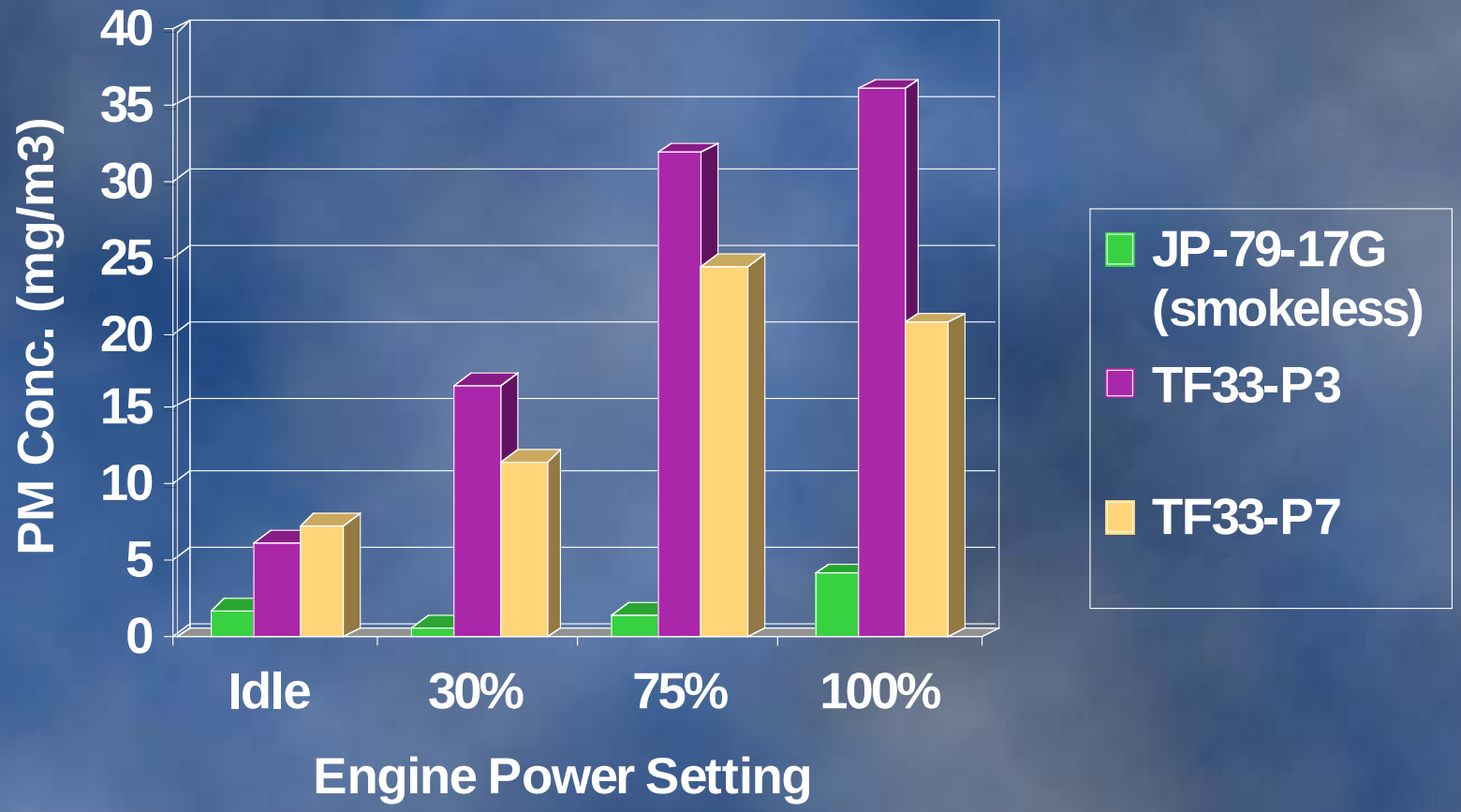
Source: *Particulate Emissions from Aircraft Engines,* AESO Report No. 2-90, Naval Air Station, San Diego, CA, June 1990.

U.S. Navy Data (continued)



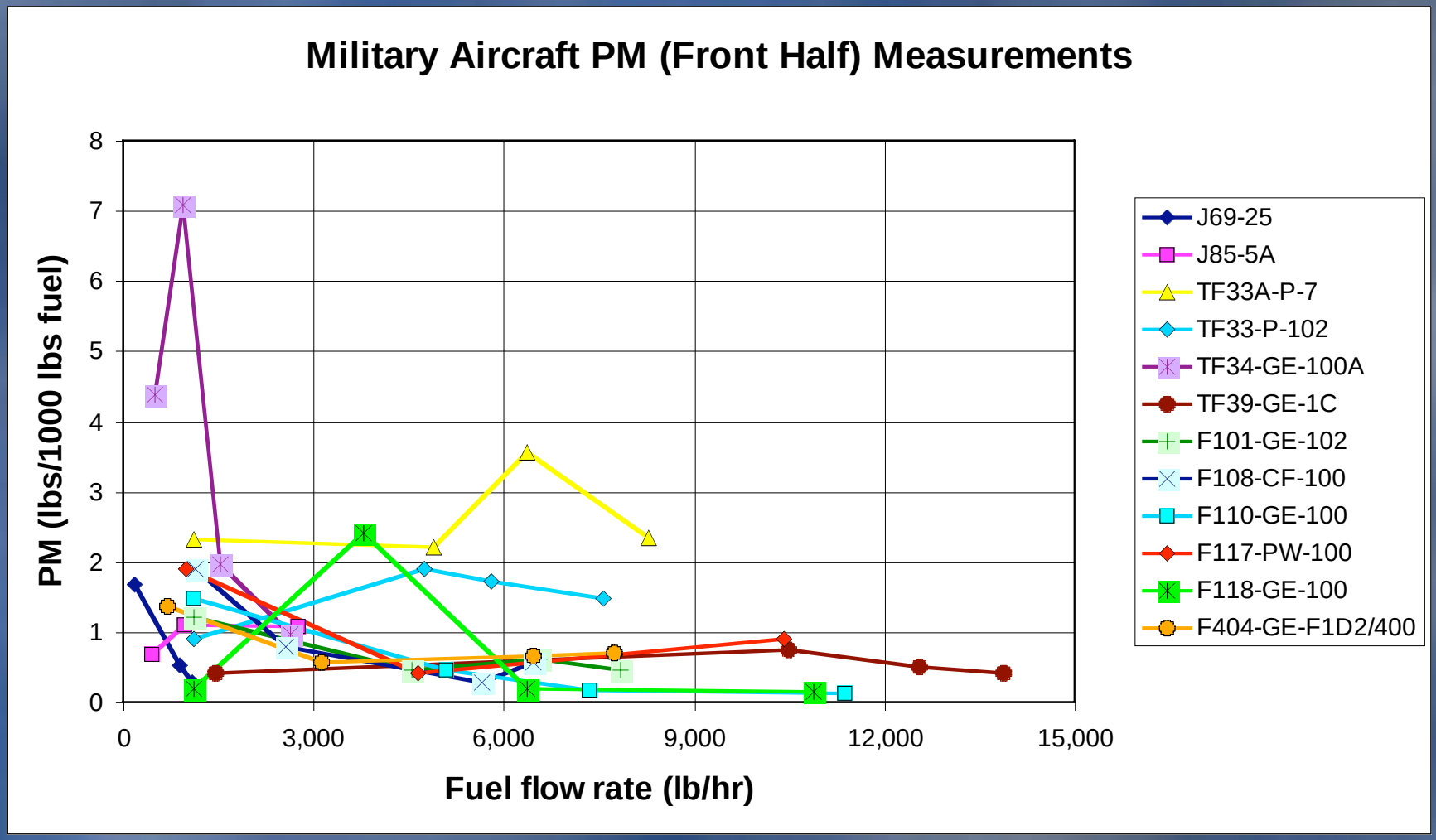
Source: *Particulate Emissions from Aircraft Engines,* AESO Report No. 2-90, Naval Air Station, San Diego, CA, June 1990.

