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ENGINE START EMISSION RATES DERIVED FROM FEDERAL TEST PROCEDURE LABORATORY DATA

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Motor vehicle emission rates are elevated during the first few minutes of vehicle operation. The magnitude of the elevation is a function of: duration and magnitude of commanded enrichment, engine temperature and combustion efficiency, and catalyst temperature. Once combustion stabilizes, commanded enrichment ceases and the catalytic converters reaches "light-off" temperatures (not necessarily in that order), dramatically reducing emission rates. This preliminary stage of high emission rates is modeled differently than running exhaust rates due to the differences in important cause and effect relationships, and the generalized locations of vehicles operating under start conditions.

The grams/start increment for cold starts can be defined as the emissions that occurred under the FTP Bag 1 test with overnight soak and the emissions that would have occurred if the vehicle had run the same test cycle under hot stabilized conditions. Given the lack of hot stabilized FTP Bag 1 data, there has been an ongoing debate as to whether the gram/second emissions under Bag 2 (a lower load hot stabilized cycle) or Bag 3 (the same test cycle with a small potential contribution of elevated emissions from a short engine soak) should be used as the baseline for development of the start increment. The selection of an incorrect baseline would systematically bias engine start increment estimates.

In 1997, the US Environmental Protection Agency collected hot stabilized Bag 1 emissions from 54 automobiles for use in development of engine start emissions in MOBILE6. The research team has analyzed the data to determine the appropriate engine start increment baseline for estimating cold start engine emissions. The analytical results indicate that there is no statistically significant difference in engine start emissions predicted using the gram/second baseline from hot stabilized Bag 1, Bag 2, or Bag 3 for HC and CO and using the gram/second baseline from hot stabilized Bag 1 or Bag 3 for NOx. The comparisons were made for the subfleet of 54 vehicles as a whole and across a variety of technology subsets of the test vehicles using model year, fuel delivery technology, and other technology factors in comparisons. Further analyses lead the researchers to believe that the FTP Bag 3 emissions rate (grams/second) should be used as the baseline for all NOx engine start increments, that Bag 3 should be used for modern vehicle CO and HC engine start increments, and that Bag 2 should be used as the baseline for older vehicle CO and HC engine start increments.

The final gram per start emission rates for various technology groups in the fleet were developed by the authors through statistical analysis of the comprehensive Federal Test Procedure (FTP) database, containing more than 30,000 test results across more than 19,000 vehicles. Using the engine start baselines discussed above, the engine start increments were derived through a combination of regression tree and subsequent ordinary least square regression analysis. The regression tree analysis serves to identify appropriate engine start technology groups for normal and high emitting vehicles and the OLS regression serves to develop the final model and ensure that all standard regression assumptions (i.e. residuals analysis) are met and that all variables employed are statistically significant.

Engine Start Emission Rates Derived from FTP Data

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Introduction

- Define engine start increment (grams)
- Examine results of EPA's engine start testing program
- Develop baseline emission rates for estimating incremental engine start emissions
- Analyze Federal Test Procedure database
- Develop engine start emission regression models by main effect and technology group
- Conclusions and next steps

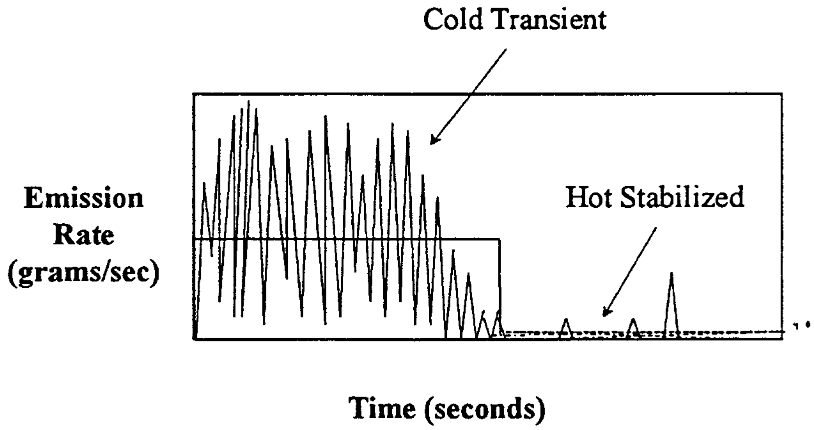
Engine Starts

- Elevated Emissions:
  - Commanded Enrichment (timed)
  - Combustion Stabilization (temperature)
  - Increased fuel consumption (drivetrain friction)
  - Catalyst Light-Off Time
- Initial Operation (1-3 minutes)
- Emissions are a Function of:
  - Vehicle technology, soak time, (modal activity)
- Gram/start emission rates
  - MEASURE 2.03 will employ a continuous starts methodology (emissions as a function of soak time)

