Motor Vehicle Emissions

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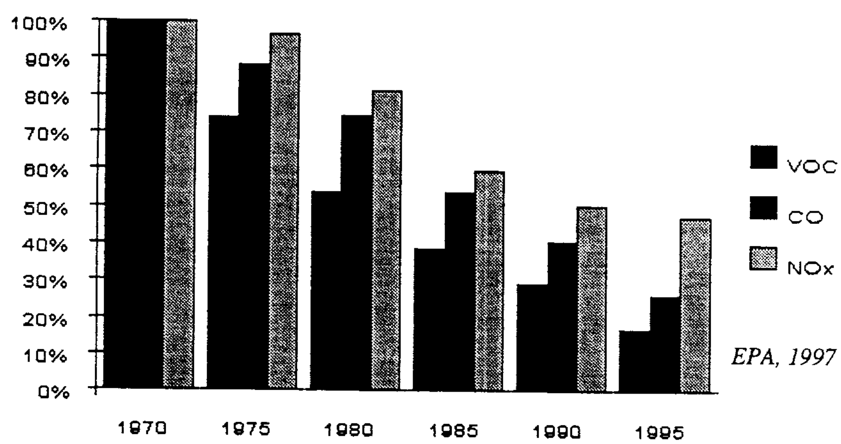
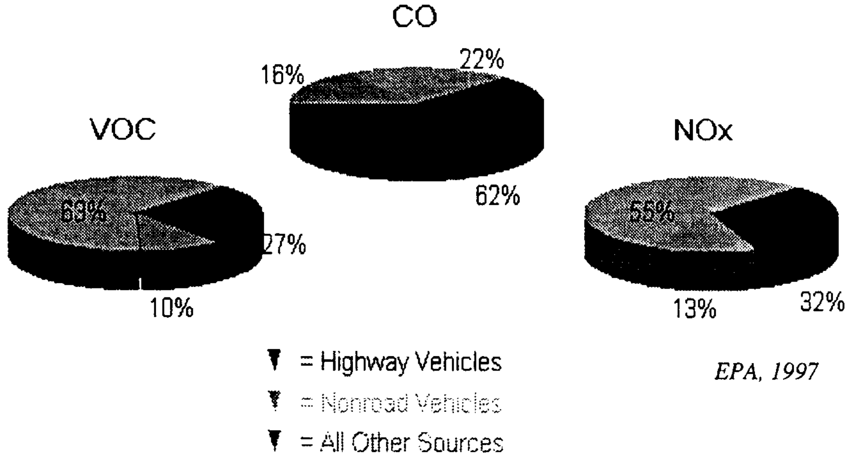
Fleet Average Emissions as a Percentage of 1970 Levels



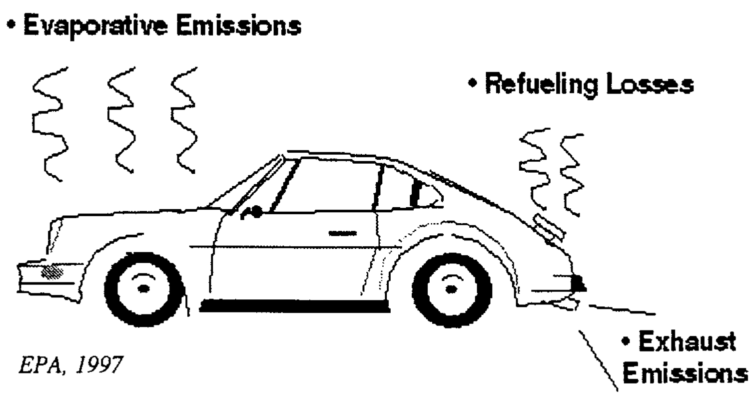
EPA, 1997

Emissions in 1994



EPA, 1997

Vehicle Emissions Sources



EPA, 1997

Emission Formation

Combustion Products

Evaporation

Atmospheric Chemistry

Combustion of Hydrocarbons Formation of CO and HC

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$C_nH_m + \left(n + \frac{m}{4}\right)O_2 \rightarrow (n)CO_2 + \left(\frac{m}{2}\right)H_2O$$

- **Gasoline is a complex soup of hydrocarbons**
- **With insufficient air or temperature:**
  - CO formation
  - Some fuel (HC) remains unburned

Ambient Air Composition

- Nitrogen (N2) - 78%
- Oxygen (O2) - 21%
- Argon (Ar) - 1%
- Carbon Dioxide (CO2) - 0.03%
- Trace amounts of: methane, krypton, hydrogen, xenon, helium, neon, nitrous oxide, etc.

Combustion: Formation of NOx

- In the ambient air, for every mole of oxygen there are 3.76 moles of nitrogen, thus:

$$C_nH_m + \left(n+\frac{m}{4}\right)O_2 + 2(3.76)N_2 \rightarrow (n)CO_2 + \left(\frac{m}{2}\right)H_2O + 2(3.76)N_2$$

- However, at high temperature and pressure, the nitrogen becomes reactive:

In cylinder: $N_2 + O_2 \longrightarrow 2NO$

Later in ambient air: $2NO + O_2 \longrightarrow 2NO_2$

High Exhaust CO and HC Emissions

- **High CO:**
  - Incomplete combustion (insufficient O_2)
  - Incomplete catalyst HC conversion

- **High HC:**
  - Incomplete combustion (insufficient O_2)
  - Cylinder wall quenching
  - Gaps and Crevices
  - Misfiring (raw and pyrolized gas)
  - Transients: manifold flash-off (burdens catalyst)