U.S. Air Force Data



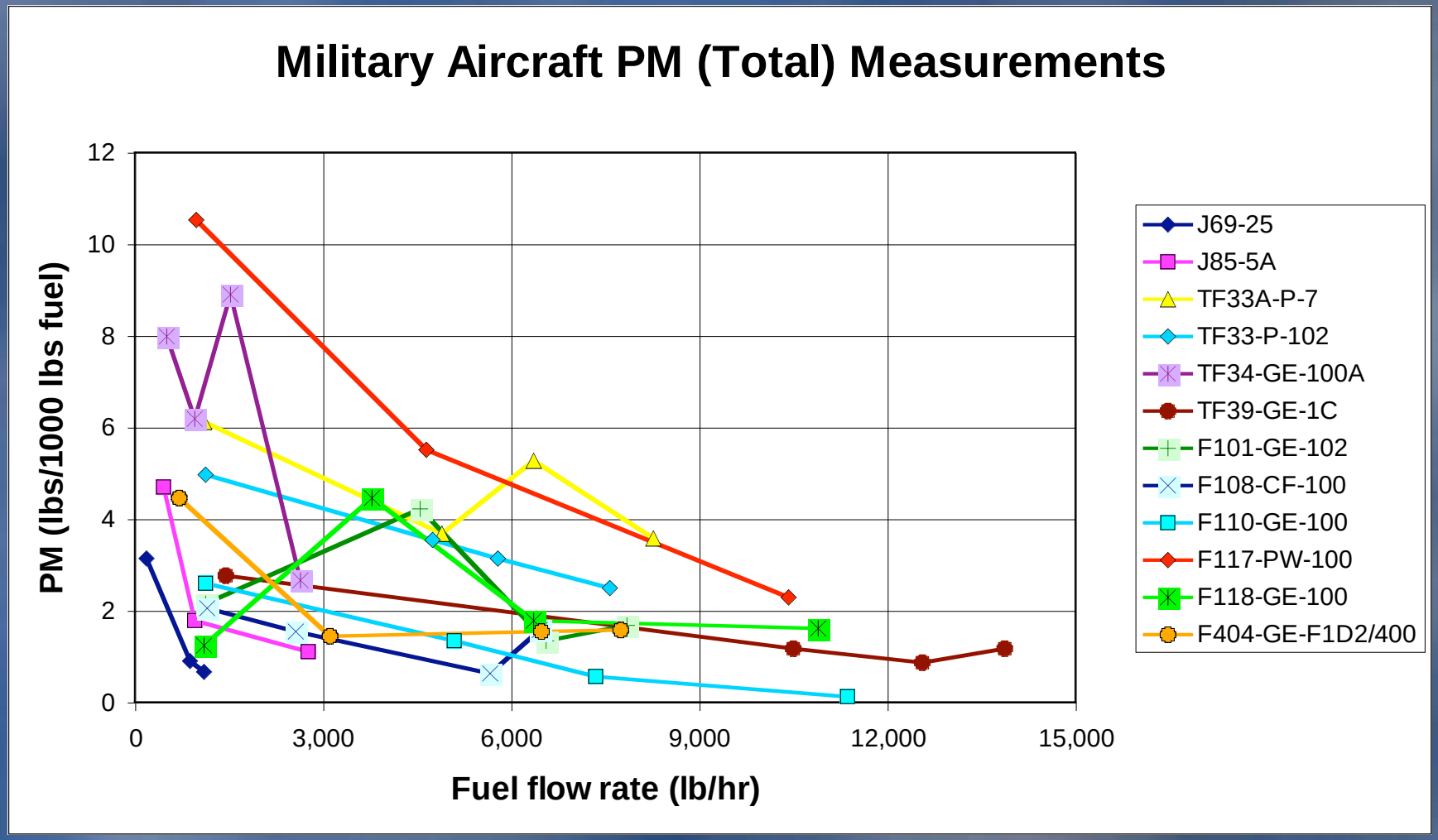
Source: Spicer, C.W., M.W. Holden, S.E. Miller, D.L. Smith, R.N. Smith, and D.P. Hughes, *Aircraft Emission Characterization*, Report No. ESL-TR-87-63, Battelle Columbus Division, Columbus, OH, March 1988.

U.S. Air Force Data (continued)



Source: Gerstle, T., P. Virag, M. Wade, and L. Kimm, Major USAF, *Aircraft Engine and Auxiliary Power Unit Testing: Volume 3, Particulate Matter Emissions*, IERA-RS-BR-TR-1999-0006-Vol.3, Institute for Environment, Safety, and Occupational Health Risk Analysis, Brooks Air Force Base, TX. March 1999.

U.S. Air Force Data (continued)