Problems with Existing Engine Start Emissions Estimates

- Single test method (FTP) and soak time
- Problematic statistical methods:
  - USEPA (elevated g/mi)
  - CARB (g/start emissions puff)
- Limited Data
  - Second-by-second and commanded enrichment
  - Catalyst light-off times
- No modal or super-emitter effects accounted for

Engine Start Emissions
FTP Bag 1



Incremental Engine Start Estimate

(Bag1 - Baseline) * 505

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[FTP Bag 1 emissions rate (grams/second)

minus

Baseline hot stabilized bag

(Bag 2, Bag 3, IM240, or Hot505)

emissions rate (grams/second)]

times

505 seconds

Incremental Start Baseline

- Hot-Stabilized 505 is appropriate baseline for lab tests
  - Same cycle as FTP Bag1 and Bag3
  - Same speed/acceleration profile, engine load, etc.
  - However, we do not collect HS505 data
- FTP Bag 2 - different cycle/engine load
- FTP Bag 3 - potential short soak emissions effects
- IM240 - different load and pre-conditioning uncertainty

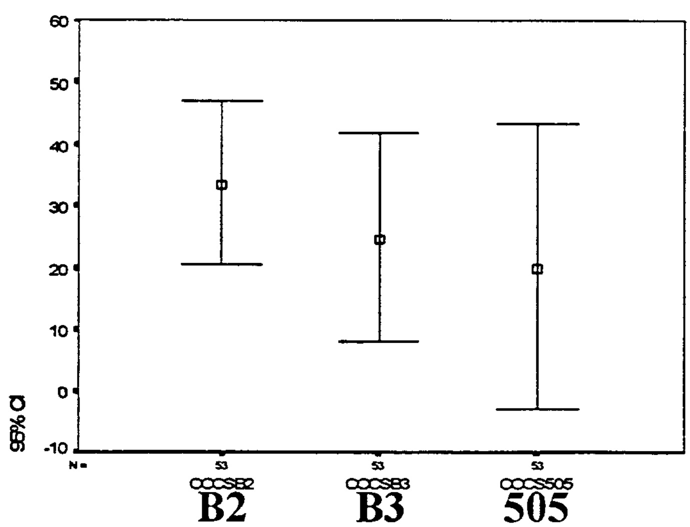
EPA Engine Start Data

- Determine appropriate engine start baseline
- 54 vehicles tested (53 reported)
  - 4 1983-86, 18 1987-89, 23 1990-94, 8 1995-96
  - 30 fuel injected, 20 throttle body, 3 unknown
  - 1 3-cylinder, 33 4-cyl., 17 6-cyl., 2 8-cyl.
  - 34 3-way catalyst, 12 3-way+ox, 7 ox

EPA Engine Start Testing

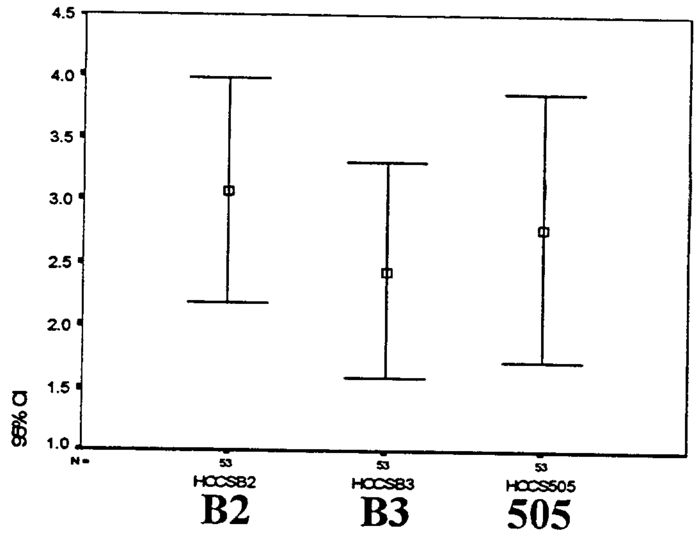
- **Federal Test Procedure Cycles**
  - **Bag 1**
    505 seconds, 16mph, cold start after overnight soak
  - **Bag 2**
    856 seconds, 26mph, hot and running (no soak)
  - **Bag 3**
    505 seconds, 16mph, warm start after 10 minute soak
  - **Hot Stabilized 505**
    505 seconds, 16mph, hot and running (no soak)

