

Recovery of Tail Pipe Species Concentrations and Its Effect on Emissions Calculations from Raw Exhaust Gas Streams during Chassis Dynamometer Tests

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ABSTRACT

This paper proposes a method to recover species concentrations at the tail pipe exit of heavy-duty vehicles during chassis dynamometer tests, and investigates its effect in the calculation of emissions from their raw exhaust streams. It was found that the method shown in this paper recovered the sharp peaks of the gas species. The effect on calculations was significant, as time-variant raw exhaust flow rate and emissions concentrations data are acquired continuously during a test (at 10 Hz), and their product is integrated during calculations. The response of the analyzer is delayed due to the time taken for transport of the sample gases from the probe tip to the analyzer, and deformed due to mixing and diffusion during this transport. This 'convolution' of the concentration data stream introduces an error in the final result, calculated in g/mile.

The convolution of the concentration data is corrected by the following method: the analyzer response (output) to a step change in the concentration of the species at the probe tip (input) is recorded to determine the 'convolution function'. The inverse of the convolution function is applied to the output to recover the input concentrations at the probe tip. The signal processing is carried out in the frequency domain and appropriate filters and windowing are applied to improve the quality of the reconstructed signal. This deconvolution algorithm is then applied to the analyzer data collected during a test to recover the concentrations at the probe tip, which is thus corrected for time delay and signal deformation. The deconvoluted concentration data, exhaust flow rate data, and dynamometer data are used to calculate the emission of a gas species (g/mile).

Results for tests conducted in the laboratory for CO₂, CO, NO_x, NO, THC, and CH₄ are presented. The results obtained from the 'asrecorded' raw exhaust data and reconstructed data are compared with those from bag samples for the same test. It is shown that the emissions calculations using deconvoluted concentration data from the raw exhaust stream match well with the results from the bag samples for the same test in a full-scale dilution emissions measurement system.

KEYWORDS: Dynamometer tests, Emission measurements, Signal reconstruction

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INTRODUCTION

Air pollution due to vehicles powered by internal combustion engines using carbon based fuels are likely to include genotoxicants and carcinogens which are health hazards [1] and may lead to environmental effects like acid rain and global climatic change [2]. In order to mitigate these ill effects, the United States Environmental Protection Agency (US EPA) and regulatory agencies of other countries have introduced strict emission mandates for gaseous and Particulate Matter(PM) emissions from automobiles. Engine manufacturers and automobile companies are developing new combustion and after-treatment technologies to meet these strict emission mandates. Emissions measurement facilities around the world are challenged to consistently and accurately measure small concentrations of engine and tail pipe emissions from automobiles.

Tail pipe emissions are conventionally measured in g/mile during chassis dynamometer based tests using simulated test cycles [3, 4, 5, 6, 7]. The exhaust gas is diluted with ambient air and gaseous emissions for a test can be determined using three approaches; integration of continuous measurements from raw exhaust stream before dilution, integration of continuous measurements from diluted exhaust stream, and from measurement of concentrations of a fraction of diluted exhaust collected in a bag during a test cycle. The US EPA generally prefers dilute bag method for regulatory tests for gaseous emissions because the bag represents an integrated sample for the test, and is not prone to errors due to time misalignment between measured signals. However, the dilute bag measurements lack real time data and information about transients in engine emissions, which are useful to engine manufacturers for research and development. Continuous measurements from diluted exhaust stream pose

measurement challenges due to further dilution of certain species that are already in low concentrations in exhaust gas. This can result in low signal to noise ratios and high measurement uncertainties for these species [6]. Meanwhile, continuous measurements of raw exhaust stream can yield results with lower measurement uncertainties due to higher species concentrations [7]. In this method, time varying exhaust flow rate data, emissions concentration data, and dynamometer data are acquired continuously during a test and their incremental product is integrated over time to yield emissions in g/mile for a test. This makes the time alignment between these data streams critical for accurate calculations.

This paper investigates the recovery of species concentrations at the tail pipe exit of heavy-duty vehicles during chassis dynamometer tests, and its effect in the calculation of emissions from their raw exhaust streams. A signal reconstruction procedure which also time aligns the species concentration signal with the exhaust flow rate signal is presented and is shown to significantly improve the accuracy of emissions calculations from the raw exhaust stream. The results obtained from the as-recorded data and reconstructed data are compared with those from dilute bag samples for the same test conducted in a full scale dilution emissions measurement facility.

A list of abbreviations is provided at the end of the paper.