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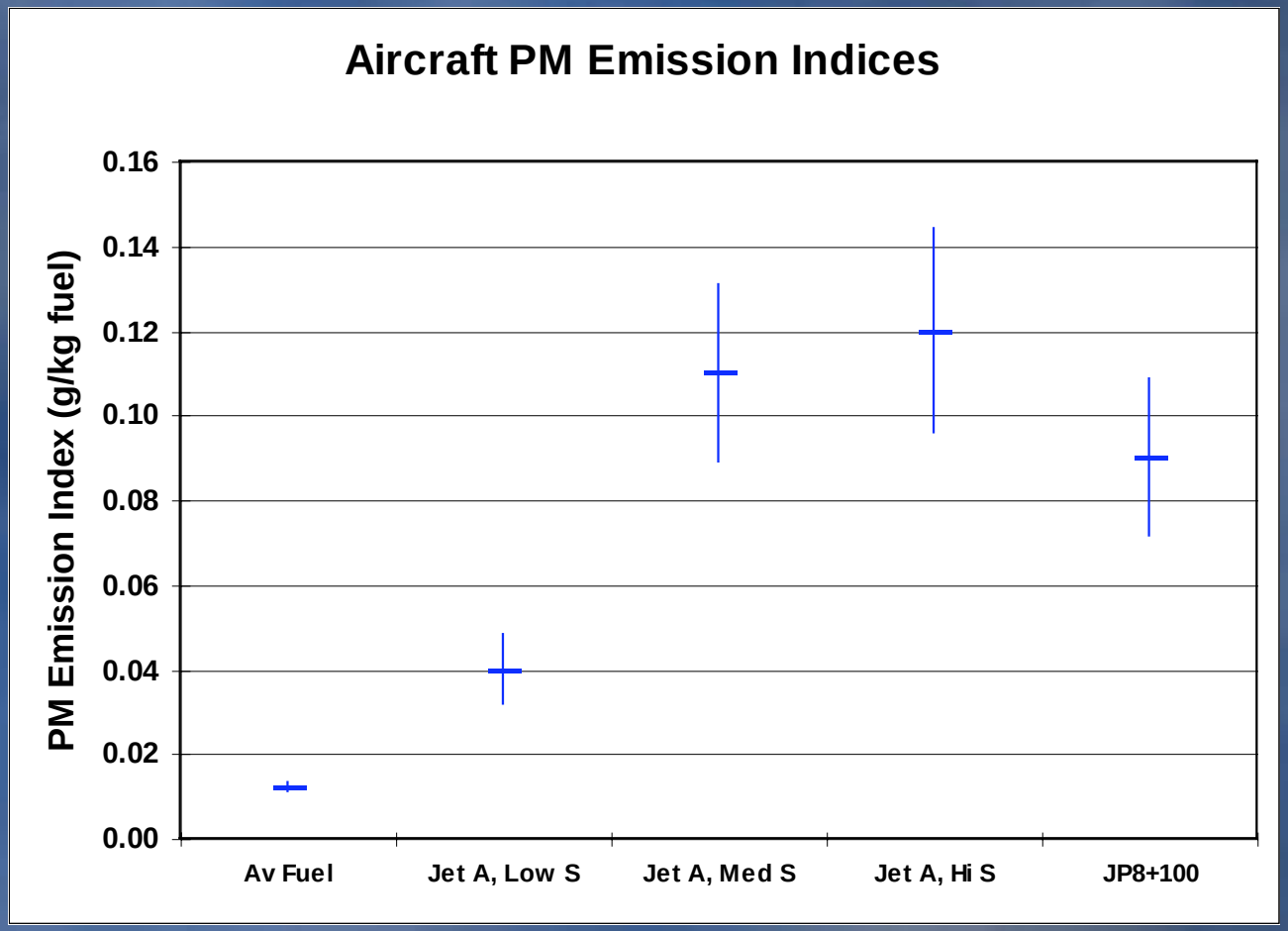
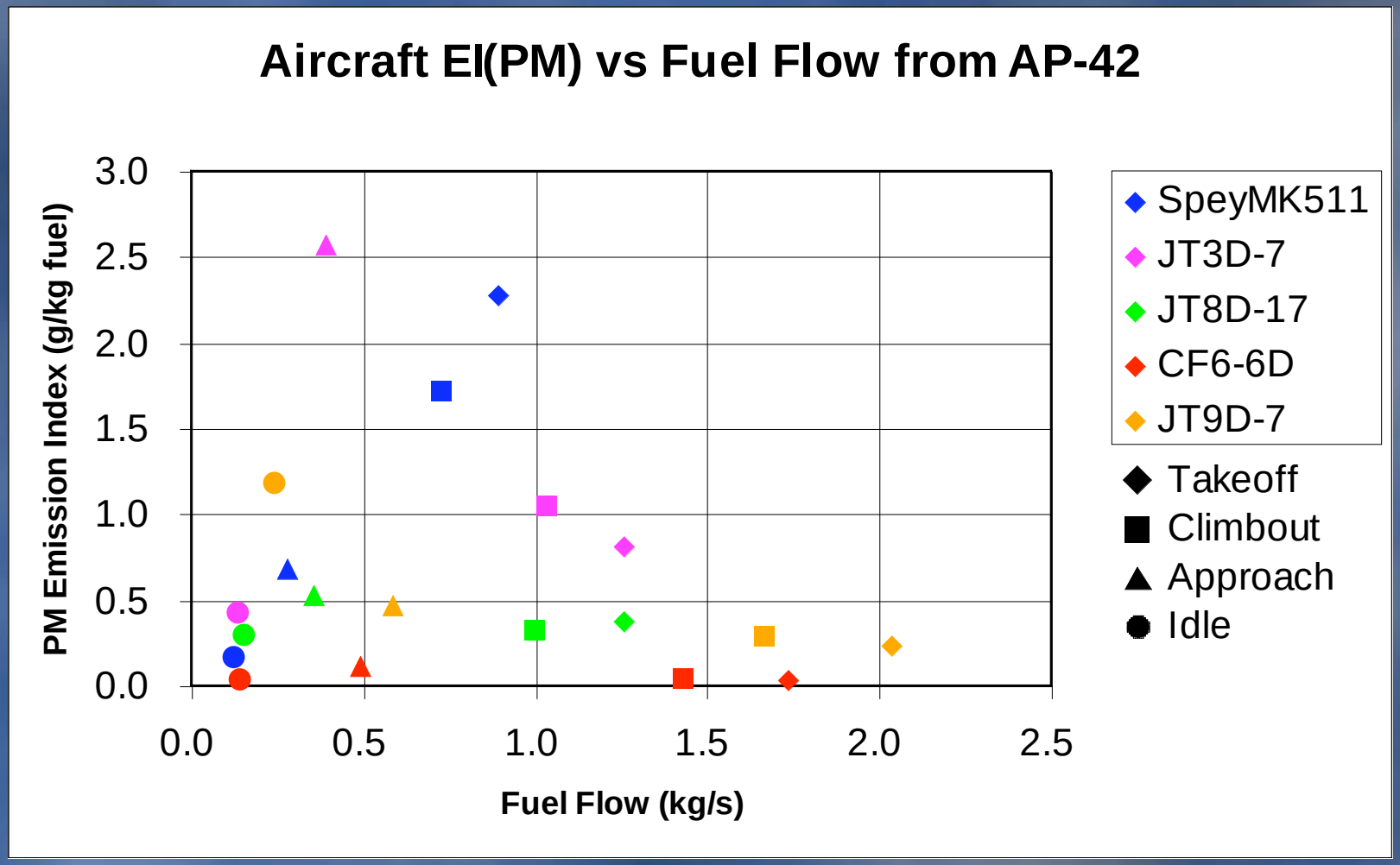
Simulated High Altitude Data



Sources: (1) Howard, R.P., R.S. Hiers, Jr., P.D. Whitefield, D.E. Hagen, J.C. Wormhoudt, R.C. Miake-Lye and R. Strange, *Experimental Characterization of Gas Turbine Emissions at Simulated Flight Altitude Conditions*, Report No. AEDC-TR-96-3, Arnold Air Force Base, TN, Sept 1996. (2) Wey, C.C., C. Wey, D.J. Dicki, K.H. Loos, D.E. Noss, D.E. Hagen, P.D. Whitefield, M.B. Trueblood, M.E. Wilson, D. Olson, J.O. Ballenthin, T.M. Miller, A.A. Viggiano, J. Wormhoudt, T. Berkoff and R.C. Miake-Lye, *Engine Gaseous, Aerosol Precursor and Particulate at Simulated Flight Altitude Conditions*, Report No. NASA/TM-1998-208509, ARL-TR-1804, Cleveland, OH, October 1998.

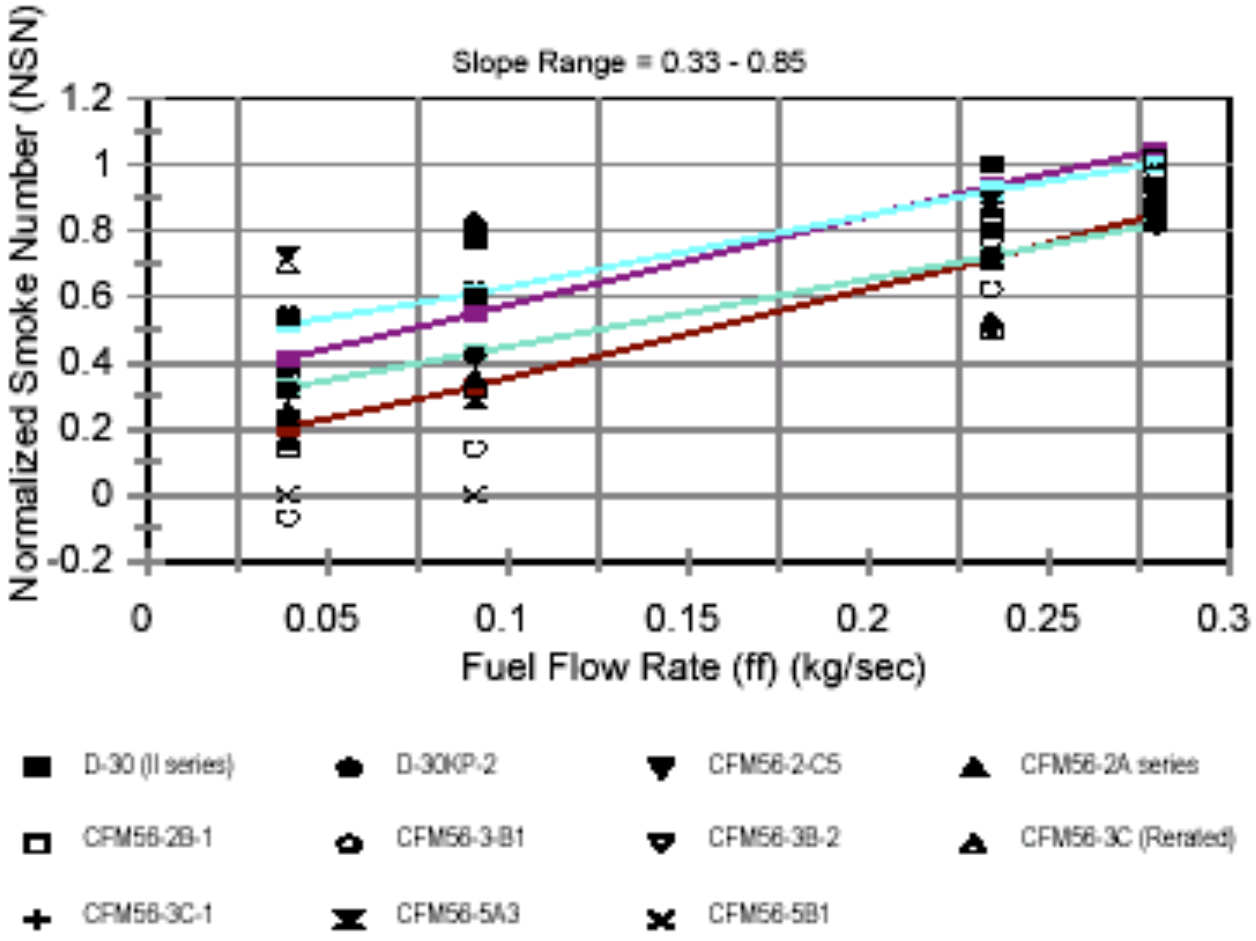
Commercial (Sea Level) Data



Sources: Platt, M., R.C. Baker, E.K. Bastress, K.M. Chng and R.D. Siegel, *The Potential Impact of Aircraft Emissions Upon Air Quality*, Report No. 1167-1, Northern Research and Engineering Corporation, Cambridge, MA, 1971.