CO Incremental Engine Starts Bag2, Bag3, and HS505 Baselines



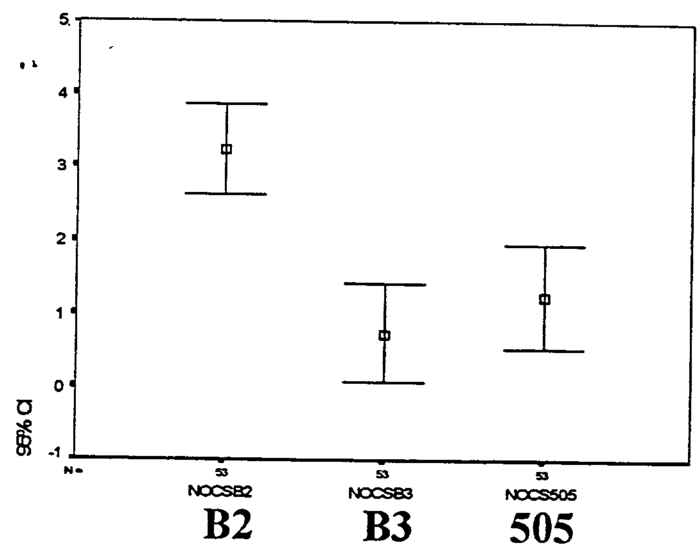
EPA Start Data

HC Incremental Engine Starts Bag2, Bag3, and HS505 Baselines



EPA Start Data

NOx Incremental Engine Starts Bag2, Bag3, and HS505 Baselines

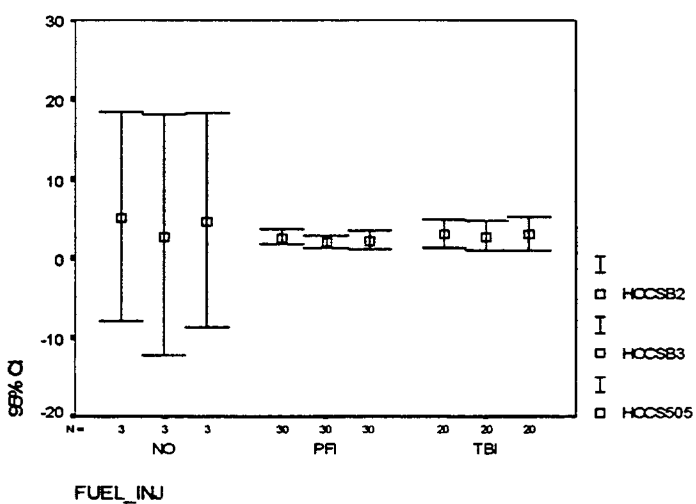


EPA Start Data

Cross Tabulation Results

- No statistically significant difference for CO and HC engine start increments (Bag 2, Bag3, and HS505 baseline) and NOx engine start increments (Bag3 and HS505 baseline) by:
  - fuel delivery technology
  - catalyst type
  - number of cylinders
  - model year group

