FUEL-BASED PARTICULATE MATTER AND GASEOUS EMISSION FACTORS DETERMINED FROM VEHICLES IN PITTSBURGH, PA'S SQUIRREL HILL TUNNEL

Andrew Grieshop, Eric Lipsky and Allen Robinson

Carnegie Mellon ENGINEERING

Carnegie Mellon University, Pittsburgh, PA

Why a Tunnel Study?

In general, emissions studies in traffic tunnels are used to provide a composite emissions profile of the full range of vehicles found in a geographical region. This study was specifically undertaken to provide an automotive traffic source profile for the Pittsburgh Air Quality Study (PAQS) EPA Supersite project. Along with taking a small suite of gas-phase measurements, we concentrated on characterizing the composition, size distribution and mass and number emission rates emitted by automobiles and trucks (Heavy Duty Diesel Vehicles – HDDV) in an urban traffic tunnel in Pittsburgh, Pennsylvania. Later work examined the effect of dilution on the measured PM mass. A sampling of this work is presented here.

In short…

- Vehicles are a major source of fine particles and other pollutants:
  - Carbonaceous Aerosol (OC and EC)
  - Ultra-fine particles
  - Gases (NO_x, CO, VOCs, NH_3, SO_2, etc.)
- Reliable, representative Emission Factors (EFs) are needed.
  - E.g. $mg_{pollutant}/kg_{fuel}$ or $mg_{pollutant}$ /mile
- Emission profiles can be determined for use in source-receptor modeling.
- Emissions from different vehicle classes/types can be determined.
  - E.g. gasoline, heavy-duty diesel (HDDV), light-duty (LDV), 'smokers'

The Squirrel Hill Tunnel

The western portal of the Squirrel Hill Tunnel

The Squirrel Hill Tunnel is a 4-lane highway tunnel on Interstate 376 on the eastern edge of the City of Pittsburgh. It is 4,225 feet long, has a 2.5% up-grade in the westerly direction and carries both commercial and non-commercial traffic. Our testing took place in the tunnel's west-bound tube. The majority of the data collection took place in November of 2002, while later work on the effects dilution of aerosol mass took place during the summer of 2004.

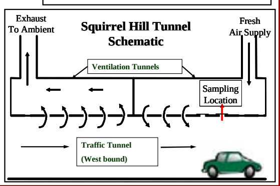
Measurements taken in the tunnel were corrected for background levels using data taken from remote sites: stations run by the Allegheny County Health Department for gas concentrations and instruments on the CMU campus for PM measurements.

Data collected during study:

Continuous Air Quality Measurements
- Gases: CO_2, CO, SO_2, NO_x, NH_3
- $PM_{2.5}$: 30° C TEOM
- Size/Number: SMPS and nano-SMPS
- Traffic Count: PennDOT Sensors
- Traffic Video: Highway Patrol video

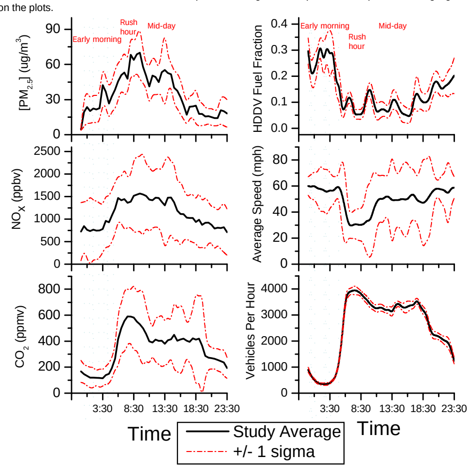
Integrated Air Quality Samples
- Artifact-corrected samples for OC/EC
- Filters for Organic Speciation (results pending)
- MOUDI for size-resolved mass and OC/EC
- Inorganic gas/PM samples
- Filters for metals analysis (results pending)
- Canisters for VOC speciation

These measurements and samples were collected from the ventilation shaft above the traffic tunnel (as shown in the schematic below).



Diurnal Patterns in Traffic and Concentration Data

These plots show time series of average daily traffic conditions and background-corrected pollutant concentration - all exhibit consistent diurnal patterns. Integrated sample collection periods are highlighted on the plots.



Trends in concentrations :

•CO_2 level in the tunnel closely tracks traffic volume, implying that there is less dilution of exhaust during high-traffic periods.

•NO_x levels show a less-clear trend.

•All concentrations show peaks during rush-hour period (7 AM to 9 AM)

Trends in traffic:

•Rush hour period has highest hourly traffic volume and lowest average speed.