Smoke Number vs. Fuel Flow

Figure 2. A plot of normalized smoke number versus fuel flow rate for 11 engines taken from the ICAO database.



Source: Whitefield, P.D., D.E. Hagen, G. Siple and J. Pehrson, *Estimation of Particulate Emission Indices as a Function of Size for the LTO Cycle for Commercial Jet Engines,* Paper No. 347, AWMA Annual Conference & Exhibition, Orlando, FL, June 2001.

Smoke Number vs. PM Concentration

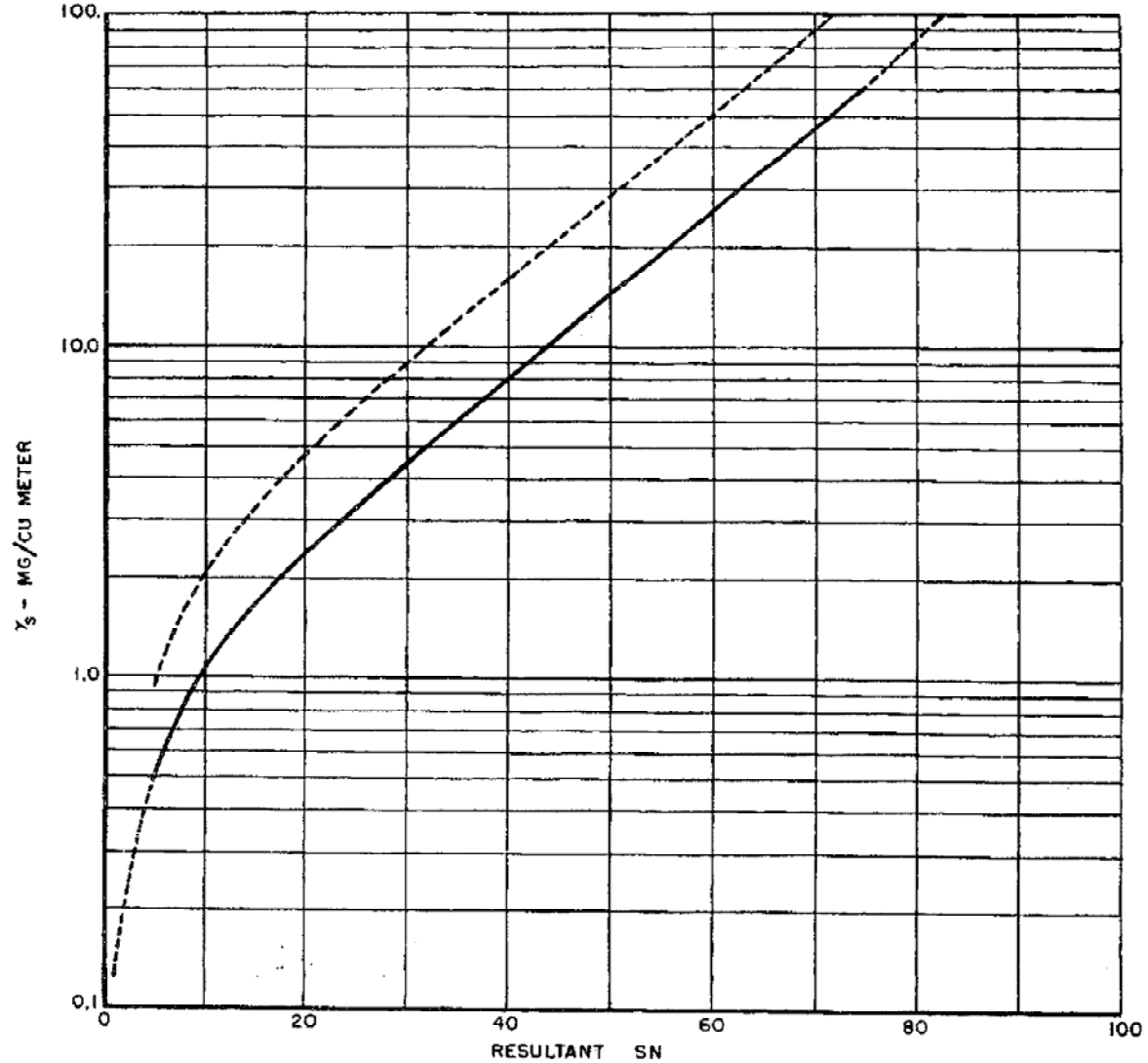
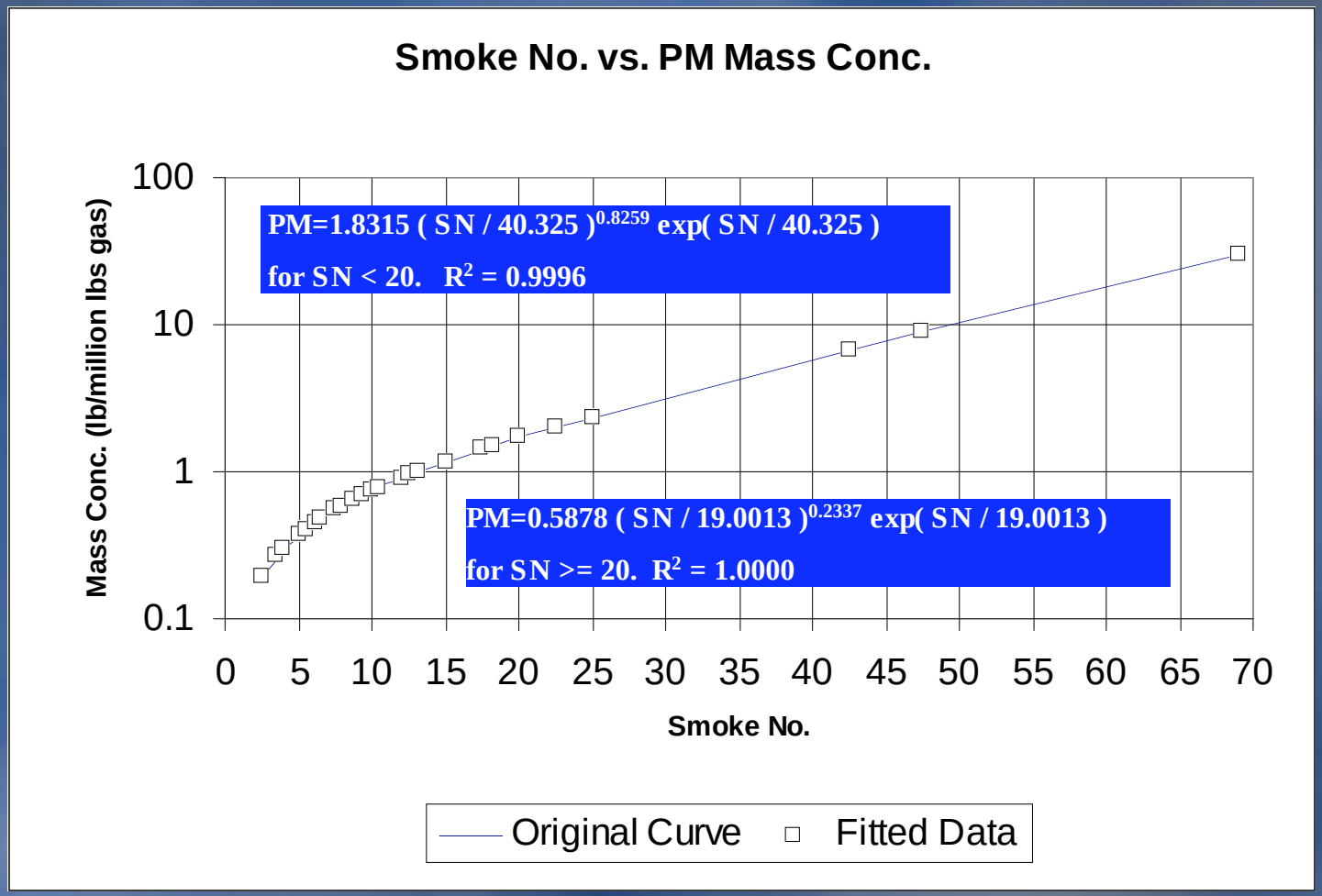