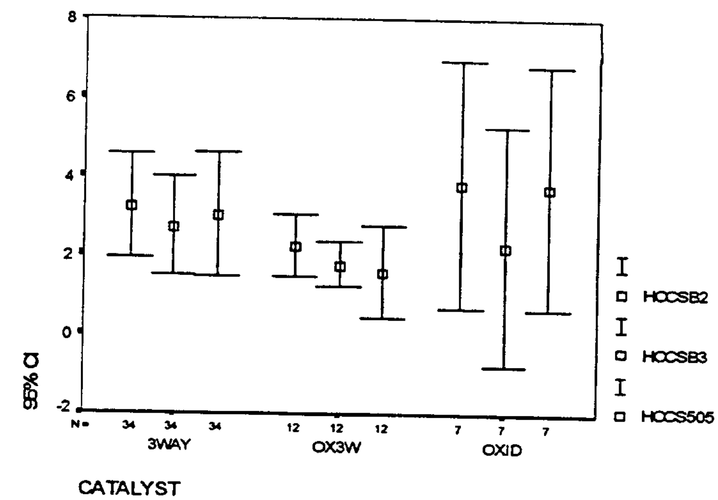
HC Engine Start Increments by Fuel Delivery Technology



CARB PFI TBI

EPA Start Data

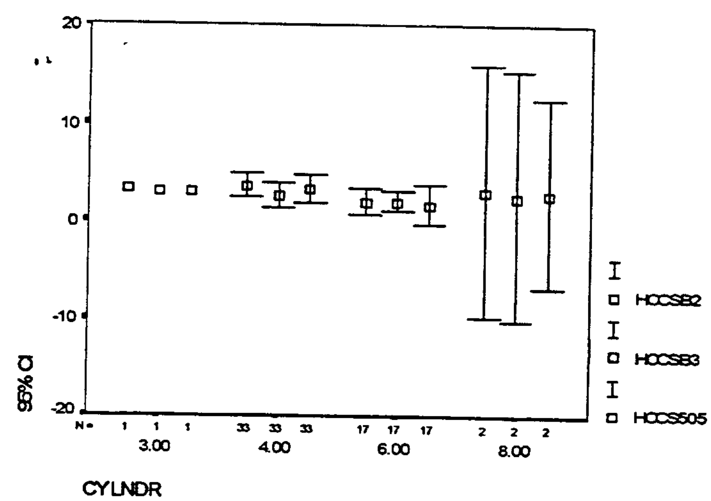
HC Engine Start Increments by Catalyst Technology



EPA Start Data

3WAY OX3W OX

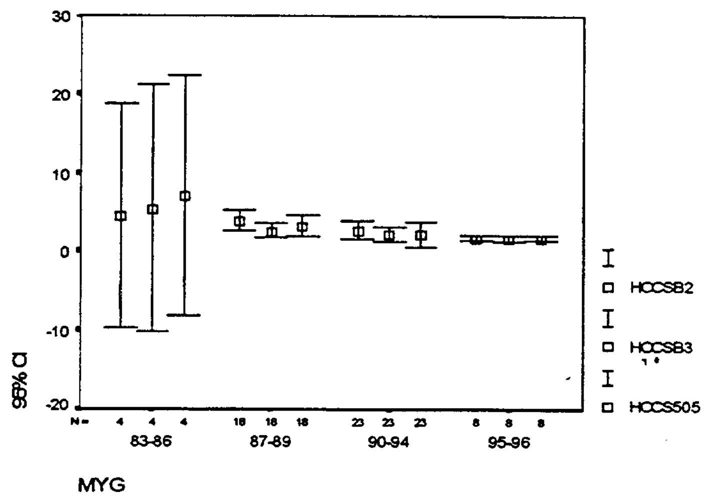
HC Engine Start Increments by Number of Cylinders



EPA Start Data

3 4 6 8

HC Engine Start Increments by Model Year Group



EPA Start Data

83-86 87-89 90-94 95-96

Conclusions from EPA Tests

- **EPA data**
  - **Large variability in start emissions**
  - **No statistically significant difference in cold start increments (grams) between Bag 2, Bag 3, and H505 baseline for CO and HC**
  - **No statistically significant difference in cold start increments (grams) between Bag 3, and H505 baseline for NOx**
- **Use Bag 3 as the baseline emissions rate for start increment analyses**