Hydrocarbon Emissions

Unburned and Partially Burned Fuel

- **Evaporation**
  - Refueling
  - Diurnal and multi-day diurnal tank losses (volatility)
  - Hot soak
  - Running evaporative emissions – fuel circulation
  - Consumer products (washer fluid is often methanol)
- **Exhaust**
  - Crankcase blow-by
  - Incomplete combustion (exhaust)
  - Control system efficiency (catalyst warm-up)

Evaporative Emissions

- **Function of temperature and fuel volatility**
- **Fuel tank air becomes saturated with gasoline vapors**
  - When fuel is pumped into the gas tank, vapors are displaced into the atmosphere
  - Diurnal expansion of headspace drives vapors out of tank as temperature rises during the day
- **Other losses**
  - Liquid leaks (high emitters)
  - Durability of materials and seepage - resting losses

Super Emitters

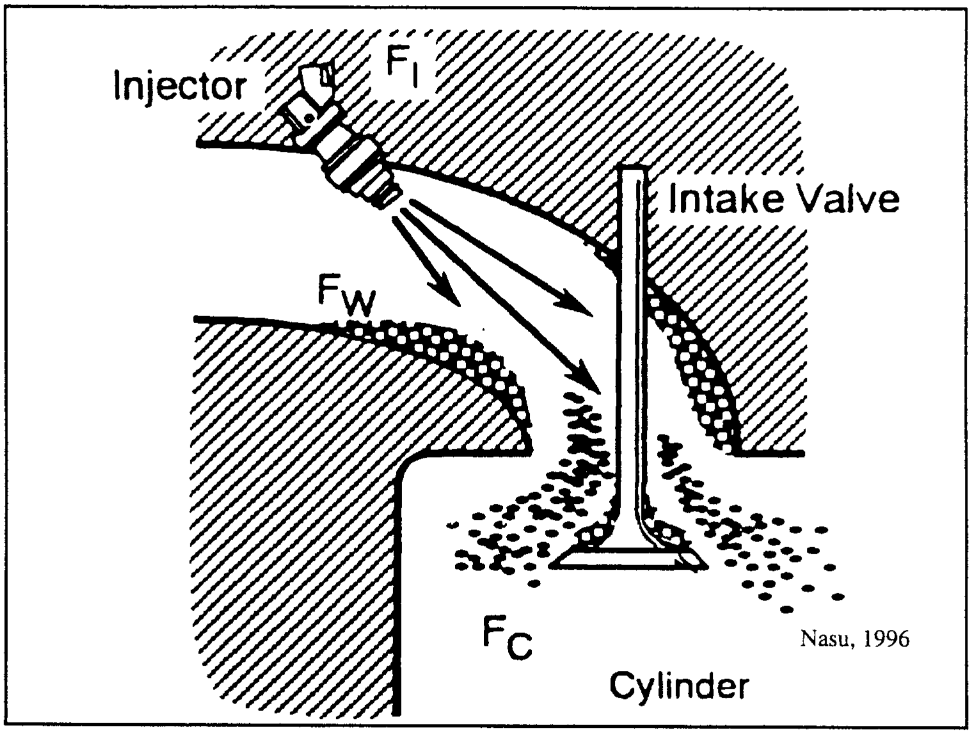
- **A small fraction of vehicles account for a large fraction of fleet emissions:**
  - "5% of the vehicles are causing 50% of the pollution"
- **Generally these vehicles are high emitters under most testing conditions**
- **Conclusions are inferred from data collected in the lab or in the field during laboratory testing, remote sensing [CO] studies, or roadside I/M validation**