Fig. 7 Relationship between resultant SN and true smoke density (γ_S)

Source: Champagne, D.L., *Standard Measurement of Aircraft Gas Turbine Engine Exhaust Smoke,* ASME 71-GT-88, 1971.

Smoke Number vs. PM Mass Conc.



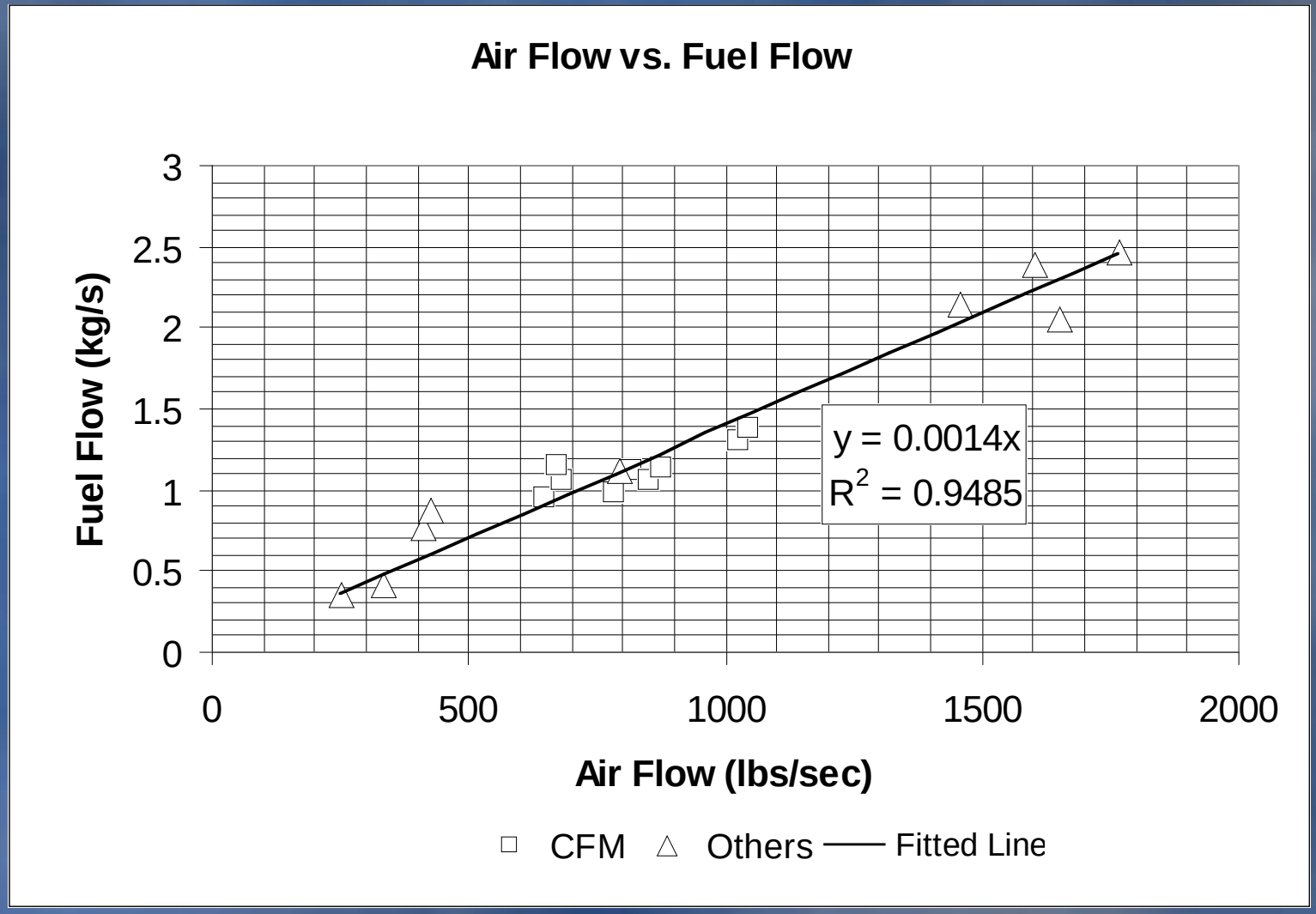
Source: U.S. EPA, California 1994 FIP Docket

Air Flow Data from the Internet

Engine	Air Flow (lb/s)	Thrust (lbs)
CFM56-2A2	817	24000
CFM56-2B1	784	22000
CFM56-3B1	646.5	18500
CFM56-3B2	683	22000
CFM56-3C1	674	18500
CFM56-5A1	852	25000
CFM56-5A3	876	26500
CFM56-5C2	1027	31200
CFM56-5C3	1045	32500
CF6-80A	1460	49000
CF6-80C2	1769	57000
JT9D-7R4	1650	52000
RB211-524	1604	56500
TAY Mk 620	414	13850
TAY Mk 650	425	15100
CF34	332	9200
ALF507-1F	252	7000
V2500	792	25000