BACKGROUND

The response of a gas analyzer in an emissions measuring system during transient testing is changed from the gas concentration at the probe tip due to the time taken for gas transport through the exhaust and measurement systems, and the mixing and diffusion of gases during this transport. Previous research conducted to investigate these signal distortions and recover probe tip emission signals includes correlation optimized warping, smooth transition regression, NO_x sensor response, and development of gas transport models through exhaust and measurement systems [8, 9, 10, 11, 12, 13, 14, 15].

Real world CO₂ emission from tail pipes of vehicles were investigated [8]. Correlation Optimized Warping (COW) was used to align non-linear time variant signals, like exhaust flow and emissions signals. COW warps time series by fitting the main features in each segment by uniform expansion or compression. However, there is a tendency for COW to over-exaggerate or under-exaggerate time-series, resulting in a solution that is not area conserving [8].

A statistical framework for modeling instantaneous vehicle emissions data that accounts for variability in exhaust gas transport dynamics was developed [9]. A Smooth Transition Regression (STR) model was proposed which described the inherent nonlinear associations between emissions and engine or vehicle operating variables. In contrast to conventional linear models that are widely applied where a constant time shift is adopted, these models allow for the presence of different regimes: each regime relates instantaneous emissions measurements to different time lags of the engine or vehicle operating variables. Transition from regime to regime was considered a smooth function of exhaust flow rate, characterized by a pair of coefficients

that were estimated from the data. A limitation of this formulation was that it failed to capture convolution of exhaust gases by turbulence during exhaust gas transport [9].

An on-engine method for dynamic characterization of automotive NO_x concentration sensors was developed [10] to determine the dynamic response of the sensor over its entire useful life. This method uses real time calibration to develop adaptive models in a predictive control structure. The engine was used as a gas generator, generating exhaust gases with step transition of NO_x concentration level, by varying the start of fuel injection during normal operation. The NO_x sensor response to the step transition concentration input was recorded and investigated. The time delay and the response time of the sensor were determined experimentally and a simple linear first order model, which was a function of the delay parameters, was used to recover the engine-out NO_x concentration levels.

Gas transport dynamics in the exhaust and the measurement systems were modeled [11]. Oxygen signals at the end of catalytic converter were reconstructed from tail pipe gas measurements. This study addresses gas transport dynamics using invertible mathematical models of the exhaust and the measurement system. This work was extended [12] to include reconstruction of converter outlet signals from dilute gas measurements, and further extended to determine fleet average emissions [13] to improve prediction quality.

A model for the improvement of time resolved tail pipe measurements from the diluted sample of a Constant Volume Sampling (CVS) system was reported [14], using purely mathematical tools derived from system control theory. The parameters of the model were estimated using measurement of the system response to known and controlled emission step inputs. Different subsystems were individually modelled due to their specific design and flow characteristics, and were combined to obtain the final model. The time response of each subsystem was evaluated using a gas injection device. The accuracy of the model is validated using ultra-fast response emission analyzers.

A mathematical model of gas transport and mixing within the sampling and measuring system to improve response times of emission measurements was presented [15]. This model compensates for the effects of diffusion and mixing of gases separately. Transport delay is also accounted for. Model parameters were estimated by exciting the system with square pulses and fitting the model response to the resulting data to show significant recovery of detail in transient vehicle emissions data.

An experimental method for determining uncertainties for vehicle emissions tests was reported [16] that was based on repeating an experiment a sufficient number of times to determine statistical uncertainty. More recently, a method to determine uncertainties for raw continuous, dilute continuous and dilute bag measurements during chassis dynamometer tests for full scale and partial dilution systems were reported [6, 7], based on the propagation of uncertainties of subsystems like flow meters and analyzers. It was noted that the emission calculations from raw exhaust stream can

have least uncertainties among the three methods, if it can be ensured that time misalignment between emissions concentration signals and exhaust flow rate signals are minimized [6].

In addition to time misalignment between emission concentration signals and exhaust flow rate signals, the concentration signals are subjected to deformation by mixing due to turbulence and diffusion during transport. Sharp peaks with shorter time durations are deformed to flatter peaks with longer time durations [11, 12, 13, 14, 15]. Thus the reconstructed signal should account for both time delay and deformation.