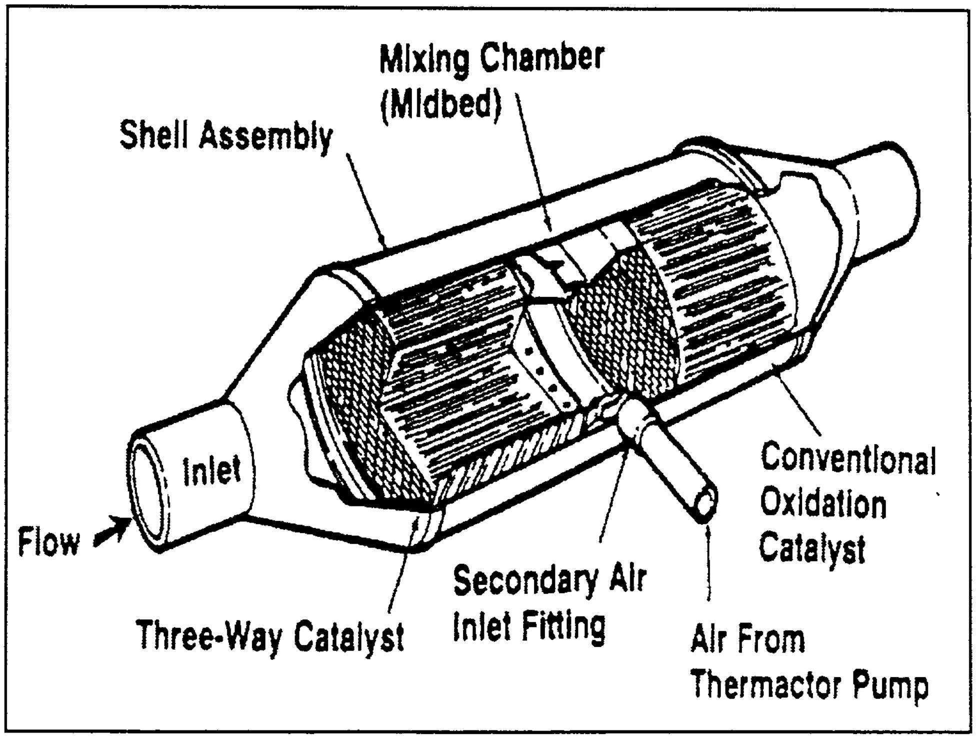
Fuel Delivery System Impacts

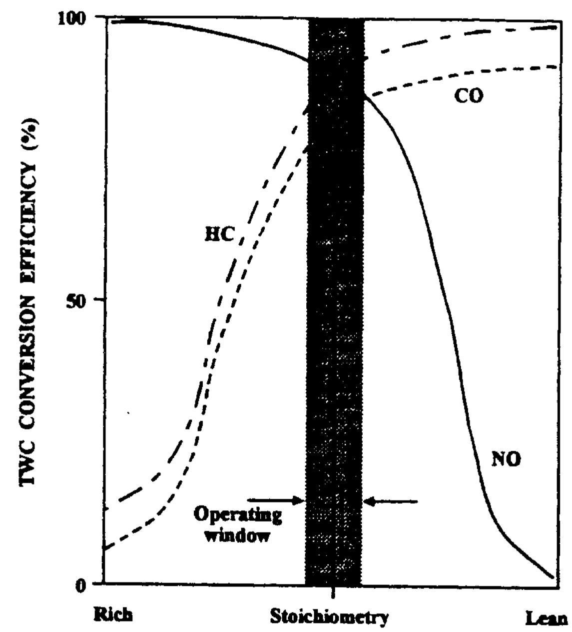
- **Combustion control (air:fuel) is less flexible and responsive with carbureted systems**
- **Running exhaust and evaporative emissions are high with carburetors**
- **Fuel injected vehicles behave significantly differently from carbureted in laboratory testing**
- **Large technology shift in 1980 and again in 1987, notable in onroad emission rates for the fleet**

Fuel Delivery Technologies

- **The most critical emission-related factor is air:fuel control**
- **Hundreds of variations of three basic technologies:**
  - Carburetion
  - Throttle Body Injection
  - Port Fuel Injection


Injector
F_I
Intake Valve
F_W
F_C
Nasu, 1996
Cylinder


Mixing Chamber
(Midbed)
Shell Assembly
Inlet
Flow
Conventional
Oxidation
Catalyst
Secondary Air
Inlet Fitting
Three-Way Catalyst
Air From
Thermactor Pump



Source: Chowanietz, 1995

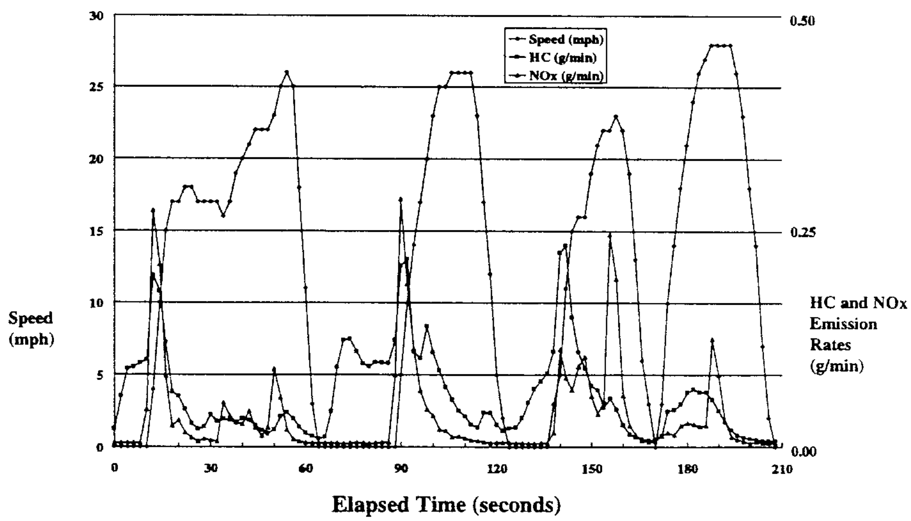
Super Emissions (Enrichment Emissions)

- **A small fraction of a vehicle's activity accounts for a large fraction of the vehicle's emissions:**
  - "5% of each vehicle's activity is causing 50% of the vehicle's emissions"
- **High fuel/air ratio (insufficient oxygen)**
- **2000 to 3000 times normal g/sec CO rates for clean cars**
- **All vehicles undergo some enrichment**
  - By design (performance or component protection)
  - By failure (faulty sensors)

Commanded Enrichment

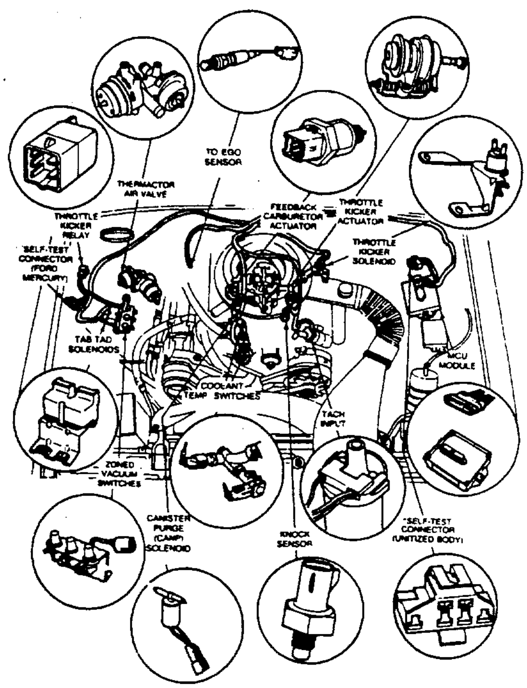
- Engine operating parameters (rpm, map, Δmap, Δtp, etc.) are monitored and used to determine instantaneous change in air:fuel ratios
- Various ECU control schemes employed
- As power is demanded for acceleration, grade climbing, or accessory use, or increased torque is needed, the ECU adjusts air:fuel
- Peak torque occurs at ratios more rich than stoichiometric… command enrichment
- As temperatures rise due to increased power output, components can be damaged… command enrichment