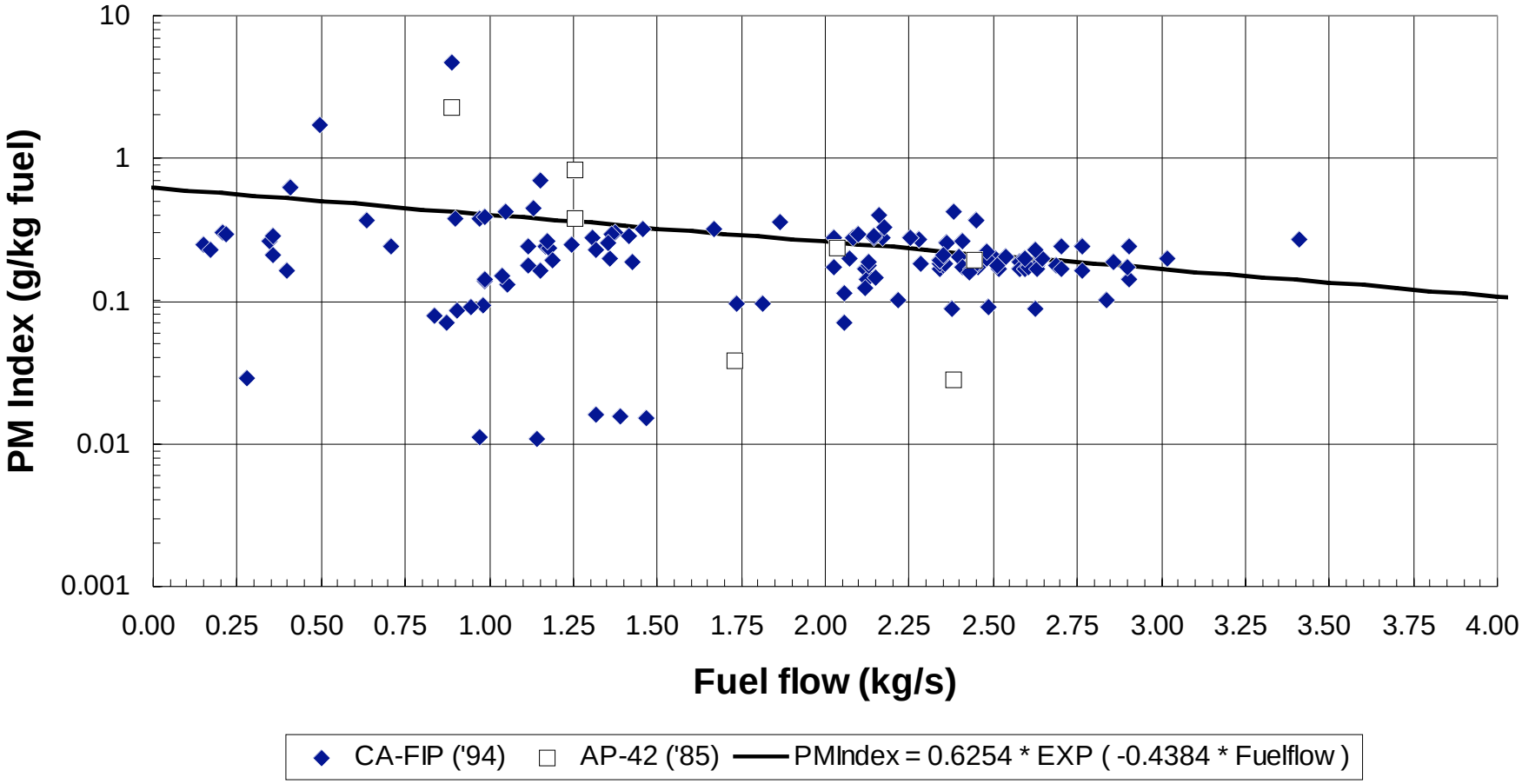
Source: CDM 1999

Air Flow vs. Fuel Flow



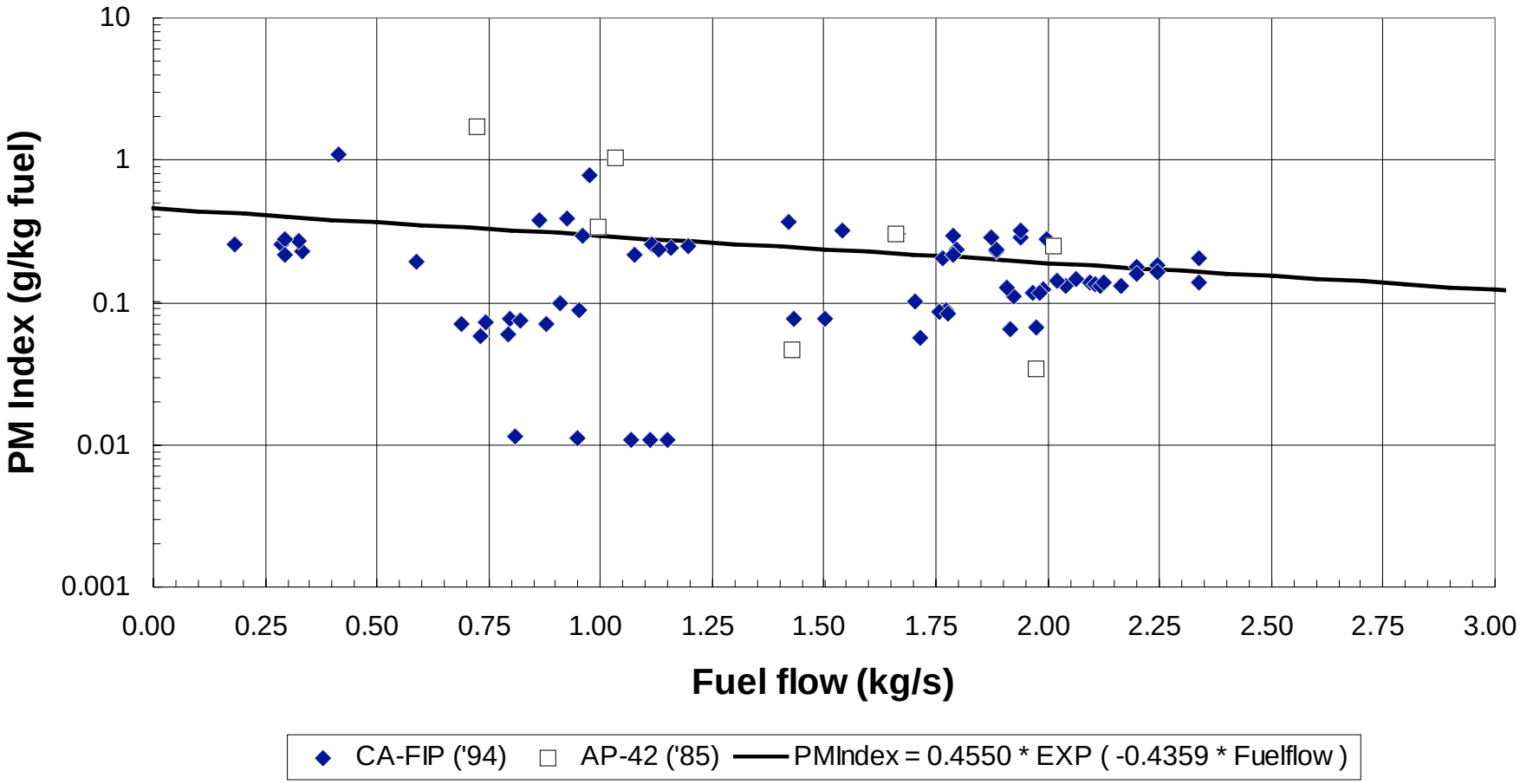
Source: CDM 1999

PM Indices - Takeoff



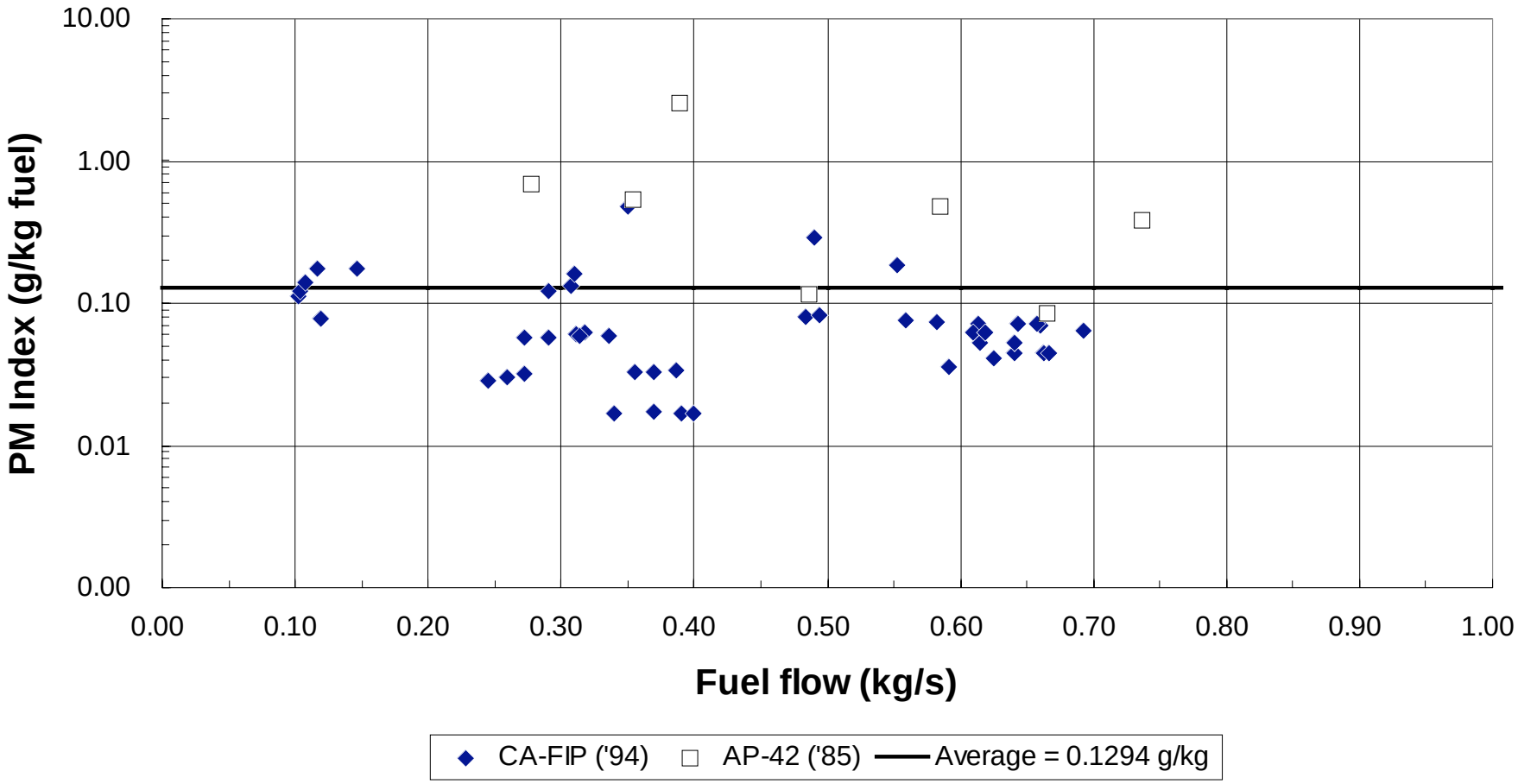
Source: Los Angeles World Airports, *Draft EIS/EIR for Proposed Master Plan Improvements,* January 2001.