•Rush hour (7 AM to 9 AM) and the early morning hours (12 AM to 6 AM) have the lowest and highest proportion of fuel consumed by HDDV's, respectively.

Fuel-based Emission Factors

- Fuel-based EFs were determined (i.e. mg/kg fuel vs. mg/mile or mg/hp-hr)
- Kg fuel determined through a mass balance on the carbon in fuel
- Ideal, stoichiometric combustion of octane (gasoline):

$$C_8H_{18} + (12.5O_2 + 47N_2) \longrightarrow 8CO_2 + 9H_2O + 47N_2$$

- Actual combustion also yields: CO, carbonaceous PM, NO_x, etc.
- CO < 2% of emitted carbon, PM << 1%
- Therefore, fuel mass can be determined with $[CO_2]$ and [CO]
- However, to calculate EFs from our data, we must:
  - Adjust concentrations for background
  - Account for the fraction of carbon in fuels
- Emission Factors calculated with:

$$EF = \left[\frac{P_{tun} - P_{amb}}{\left[(CO_2)_{tun} - (CO_2)_{amb}\right] + \left[(CO)_{tun} - (CO)_{amb}\right]}\right]\left[\frac{MW_p}{MW_C}\right] w_c$$

  - P is species concentration
  - w_c is carbon fraction in fuel: weighted average of gasoline (85%) and diesel fuel (87%)
  - $MW_{p/c}$ are molecular weights of species/carbon

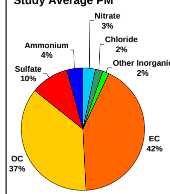
Tunnel Emission Factors

(per kg fuel)	Overall	High-speed (Mid-day)	Low-speed (Rush-hour)	High Truck (Early Morning)
NO_X (g/kg)	10.4 ± 1.9	11.0 ± 1.9	8.0 ± 1.4	17.9± 3.8
$PM_{2.5}$ (mg/kg)	194 ± 28	174 ± 24	175 ± 23	253± 72
OC (mg/kg)	58 ± 14	56 ± 10	51 ± 16	101 ± 20
EC (mg/kg)	83 ± 18	95 ± 18	66 ± 17	140±27
NH_3 (mg/kg)	260 ± 65	209 ± 85	265 ± 57	294 ± 30
	~ 17% HDDV	~ 19% HDDV	~ 11% HDDV	~ 36% HDDV

•Overall tunnel emission factors were calculated using a fuel-weighted average of sampling period emission factors.

•NO_x, $PM_{2.5}$, Elemental Carbon and Organic Carbon emission factors are strongly influenced by the proportion of HDDV in the fleet.

Study Average PM



•Carbonaceous aerosol predominates, representing ~80% of PM mass.
•Average PM mass concentration in the tunnel is ~ 50 µg/m³.

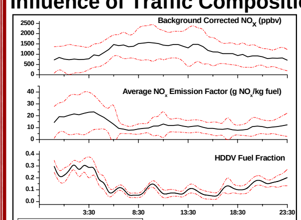
Determining the Fraction of Fuel Used by Trucks

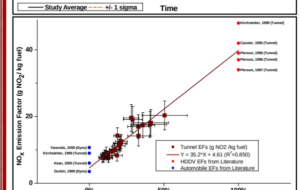
- Fleet composition has large impact on EFs
- Can we separate emissions from different vehicle types?
- Identify HD vehicles from video tape
- All HD vehicles assumed diesel-powered
- Fraction of fuel consumed by HDDV:

$$\%fuel_{HDDV} = \frac{f_{truck}\left(\frac{1}{mpg}\right)_{truck}}{f_{truck}\left(\frac{1}{mpg}\right)_{truck} + f_{car}\left(\frac{1}{mpg}\right)_{car}}$$

Assumed: 6 mpg for trucks, 21 mpg for cars

Influence of Traffic Composition on NO_x Emissions





Comparing NO_x emission factor and fleet composition indicates vehicle classes can be clearly separated.