1990 Caravan - FTP Segment
Hot Stabilized Mode
Second-by-Second Speed and Emission Data



Electronic Control Units (ECUs)

- **Parameters Monitored:**
  - Time from engine start
  - Coolant temperature
  - Intake manifold temperature
  - Engine speed (rpm)
  - Manifold absolute pressure
  - Change in manifold absolute pressure
  - Throttle position
  - Change in throttle position
  - Exhaust gas oxygen content
  - Knock (listening device)



Stubblefield and Haynes, 1994

Engine Technology Conclusions

- **The ECU reads sensor signals and controls actuators**
- **Computer controls maintain air:fuel ratios and affect both engine-out and catalyst-out emissions**
- **Vehicle performance and emissions control are both inexorably tied to computer control systems**
  - Programming and sensor and actuator condition
- **Emissions control strategies need to tie back to these technologies (inspection and maintenance and OBD)**
- **Emissions modelers also needs to keep in mind that vehicle technologies (fleet characterization) significantly affect estimates**

Motor Vehicle Emission Control Strategies

- **New Vehicle Certification Programs**
- **Inspection and Maintenance**
- **Onboard Diagnostics**
- **Clean Fuels**
- **Transportation Control Measures**

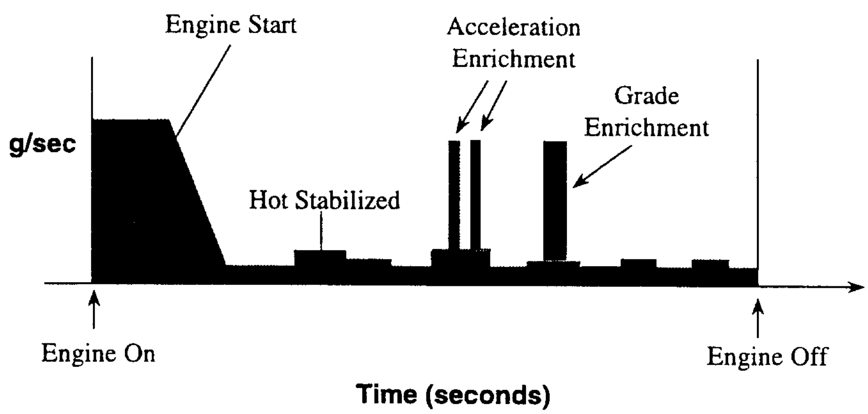
Modeling

- **Using a mathematical representation of 'reality' to forecast future conditions (e.g. emissions levels, traffic volumes, congestion, etc.)**
  - Represent cause-effect relationships
- **Accuracy and confidence in outputs are important issues, but their importance depends upon model use**
  - Will random input errors cancel each other out?
  - Does it matter if the model always underestimates emissions by 20%?
  - Does it matter if the model outputs are +/- 10% or +/- 70%?

General Model Development Strategies

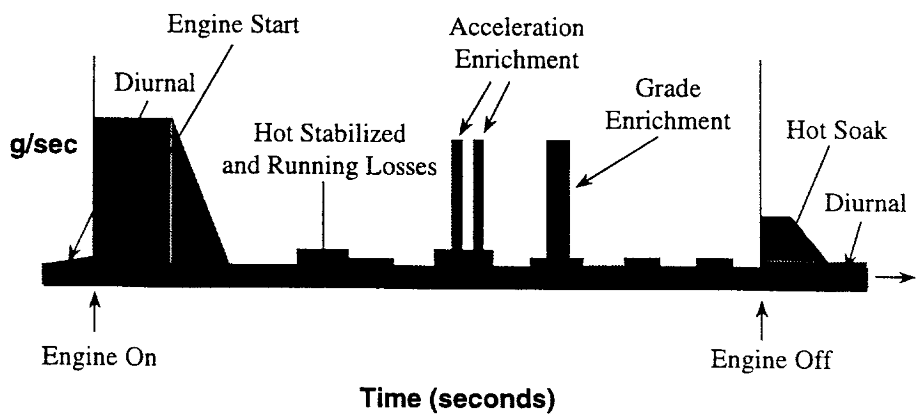
- **Test representative samples of vehicles and fuels**
- **Identify emissions-producing activities and test representative operating modes**
- **Define and control influential variables**
- **Investigate and model interactions**
- **Over-sample infrequent emissions-critical events**
- **Improve spatial and temporal emissions allocation**
- **Compare laboratory and onroad data**
- **Explicitly address uncertainty**
- **Validate, validate, validate ...**