PM Indices - Climbout



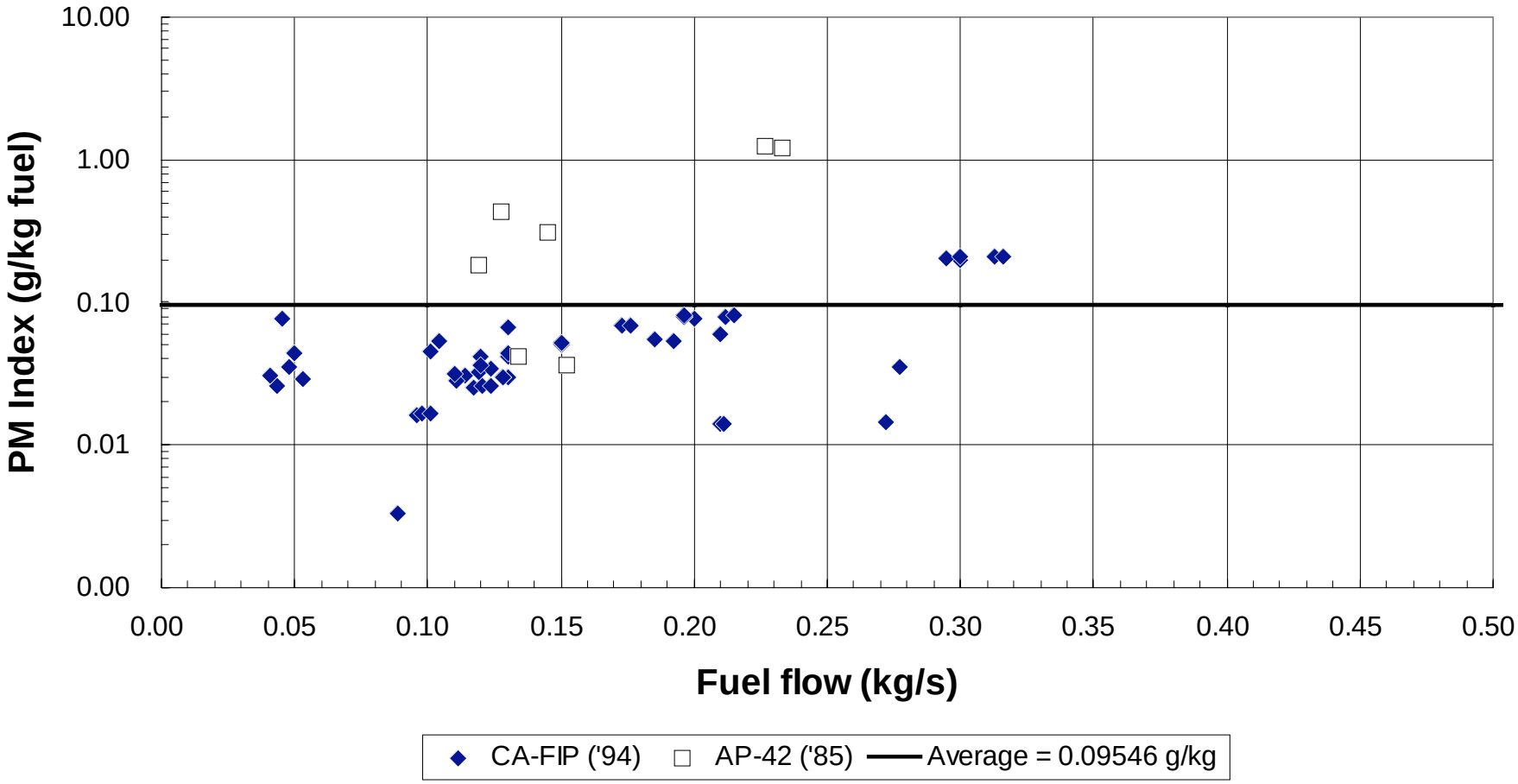
Source: Los Angeles World Airports, *Draft EIS/EIR for Proposed Master Plan Improvements,* January 2001.

PM Indices - Approach



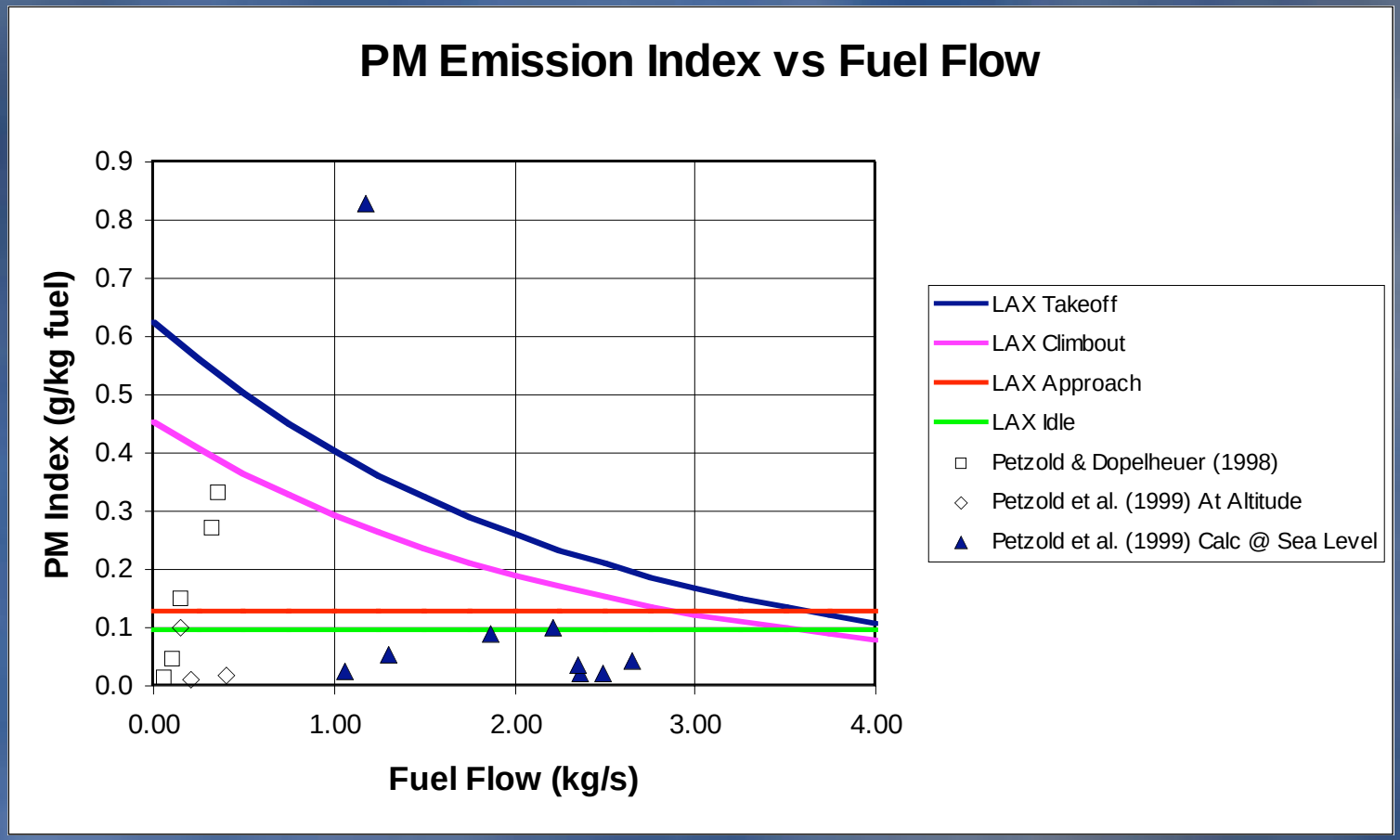
Source: Los Angeles World Airports, *Draft EIS/EIR for Proposed Master Plan Improvements*, January 2001.