Although previous research addresses the issue of time misalignment and signal deformation in continuous concentration measurements, they do not provide a comparison of final emissions results in g/mile with those from the conventional methods like bag dilute measurements. This paper builds upon previous work and a signal reconstruction procedure is developed to recover the sharp transients in the concentration signal and time align the concentration signal with the flow rate signal in order to reduce the error and improve the accuracy of emissions calculations from the raw exhaust stream. Appropriate filter and window functions are used to reduce noise in the reconstructed signal while endeavoring to recover the amplitude and transients in the original signal. The signal processing is performed using codes generated with MATLAB[®] software. Results for tests conducted in a full scale dilution emissions testing laboratory for CO₂, CO, NO_x, NO, THC, and CH₄ are presented. The results obtained from the original ‘as-recorded’ data and ‘reconstructed’ data are compared with those from bag samples for the same test. It is shown that the emissions calculations using reconstructed concentration data from the raw exhaust stream match well with the results from the bag samples for the same test in a full-scale dilution emissions measurement system. Additionally, the relative contributions to the error from time delay and signal deformation on final emission results are also discussed.

EXPERIMENTAL FACILITIES

This investigation was carried out at the emissions testing facility of the Vehicle Testing Laboratory at the Larson Transportation Institute of the Pennsylvania State University. The details of the facility are available elsewhere [6] while a brief description is included here. This facility is equipped with a full-scale dilution tunnel with constant volume sampling (CVS) system, laboratory grade emission analyzers, and a large-roll heavy-duty chassis dynamometer. The Schematic diagram of the emissions measurement system is shown in the [Figure 1](#). It consists of a dilution air conditioning unit (DAU), which conditions the ambient air for temperature and humidity before it enters the dilution tunnel. The vehicle's tail pipe is plumbed into this tunnel so that all vehicle exhaust enters the tunnel and is diluted with the dilution air. The dilution tunnel is fitted with two sub-sonic venturi flow meters (smooth approach orifices, SAO); one measures the dilution air flow rate while the other measures the diluted exhaust flow rate; the difference between the two provides the exhaust flow rate from the tail pipe. Heated probes and sample lines are used for sampling both raw exhaust before it enters the tunnel and the diluted exhaust in the tunnel. The sampled gas passes through two banks of heated oven analyzers (OVN) for NO_x , THC, and CH_4 measurements. Two additional banks of unheated

analyzers measure concentrations of CO₂, CO, and NO. Thus, two independent sets of gas analyzers measure the concentrations of dilute and raw exhaust at a frequency of 10Hz. At the end of a test, the dilute gas analyzers are used to measure the concentration of a representative sample collected continuously in a set of heated bags during the test (dilute bag measurement).

A computer program processes data from the analyzers, flow sensors, and dynamometer and calculates the gaseous and particulate emissions in g/mile for the test. Vehicles can be tested on different simulated driving cycles with a driver aid that provides the driver with a real time trace of the drive cycles showing allowable tolerances.

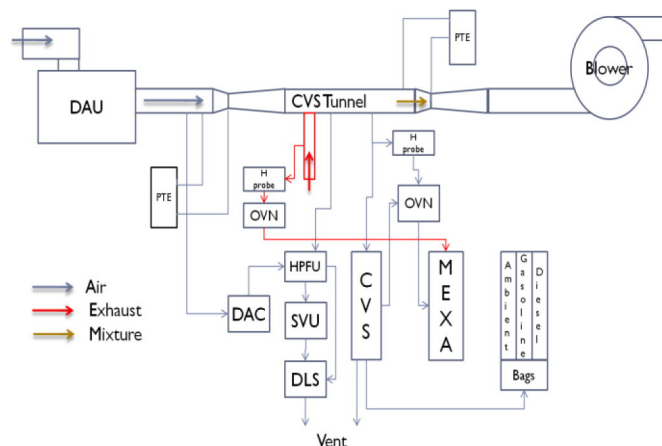


Figure 1. Schematic diagram of emission system in LTI.

THEORETICAL APPROACH

Emission calculation from raw exhaust stream

The emission of a species in g/mile is calculated from continuous measurements of the raw exhaust stream using equations:

$$\text{mass emissions}(g) = \sum_0^t \left\{ \begin{array}{l} \text{tailpipe flow rate} \left(\frac{m^3}{hr} \right) * \\ \text{species} \\ \text{concentration} \end{array} \right\} (10^{-6} ppm \text{ or } 10^{-2} \%) * \left\{ \begin{array}{l} \text{species density} \\ \text{density} \end{array} \right\} \left(\frac{g}{m^3} \right) * \Delta t(hr)$$

$$distance(miles) = \sum_0^t vehicle\ speed \left(\frac{miles}{hr} \right) * \Delta t(hr) \quad (1)$$

Multiple analyzers sample from the exhaust stream, and the bleed off to the analyzers is compensated for in exhaust flow rate calculations.