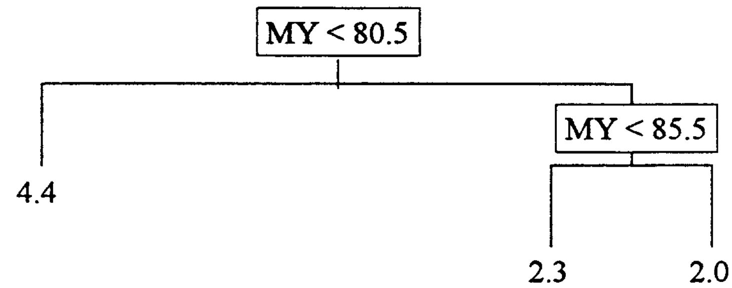
FTP Testing Database

- Comprehensive EPA database
  - Intermittent testing programs over a 20 year period
- Supplemented w/Industry and CARB data
- 114 data fields for each test (vehicle, engine, fuel, and cycle characteristics, and test results)
- 30,834 FTP test results (19,092 vehicles)
  - 17,425 on Indolene, tested as received
  - Used to develop technology classes
  - Used to develop baseline emissions rates
- 17,417 non-FTP hot-stabilized test results (8171 vehicles)
  - Used to develop technology groups
  - Used to develop aggregate model model emissions rates

Emitter Groups

- Employ FTP database tests
- Regression tree analysis identifies 'homogenous' emitter groups
  - Classifies observations into homogenous groups based on optimized variance reduction algorithm
  - Hierarchical split (variables reducing most variability)
  - All FTP database vehicle technology variables employed
  - Addresses correlation and a variety of statistical issues
  - Separates first and second order effects
  - See Washington, et al., 1996
- A few emitter 'groups' are defined for modeling convenience
  - Cutpoint defined to separate top 5% of each group

Emitter Classes
NOx Regression Tree



Bachman and Guensler, 1996

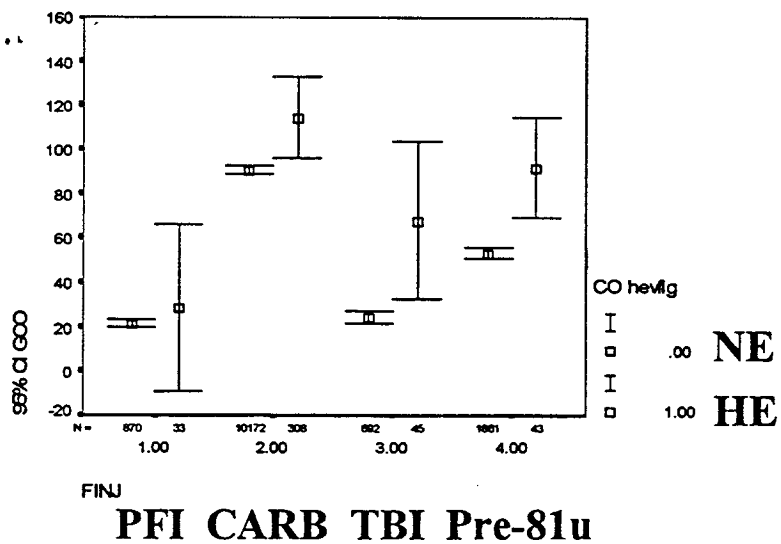
High Emitter Analysis

- Select highest emitters of each technology-based high-emitter vehicle class (top 5% of each group)
- Tag vehicles as high emitters and separate into a second database for analysis
- Run regression tree analyses separately for normal and high emitting vehicle databases
- Examine critical variables from each analysis
  - Similarities indicating similar behavior (regroup)
  - Differences indicating likely need for separate tracking