Carbon Monoxide Emission Rates for a Hypothetical Trip



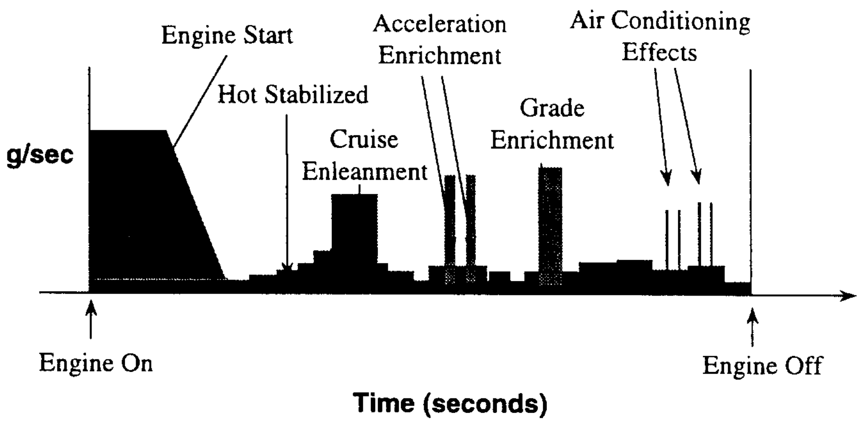
Bachman and Guensler, 1996

Hydrocarbon Emission Rates for a Hypothetical Trip



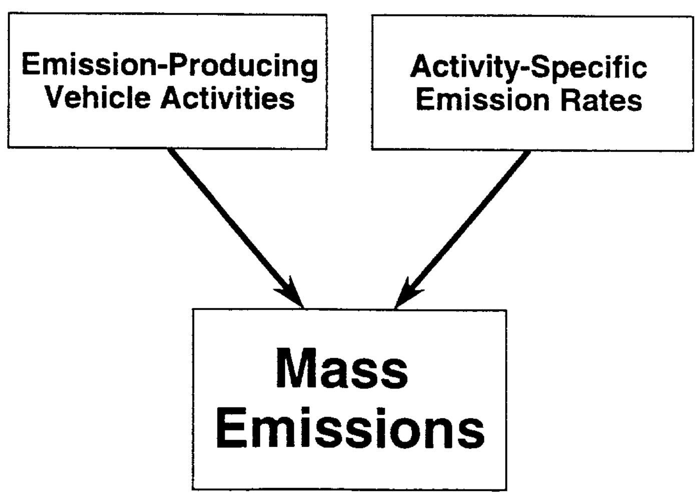
Bachman and Guensler, 1996

Oxides of Nitrogen Emission Rates for a Hypothetical Trip



Bachman and Guensler, 1996

Emission Estimation



Guensler, 1993

Emission-Producing Vehicle Activities and Emissions Produced

Vehicle Miles Traveled →	Running Exhaust Running Evaporative
Engine Starts →	Elevated Running Exhaust
Hot Soaks →	Evaporative
Engine Idling →	Running Exhaust Elevated Evaporative
Exposure to Temp Cycles →	Evaporative
Vehicle Refueling →	Evaporative
Modal Behavior →	Elevated Running Exhaust

Guensler, 1993

Activity-Specific Emission Rates

Vehicle Parameters

Operating Conditions

Fuel Parameters

Environmental Factors

Guensler, 1993

Vehicle Parameters Impacting Emission Rates

Vehicle Class

Model & Year [weight, engine size, HP, etc.]

Accrued Vehicle Mileage

Fuel Delivery System

Emission Control System

Onboard Computer Control System

Control System Tampering

Inspection and Maintenance History

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Fuel Parameters Impacting Emission Rates

Fuel Type

Oxygen Content

Fuel Volatility

Sulfur Content (SOx)

Benzene Content

Olefin and Aromatic Content

Lead and Metals Content

Trace Sulfur - Catalyst Effect*

Guensler, 1993

Environmental Factors Impacting Emission Rates

Altitude

Humidity

Ambient Temperature

Diurnal Temperature Sweep

Road Grade*

Guensler, 1993

Vehicle Operating Conditions Impacting Emission Rates

Engine Start Condition (soak duration)

Average Vehicle Speed

Modal Activities - Enrichment & Enleanment

Other Loads (e.g., towing, a/c, passengers)

Trip Length and Number of Trips per Day

Influence of Driver Behavior

Guensler, 1993

General Modeling Approach

- **Laboratories test vehicles on the FTP and other driving cycles, using various fuels, and under a variety of environmental conditions**
- **Analysts develop baseline emissions rates (grams/mile or grams/hour) for various vehicle groups (vehicle class and model year) on a standard test cycle (FTP)**
- **Modelers develop correction factors to modify the baseline emissions rates for conditions that differ from the FTP (most of which are assumed to be independent from each other)**

Laboratory Testing Data

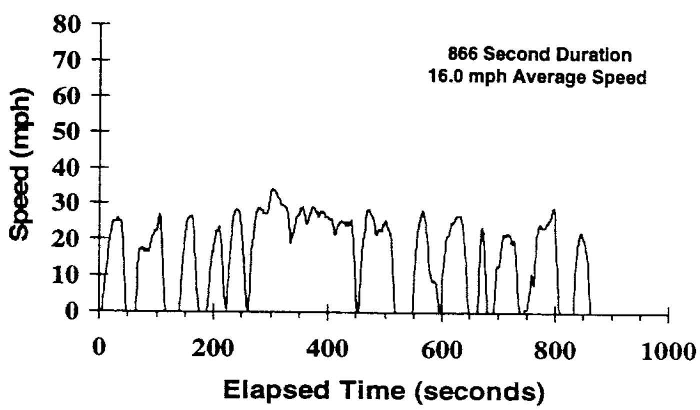
- **Emissions data collected under controlled conditions**
  - Vehicle Parameters
    - Record all relevant technology characteristics
  - Operating Conditions
    - Standardized driving cycles
  - Fuel Parameters
    - Indolene test fuel
  - Environmental Factors
    - Temperature, humidity, altitude, etc.

