

Semi-empirical Analysis of Cold Start Emissions

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ABSTRACT

Automobile time-resolved emissions of CO, CO₂, HC, and NO_x during engine and catalyst warm-up have been analyzed by fitting the emissions to the product of vehicle tractive power and a series of gaussian functions whose relative magnitudes were allowed to vary in time. From this analysis the emissions were discerned into four components : (1.) the emissions due to vehicle power demand, (2.) key-on emissions, (3.) a catalyst warm-up emissions function, and (4.) a fast idle emissions function. Both the emissions associated with the engine and the catalyst warm-up decline exponentially with time. Two additional characteristics (a.) emissions occurring during idling and (b.) emissions due to catalyst cooling during idle were observed, but not quantified. Also, a semi-empirical formula to approximate cold start emissions for light duty cars which includes the vehicle tractive power, time constants which define the emissions decrease in time, and the power demand characteristics has been developed. The data included thirteen light duty cars with model years ranging from 1995 through 2010. The driving cycles included the FTP, ST01, and LA92.

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INTRODUCTION

Effectiveness of the catalytic converter and engine operation to reduce emissions has been increased during normal vehicle operation and a greater proportion of the emissions during federal test procedures occur during cold vehicle operation. When a vehicle's catalytic converter and engine have been sufficiently warmed, they effectively control the emissions of regulated automobile pollutants. However, during the cold start operation of automobiles, the catalytic converter and engine are in the most inefficient operational range. Regulated pollutant (HC, CO, and NO_x) emissions during cold start are included in the automobile emissions certification procedure, i.e., the United States Environmental Protection Agency's (U.S. EPA's) federal test procedure (FTP) [e.g., Code of Federal Regulations (CFR) Title 40 Part 86¹] and in the current state of the art catalytic converter design, a large portion (>50%^{2,3,4}) of the vehicle emissions during the FTP is due to the cold start interval. Moreover, emissions standards continue to become more stringent. Hence, manufacturers are currently examining methods of decreasing the catalytic converter light-off time and thus reducing the total emissions during the FTP.

Methods of estimating emissions from vehicle fleets during cold start typically rely on a linear decline in the emissions (decreasing pass fraction) with increasing vehicle operation time and do not account for emissions due to differences in the vehicle driving pattern or power demands^{5,6}. Furthermore, these methods do not account for varying light-off temperatures or any other physical characteristics (e.g., position, size, geometry, cell density, chemical formulation, etc.) of the catalytic converter. Also, more rigorous treatments of the catalytic converter operation show the emissions concentrations decrease exponentially with time^{7,8,9} after the engine is started and as the engine and exhaust system warm-up.

This report demonstrates a semi-empirical method of estimating cold start emissions from spark ignition powered vehicles which includes the effects of vehicle tractive power and considers the catalytic converter warm-up times. FTP, LA92, and ST01 emissions from 11 light duty cars with model years between 1995 and 1997 were used to evaluate emissions during cold start vehicle operation. Additionally, analysis of emissions from an 2001 ultra-low emission vehicle (ULEV) run on the ST01 cycle which allows for comparisons of total cold start emissions and emissions reductions strategies

and a more recent 2010 technology light duty vehicle run on an FTP cycle are presented. Dynamometer emissions measurements were taken for each second of vehicle operation during the FTP, LA92, and the ST01 cold start and hot running cycles at approximately 75° Fahrenheit. Time resolved CO, CO₂, HC, and NO_x emissions were fit to a series of gauss functions weighted by the instantaneous vehicle tractive power and constant amplitudes. The values of these amplitudes determined from the fits of the CO, HC, and NO_x emissions were found to decrease exponentially with increasing vehicle operation time. CO₂ emission amplitudes decreased only slightly and linearly. Additionally, emissions from key-on and fast idle terms could also be resolved and quantified from the fits.

DATA

A number of data sources have been used in this study, but the main quantitative results presented were determined from a set of ten light duty vehicles taken from the EPA's Mobile Source Emissions Database (MSOD), a 1996 cold start study done by the California Air Resources Board¹⁰, and a more recent cold start study of ultra-low and super-low emission vehicles¹¹.

Table 1. Listing of the model years, test weights, engine sizes, and test cycles used to analyze the time resolved cold start emissions. Although preliminary analysis of time resolved emissions for other vehicles (selev's and light duty trucks) have been done and is ongoing, this study reports the results from the vehicles listed in this table.

Model year	Test weight (kg)	Catalyst type	Engine size (liters)	Test cycle	Data Source
1995	1171	3-way	1.9	FTP	EPA MSOD
1995	1510	3-way	2.5	FTP and ST01	EPA MSOD
1995	1812	3-way	3.1	FTP and ST01	EPA MSOD
1996	1487	3-way	3.1	FTP and ST01	EPA MSOD
1996	1514	3-way	2.4	FTP and ST01	EPA MSOD
1996	1648	3-way	3.0	ST01	EPA MSOD
1996	1664	3-way	3.1	FTP and ST01	EPA MSOD
1997	1281	3-way	2.0	FTP and ST01	EPA MSOD
1997	1632	3-way	3.1	FTP and ST01	EPA MSOD
1997	1678	3-way	3.0	FTP and ST01	EPA MSOD
1996	1474	3-way, close coupled	2.2	FTP and LA92	CARB
2001 ULEV	1361		2.0	ST01	CE-CERT
2010 tier 3	1546	3-way	2.4	FTP	EPA MSOD

Ten light duty vehicles under tier 1 emissions standards were run on the FTP and ST01 test cycles (see [Figure 1](#)). The emissions and speed data were from time resolved (one second resolution) dynamometer emissions tests performed in 1998. [Table 1](#) lists the vehicle model years, engine sizes, and weights along with the test cycles. All but one emissions test was done at 75° F. It was conducted at 95° F. All of the vehicles were equipped with three way catalysts. Typical ST01 and FTP speed-time and time resolved (with one second resolution) CO emissions traces are shown in [Figure 2](#). The CO, HC, and NO_x emissions were corrected for the time delay between the speed and the emissions measurements. Similar systematics were found for the CARB and CE-CERT vehicles.