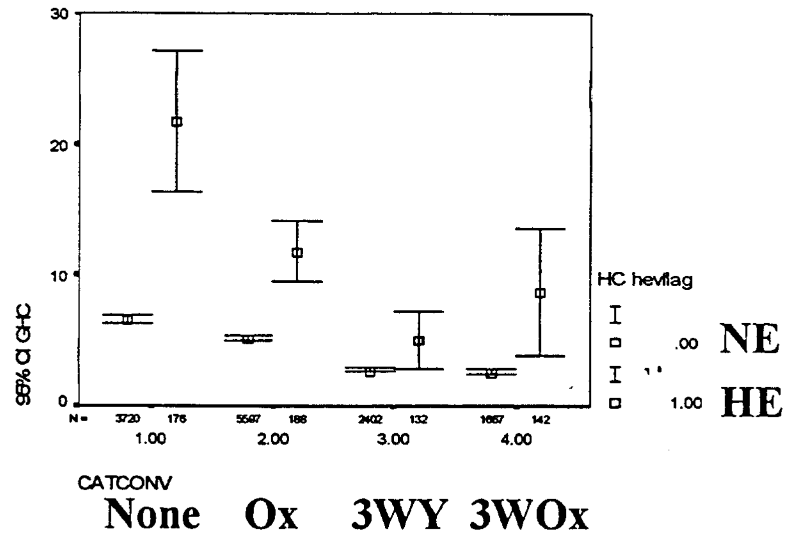
High-Emitters and Engine Starts

- High emitting hot stabilized vehicles:
  - ◆ Conventional wisdom: high emitting under all conditions
  - ◆ Analyses yield elevated gram/start emissions for CO and HC, depressed gram/start emissions for NOx for older technology vehicles
  - ◆ Noted across fuel delivery technology, catalyst type, and model year group
  - ◆ Modern vehicles may not be significantly affected
  - ◆ First order effect yielding different mean emissions and response to vehicle technologies
  - ◆ Requires independent tracking in emissions models

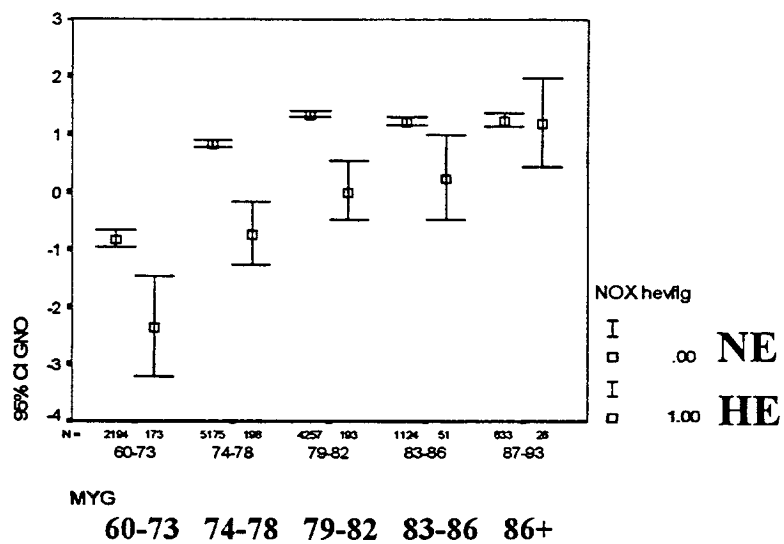
CO Engine Start Increments by Fuel Delivery and HE Class



HC Engine Start Increments by Catalyst and HE Class



NOx Engine Start Increments by MY Group and HE Class



Model Development

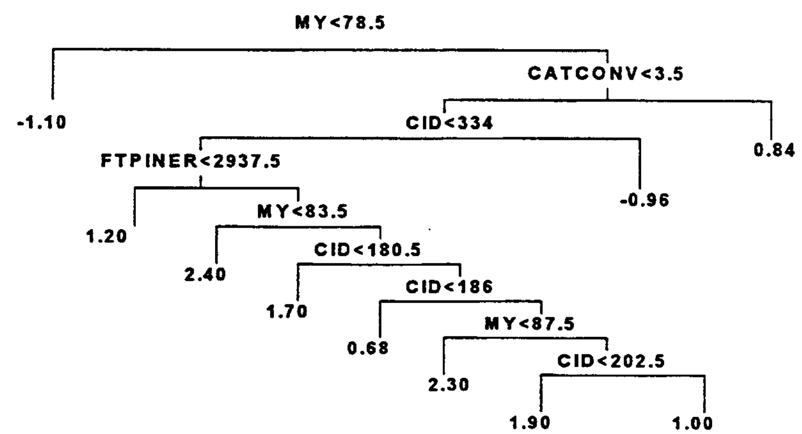
Step 1: Engine Start Regression Trees (by Pollutant and Emitter Class)

- Dependent Variable (emissions rate) :
  - Start emissions (grams) using FTP Bag3 baseline
- Independent Variables
  - MY, FTPINER, DYNOHP, CID, TRAN, FINJ, CATCONV, TESTAGE, ODOMETER, etc.
- Records missing variables omitted from analysis
- Regression trees are used to identify potential explanatory variables (technology interactions) for the generalized least squares model (non-spherical disturbances, i.e. non-normal and heteroscedastic)