Sources of Vehicle Emissions Data

- **More than 30,000 in-use vehicles have been tested by public agencies using the standardized driving cycle knows as the Federal Test Procedure (FTP)**
- **Other data sources:**
  - Manufacturer FTP data
  - Tests conducted on other laboratory test cycles
  - Inspection and maintenance two-speed idle tests
  - IM240 inspection and maintenance dynamometer tests
  - Remote sensing device data
  - Instrumented vehicle data

Federal Test Procedure - Bag 2

Hot Stabilized Test - Vehicle is not Stopped after Bag 1
Speed vs. Time Trace



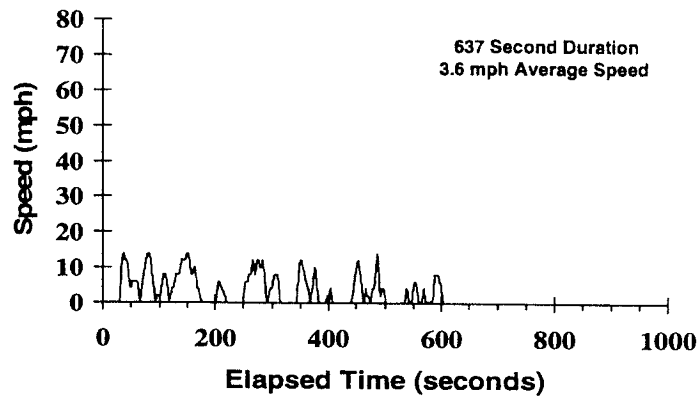
Engine Loads and Induced Emissions

- **As engine loads increase (hard accelerations, high speeds, moderate accelerations at high speeds) g/second emissions generally increase**
- **Slower congested conditions lead to elevated emissions, especially when translated to grams/mile units**
- **EPA represents these higher emissions relationships within speed correction factors**
  - g/mile rates assumed to be a function of average speed

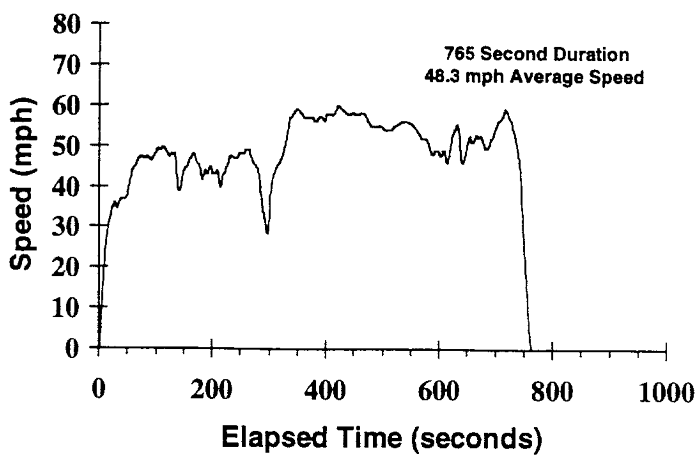
Speed Correction Factors

- **EPA and CARB tested 540 vehicles across 12 test cycles with different average speeds**
- **EPA staff developed a statistical relationship between emission rates and average speeds**
- **A number of technology groups were employed in the modeling effort (between 13 and 26)**