PM Indices - Taxi/Idle



Source: Los Angeles World Airports, *Draft EIS/EIR for Proposed Master Plan Improvements,* January 2001.

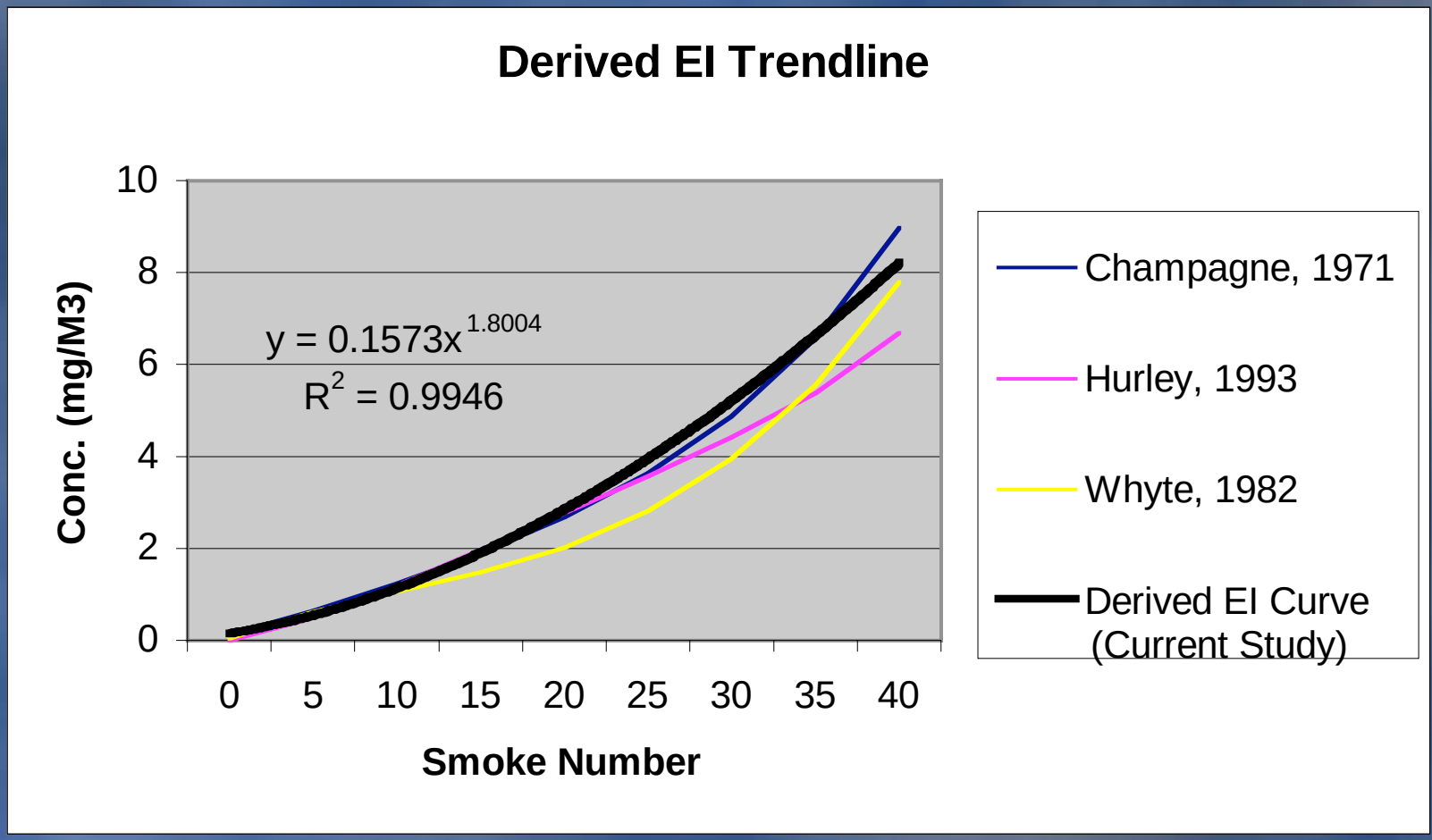
Comparison: LAX to Recent Data



Sources: (1) Petzold, A. and A. Dopelheuer, 1998. *Reexamination of Black Carbon Mass Emission Indices of a Jet Engine,* Aerosol Sci & Tech 29:355-356.

(2) Petzold, A., A. Dopelheuer, C.A. Brock, & F. Schroder, 1999. *In situ Observations and Model Calculations of Black Carbon Emission by Aircraft at Cruise Altitude,* J. Geophys Research 104(D18):22171-22181.

FAA First Order Approximation



Sources: (1) Champagne, D.L., *Standard Measurement of Aircraft Gas Turbine Engine Exhaust Smoke,* ASME 71-GT-88, 1971.
(2) Hurley, C.D., *Smoke Measurements Inside a Gas Turbine Combustor,* AIAA 93-2070, 29th Joint Propulsion Conference, Monterey, CA, 1993.
(3) Whyte, R.B., *Alternative Jet Engine Fuels,* AGARD Advisory Report No. 181, Vol. 2, 1982..

FAA First Order Approximation (cont.)

- Considered PM Conc. vs. Smoke No. from:
  - Champagne, 1971
  - Hurley, 1993
  - Whyte, 1982
- $ER(PM) = 0.6\ (\text{Fuel Flow, kg/s})\ (\text{Smoke No.})^{1.8}$
  - ER(PM) = PM Emission Index, mg/s
  - EI(PM) = ER(PM) / Fuel Flow

Sources: Wayson, R.L., G.G. Fleming, B. Kim and J. Draper, *Derivation of A First Order Approximation of Particulate Matter From Aircraft,* Paper No. 69970, AWMA Annual Conference and Exhibition, San Diego, CA, June 2003.

How Used By Regulators

- AP-42: Las Vegas (Clark Co., NV)
  - PM SIP Budget Includes Airports (w/Aircraft)
    - Made Reasonable Engine Substitutions
    - 250 tpy PM for McCarran Int'l Airport
    - 311 tpy PM for All Clark Co. airports
- AP-42: SCAQMD
  - PM SIP budget only includes aircraft specifically listed in AP-42 for which historic and forecast ops data was available
    - <10 tpy PM for All South Coast aircraft at airports

How Used by Airports

- LAX Method Used to Estimate Emissions for Proposed LAX Improvements ~ 60 tpy PM
  - 50 - 60 tpy PM
  - Emissions used in Dispersion Modeling
- FAA First Order Approximation Used to Estimate PM Emissions for Oakland Airport Development Program Supplemental EIR
  - ~10 tpy PM

Research Needs

- Aircraft PM Measurements on Modern Engines
  - Need ICAO Type Database that is consistently applied by airports and regulators
    - Jet A Fuel
    - Newer Engines
    - Verify Difference Between Jet A & Diesel
  - Ongoing Global Impact Investigations
    - PM vs CO2 Tradeoffs?