Variable Dictionary

MY	Model Year
VEHAGE	(1993 - model year)
FTPINER	FTP Inertial Weight (loaded curb weight, lb.)
DYNOHP	Dynamometer horsepower setting, compensating for such factors as drag, coast down, friction, etc.
CID	Cubic inch displacement of the vehicle's engine
TRAN	Transmission type (1 = auto, 2 = semi-auto, 3 = 3 speed manual, 4 = 4 speed, 5 = 5 speed
FINJ	Fuel delivery (1 = port injected, 2 = carburetor, 3 = throttle body, 4 = <1981, fuel injected, type?)
CATCONV	Catalytic converter type (1 = none, 2 = oxidation 3 = 3-way catalyst, 4 oxidation plus 3-way)
FTPODOM	Vehicle's odometer reading (in miles) at test
TESTAGE	Age of vehicle (in years) at test

Cold Start Regression Tree Analysis NOx Normal Emitters (Bag 3 Baseline)



Conclusions

- Hot engine starts are not evident in EPA's engine start data
  - Need more Hot505 data across vehicle technologies
- CO, HC, and NOx start emissions differ significantly for some normal and high emitter groups (track separately)
- Some vehicle groups do exhibit negative NOx increments
- There is tremendous variability in engine start emissions that is not being handled by the variables available for analysis. New data collection and analyses are required to identify additional potential explanatory variables
- Assumes that engine start emissions are not affected by operating mode: need more off-cycle and onroad data
- Need to link start emissions to onroad high emitter fractions (or fleet emitter distributions)

Next Steps

- Address sample bias - develop data set weighted by fleet penetration and run final models with weighted data
- Identify potential violations of OLS regression assumptions and employ remedial measures (i.e. transformations or generalized least squares)
- Integrate the final models into MEASURE
- Integrate the final models into a new stand-alone engine start emissions model (ARC/INFO based)
  - Registration data or VIN input capabilities to provide vehicle technology groups
  - Provide input link capabilities from TranPlan
  - Submit model and documentation to EPA for approval

Linear Regression for Normal NOx

- **Technology Dummy Variables (Cont.)**
  - **TG5** (MY>=83.5, 180.5<CID<186, etc.) **-1.76**
  - **TG2** (MY>=78.5, FTPINER<2937.5) **-0.58**
  - **TG9** (MY>=78.5, CID>=334, etc.) **0.56**
  - **PFI** **-0.46**
  - **TG8** (MY>87.5, 180.5<CID<334, etc.) **-1.61**
  - **TG4** (MY>=83.5, CID<180.5, etc.) **-1.30**
- **Technology Deterioration (/10,000 mi)**
  - **TG7** (MY>87.5, 180.5<CID<202.5, etc.) **-0.44**
  - **TG4** (MY>=83.5, CID<180.5, etc.) **0.13**

Model Performance Summary

- **Adjusted R2**
  - **CO 22%**
  - **HC 8%**
  - **NOx 15%**
- **Residuals Analysis**
  - **CO - Non-normal (transform to normal or gamma distribution)**
  - **HC - Non-normal (transform to normal or gamma distribution)**
  - **NOx - Approximately Normal**

Step 2: Regression Model Formulation

- Include variables identified in regression tree analysis for providing cutpoints (vehicle age, CID, etc.)
- Include technology dummy variables identified in regression tree analysis as providing cutpoints (fuel delivery technology, catalyst type, etc.)
- Include technology groups (potential vehicle characteristic interactions) identified in regression tree analysis
- Include an interaction of accrued vehicle mileage and technology dummy indicator to provide for changes in deterioration slope coefficients as a function of technology group
- Stepwise regression, F to enter 0.05, F to remove 0.10

Linear Regression for Normal NOx

• Intercept	4.41
• Main Linear Effects	
◆ CID	-0.003
◆ Test Age	-0.11
◆ Vehicle Age	-0.10
• Technology Dummy Variables	
◆ No Catalytic Converter	-1.19
◆ Manual Transmission	-0.74
◆ 3-Way+Ox Catalytic Converter	-1.15
◆ Oxidation Catalyst	-0.66