Low Speed 2 Cycle Speed vs. Time Trace

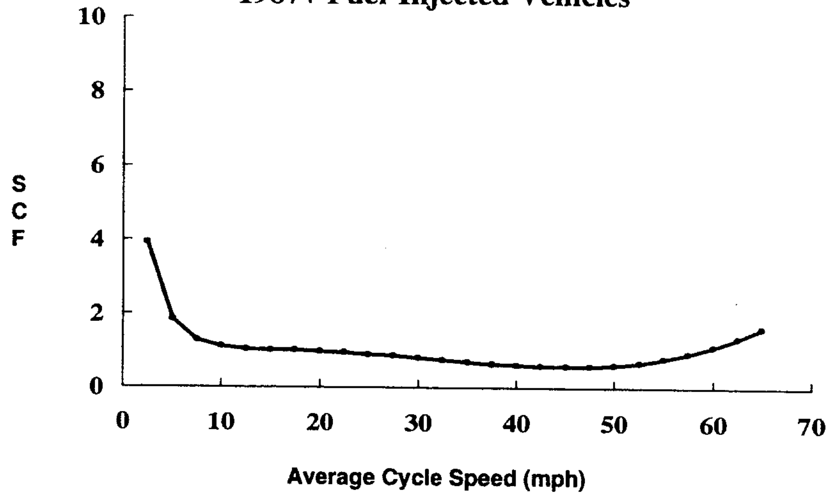


Highway Fuel Economy Test Speed vs. Time Trace

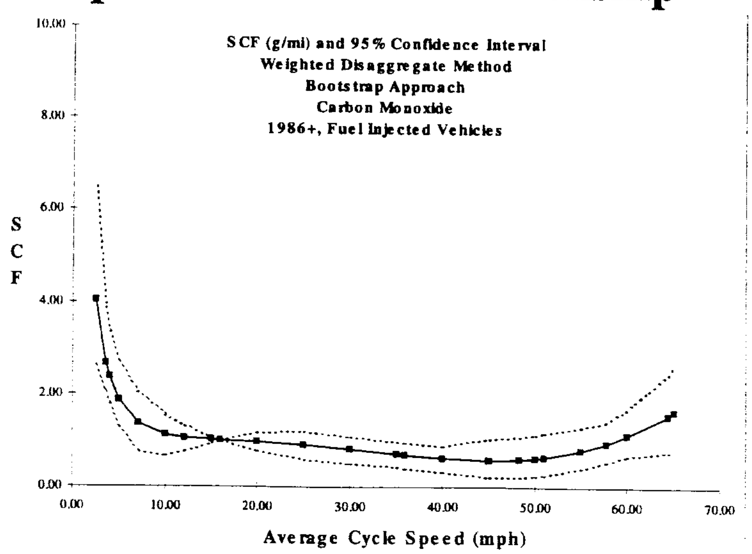


CO Speed Correction Factor (g/mile) vs. Average Cycle Speed

1987+ Fuel-Injected Vehicles



Speed-Emissions Relationship



Speed Correction Factor Notes

- **Assumes a representative vehicle sample**
- **The curves represent average emission responses only for the activity represented within the testing cycles (limited high speed and acceleration)**
- **Confidence intervals are wide due to tremendous response variability across all average speeds and limited data in the high speed region**
- **The speed correction factors are highly aggregated**
  - Freeway and arterial modes at 35 mph are not the same
- **MOBILE6 will provide separate emission rates for roadway classification and level of service**

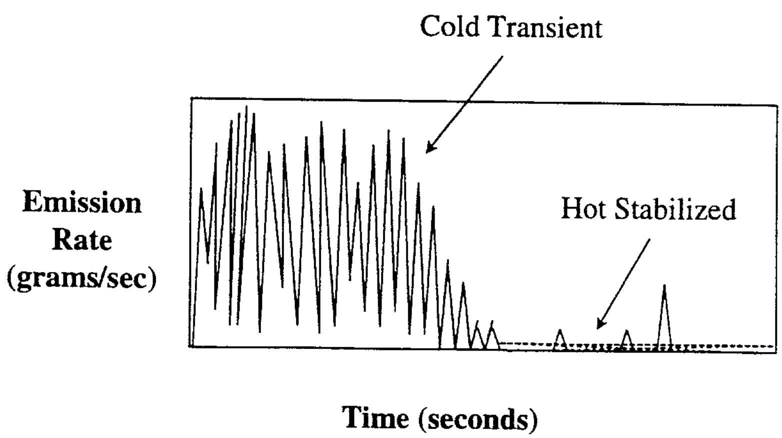
Deterioration

- **As vehicles age, emission rates increase associated with accumulated vehicle mileage and degradation of emission control systems**
- **MOBILE5a employs linear corrections to increase MY emission rates as a function of mileage accrual (grams/mile/10,000 miles accrued)**
  - Higher deterioration rates after 50,000 miles
- **Current studies show that post-1994 vehicles are deteriorating at significantly lower rates (near zero)**
  - MOBILE6 will reflect this finding
  - Durability of sensors and actuators and OBD are key

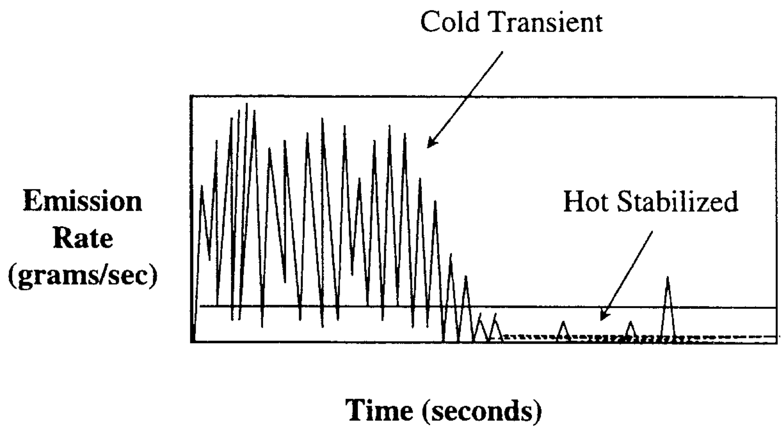
Engine Starts

- **Elevated emissions:**
  - Commanded enrichment (timed)
  - Combustion stabilization (coolant temperature)
  - Catalyst light-off time
- **Emissions are high during the first 1-3 minutes**
- **Emissions are a function of:**
  - Vehicle technology, engine programming, soak time, how the vehicle is driven after engine start
- **Technologies behave differently at engine start**
- **Model as elevated emissions (g/mi) or a puff (g/start)**