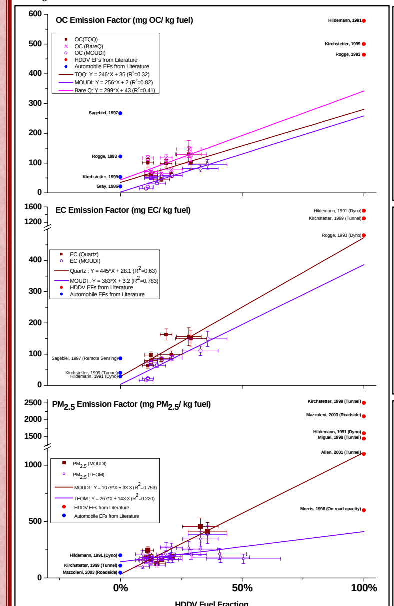
Comparison of the diurnal average time series of NO_x emission factor and fleet composition (as the portion of fuel used by HDDV) clearly suggests that vehicle types should be separable by combining these data sets.

This is the case, as is shown in the lower figure of NO_x EF versus HDDV Fuel consumption fraction. A very strong correlation is seen between the two variables. Additionally, interpolating the least-squares linear fit line to the 0% HDDV (only cars) and 100% HDDV (only Heavy Duty Diesel Vehicles) levels shows that the results of our study are in good agreement with a variety of emissions studies (ranging from other tunnel studies to dynamometer and remote sensing studies).

Note that the increased uncertainties associated with the early morning period (when a larger proportion of traffic is HDDVs) are due to the CO_2 and NO_x levels in the tunnel being less elevated above background levels. The mixing and dilution in the tunnel is far more variable under these conditions as well.

$PM_{2.5}$ Emissions as a Function of Fleet Composition

Similarly, the total $PM_{2.5}$ mass and OC and EC emissions from the different vehicle classes can be separated. In each case, multiple instruments/methods were used to determine the tunnel and background concentrations during the sample periods. The results of each are shown here, along with values from literature and a brief explanation of the methods used. OC/EC analysis was completed using NIOSH method 5040. Overall car and HDDV EFs are tabulated in the Conclusions.



Organic Carbon

•MOUDI samples collected on Al foil substrates

•BareQ indicates sample on quartz fiber filter (QFF)

•TQQ indicates QFF corrected for positive artifact with mass from a second QFF sampling behind a Teflon membrane filter

Elemental Carbon

•MOUDI data are the sum of stages with size cuts of 2.5 µm and below .

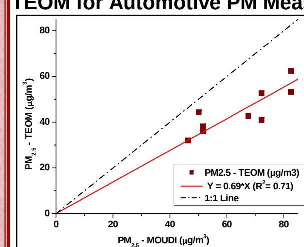
•Background correction based on scaled data from TEOM at a remote location

Total $PM_{2.5}$

•TEOM was run with the SES (Sample Equilibration System) at 30° C, and does not show good agreement with MOUDI data (see below).

•Data is background-corrected using data collected from a second TEOM at a remote site in Pittsburgh.

Loss of Semi-volatile Mass Limits Usefulness of TEOM for Automotive PM Measurements



Comparison of data taken by the MOUDI (which samples at ambient conditions) and the TEOM (which samples at 30° C) indicate significant loss of PM mass in the TEOM. This plot shows that the TEOM under-predicted $PM_{2.5}$ mass concentrations in the tunnel by ~30%. The plot above shows that the variability is even more pronounced during the early morning hours, when a larger portion of the fleet is HDDVs.

This effect in the TEOM is presumably due to the loss to the vapor phase of the portion of engine exhaust PM made up of semi-volatile organics. Later work has similarly confirmed the effects of dilution on the measured PM mass in the tunnel.

Conclusions

The following were established during this study of vehicle emissions:

•Clear diurnal patterns in pollutant concentrations, emission factors and traffic density and composition.

•Emission factors for the tunnel as a function of the time of day and associated fleet composition.

•A study average composition of tunnel particulate which shows a predominance of carbonaceous aerosol (~80%) and an average daily concentration of 50 µg/m³.

•A clear separation of emissions from cars and HDDV via the determination of fleet compositions through inspection of traffic video.

•NOx, $PM_{2.5}$, OC and EC emission factors for these two vehicle classes.

•The TEOM is not an effective instrument for measuring concentrations of fresh, automobile-sourced PM.

Fuel-based EF (per kg fuel)	Cars	HDDV
NO_X (g/kg)	4.6 ± 0.7	40.0± 3.5
$PM_{2.5}$ (mg/kg)	33 ± 48	1110± 280
OC (mg C/kg)	27± 14	294 ± 84
EC (mg C/kg)	16± 16	430±95

The table above contains interpolated emission factors based on the known fleet composition during the various sample periods. They represent composites of data taken from the sources listed above. Uncertainties were estimated based on the errors in the least-squares fit of pollutant emission factor versus traffic composition.