Exhaust flow rate, species concentrations and vehicle speed of Eq. (1) are acquired continuously in real time during a test at a frequency of 10Hz on the same time stamp, and density is considered constant. These incremental values are integrated in time to obtain their cumulative numbers in grams and miles for the test. Therefore, any time misalignment between these signals will introduce errors in incremental and cumulative calculations. The delay times for exhaust flow rate and vehicle speed during data collection are negligible, while the analyzer response is delayed and modified from the species

concentration at the probe tip, as mentioned earlier. It is essential that this signal be corrected for delay and deformation before their increments are multiplied during calculations.

It is challenging to determine the instantaneous tail pipe flow rate in a CVS system when it is calculated as a difference between two large numbers. This is more so during transient tests, when the engine is idling and the tail pipe flow is low. This facility uses an SAO to measure the diluted exhaust flow and the flow rate is adjustable from 11 m³/minute to 113 m³/minute. Therefore it is possible to set the diluted exhaust flow rate to suit the size of the engine, with sufficient dilution air flow to prevent condensation. A smaller set point flow rate of diluted exhaust for smaller engines reduces the challenges in measuring idle tail pipe flows and minimizes the potential for occasional negative values for tail pipe flow rate.

Smoothing flow response was investigated and it was found that it does not significantly affect the calculated value of emissions (g/mile). The differences observed were less than 0.5%, and therefore the present analyses were conducted with as-recorded flow rate data rather than smoothed flow rate data.

Convolution of the Concentration Signal

The output signal recorded from the gas analyzer is different from the species concentration at the probe tip because of the following two reasons.

- Time delay due to the transportation of the exhaust gas from the probe tip through the sample system which includes filters, plenums, and sample lines up to the detector of the analyzer.
- Mixing and diffusion of species during transportation, causing loss of transient response, resulting in signal deformation. Sharp peaks with short time durations at the probe tip appear as flattened plateaus with longer time durations in the analyzer output.

The above can be termed as ‘convolution’ of the concentration signal and is schematically shown in Figure 2. This can be represented by the equation:

$$y(t) = x(t) * h(t) \quad (2)$$

where $y(t)$ is the analyzer output, $x(t)$ is the concentration signal at the probe tip, and $h(t)$ is the convolution function.

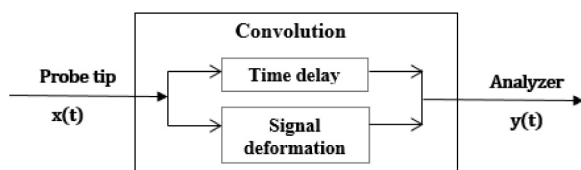


Figure 2. Convolution of the species concentration signal.

Deconvolution Process

The recorded output of species concentration from an analyzer can be deconvoluted to recover the concentration at the probe tip by post processing. Deconvolution attempts to correct the concentration signal for both time delay and deformation.

Deconvolution process for emissions measurement systems consists of the following steps.

- Recording the analyzer response to a step change of concentration at the probe tip
- Determination of the convolution function
- Deconvolution of the analyzer response to reconstruct the input signal
- Applying the deconvolution process to recorded data from an emissions test to reconstruct the probe tip concentrations

These steps are described in the next section.

SIGNAL RECONSTRUCTION

Recording the Analyzer Response to a Step Change of Concentration at the Probe Tip

The analyzer response to a step change of concentration is recorded by flooding zero gas and span gas at the probe tip using a set up with a fast acting three-way valve [17]. The schematic of the setup is shown in Figure 3.

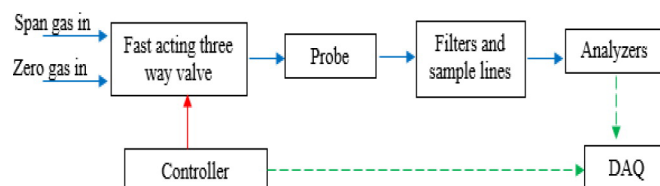


Figure 3. Schematic of the analyzer response set up.

The zero gas and span gas of the analyzer are connected to the two inlets of the three-way valve, while the outlet of the valve discharges to the probe tip. This valve is actuated by a controller which modulates the flow of zero and span gas. It is noted that during an actual test, the DAU (Figure 1) has the capability to adjust tail pipe (TP) pressure within a range of +/- 1.2 kPa, as recommended in the CFR. We endeavor to keep the TP pressure as close to zero as possible during transient tests, but practically it oscillates around zero. Therefore we did not induce any level of tail pipe pressure when we obtained system response data, as this condition most closely represents tail pipe pressure during a test.

A DAQ collects the data from the controller and analyzer at a frequency of 10 Hz. Figure 4 shows the analyzer response for a step change of concentration for a typical analyzer.