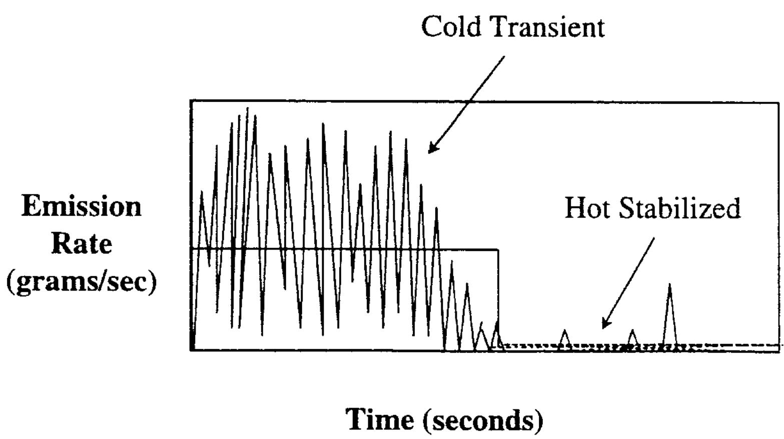
Engine Start Emissions
FTP Bag 1



Elevated Emissions From Engine Start
MOBILE5



Incremental Engine Start Emissions
MOBILE6



Problems with Existing Engine Start Emission Estimates

- **Single test method (FTP) and soak time**
- **Problematic statistical methods:**
  - USEPA (elevated g/mi)
  - CARB (g/start emissions puff)
- **No modal or super-emitter effects**
- **Assumes all vehicle operation is similar to FTP cycle**
- **Overall, the methods lack a sound scientific basis (numerous technical and analytical flaws are inherent)**
- **Need more and better data on catalyst light-off and second-by-second operating mode impacts**

Subfleet Characteristics

- **Local subfleet distributions significantly affect emissions from all activities**
- **Super-emitter fleet fraction is critical**
- **Model must relate subfleet characteristics to proximal land use, demographics, and registration data**
  - Vehicle class, model & MY [weight, engine size, HP]
  - Fuel delivery system
  - Emission control system
  - Onboard computer control system
  - Accrued vehicle mileage, tampering and I/M
  - Load (e.g., towing, A/C, heavy loads)

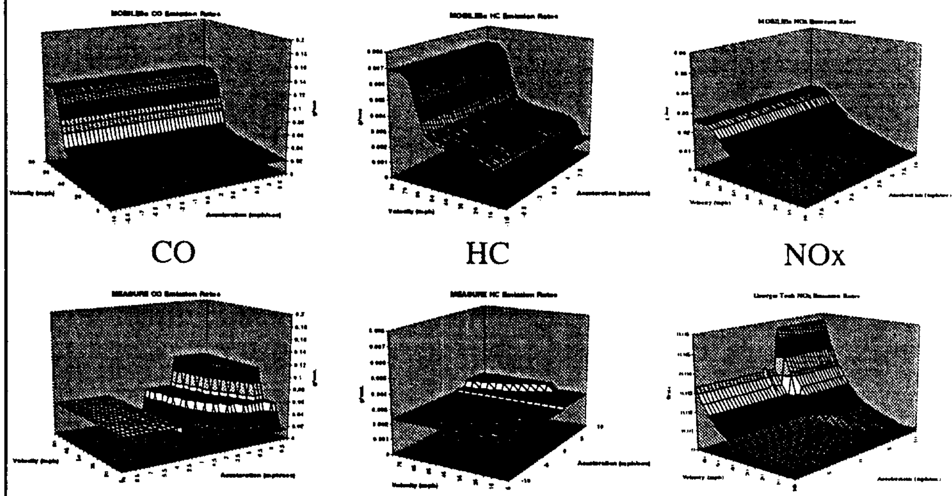
Ongoing Model Improvements

- **Short term (MOBILE6)**
  - Cycles-based modeling
  - Incremental start emissions
  - Standard activity approaches
- **Medium Term**
  - Aggregate modal modeling
  - Load-based modeling
  - Enhanced activity approaches
- **Long Term**
  - Engine parameter modeling
  - Full simulation

Modal Modeling

- **Departs from average speed modeling**
- **Emissions determined as a function of operating modes or vehicle/engine operating conditions:**
  - Engine starts, stoichiometric operation, enrichment operation, enleanment operation
- **Improved spatial and temporal resolution and ability to evaluate controls that affect vehicle operations**
- **Must balance explanatory power of internal algorithms and input data variance**
- **Must address changes in technology and sensor durability that will reduce off-cycle emissions over time**
- **Significantly increased data requirements**

MOBILE5 vs. Modal Emissions



Preliminary work by William Bachman at Georgia Tech (CO, HC, and NOx Curves from MOBILE5a and MEASURE)

Microscale Air Quality Impact Assessment for Transportation Projects

Sponsored by the Transportation Research Board
Committee on Transportation and Air Quality (A1F03)
Sunday January 10, 1999

Morning Sessions	Afternoon Sessions
Regulatory Requirements of NEPA and Conformity Lucy Garliauskas FHWA, Office of Environment and Planning HEP-40, Room 3240 400 Seventh Street SW Washington, D.C. 20950 lucy.garliauskas@fhwa.dot.gov	***MOBILE5a*** Robert G. Ireson, Ph.D. Air Quality Management Consulting 161 Vista Grande Greenbrae, CA 94904 rireson@ix.netcom.com
Vehicle Activity Modeling and Monitoring Simon Washington, Ph.D. School of Civil and Environmental Engineering Georgia Institute of Technology Atlanta, GA 30332-0355 simon.washington@ce.gatech.edu	***CALINE4 and CAL3QHC Overview*** Roger Wayson, Ph.D. Civil & Environmental Engineering P. O. Box 162450 University of Central Florida Orlando, FL 32816-2450 wayson@mail.ucf.edu
Motor Vehicle Emissions Randall Guensler, Ph.D. School of Civil and Environmental Engineering Georgia Institute of Technology Atlanta, GA 30332-0355 randall.guensler@ce.gatech.edu	***Documentation of Microscale Modeling Analyses*** Tom Wholley Vanasse Hangen Brustlin, Inc. 101 Walnut Street P. O. Box 9151 Watertown, MA 02272 TWholley@vhb.com