METHODOLOGY

Although internal combustion engine emissions estimations have relied foremost on statistical treatments and secondarily on variables related to the engine operation, current trends are toward a semi-empirical approach to emissions estimates which rely more heavily on vehicle power consumption. In particular, the EPA's MOVES model is relying on the correlation between vehicle tractive power and emissions. Moreover, time resolved emissions measurements are becoming the norm and they instill/require the analysis methods to be more closely related to the vehicle operation parameters.

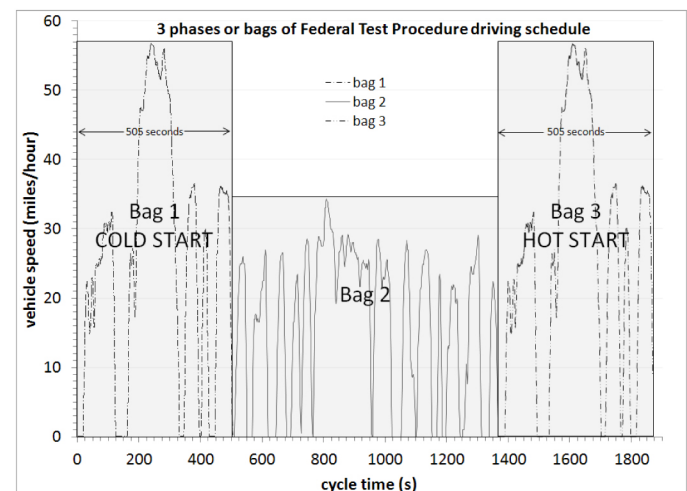


Figure 1. Graph of the Federal Test Procedure (FTP) driving cycle with the three different phases or bags (bag 1, bag 2, and bag 3) of the cycle in shaded rectangles. Bag 1 is the first 505 seconds (or COLD start) part of the FTP with the vehicle started cold. Bag 2 is a hot running portion of the cycle, and bag 3 is the last phase which begins with a vehicle (HOT) start after a 10 minute soak. In the bag 3 hot start portion of the cycle the vehicle's engine and exhaust system have been heated by the two previous FTP driving phases.

Cold start emissions especially exhibit characteristics which require a careful approach to describe the emissions as they evolve with time. The combustion efficiency of the engine increases as the engine is heated after the engine is started, the catalytic converter must also be heated to reach a temperature whereby the converter works at its most efficient level, the "keying-on" of the vehicle requires a relatively large

amount of fuel which is not burned efficiently. Figure 3 compares the vehicle tractive power with CO start emissions as a function of cycle time. These aforementioned features can be deduced from this graphical comparison. As will be shown in this work, discerning all of these factors from one another requires more than just a correlation with vehicle tractive power.

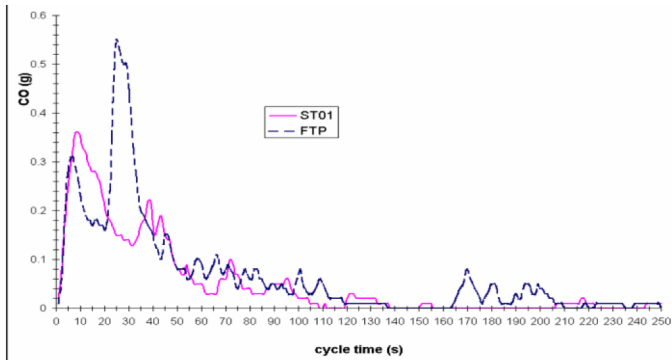


Figure 2. Measured CO emissions versus the cycle time from the cold start minus hot start FTP (bag1 - bag3) (blue dashed line) and ST01 (cold start - hot running) (purple solid line) cycles. These data are averages determined from the 10 vehicles from the EPA's MSOD listed in Table 1.

In this section a methodology is developed to quantify and discern the different components which characterize cold start emissions. In this discussion, the cold start CO emissions are time resolved multi-vehicle averages as displayed in Figure 3. These emissions are those above the vehicle emissions which would occur when the engine and catalytic converter are at their most efficient operational temperature. That is, the emissions are those additive emissions (above hot running) due to a cold engine and catalytic converter referred to for convenience in some emissions models (e.g., MOVES, MOBILE6; in a later discussion the actual measured cold start emissions will be the focus). They were determined by subtracting the (time resolved) FTP hot running (bag 3) emissions from the FTP cold start (bag 1) CO emissions. For the ST01 cycle, the ST01 hot running CO emissions were subtracted from the ST01 cold start emissions. In this work they will be referred to as the FTP or the ST01 cold start minus hot start emissions. The FTP and ST01 cold start minus hot start emissions differ due to the 10 minute soak (engine and catalytic converter cool) just before the bag 3 portion of the FTP cycle. However, in the ST01 cycle there is no opportunity for the engine or the catalytic converter to cool. The hot start portion of the ST01 begins immediately after the pre-conditioning cycle which brings the engine and catalytic converter to their most efficient operating temperatures.

For each of the pre-2000 EPA MSOD vehicles listed in Table 1 CO time resolved cold start minus hot start emissions were calculated for both the ST01 and FTP cycles and then used to obtain average CO emissions as a function of cycle time. Figure 3 illustrates these average CO cold start minus hot start emissions during the first 250 seconds of either cycle.

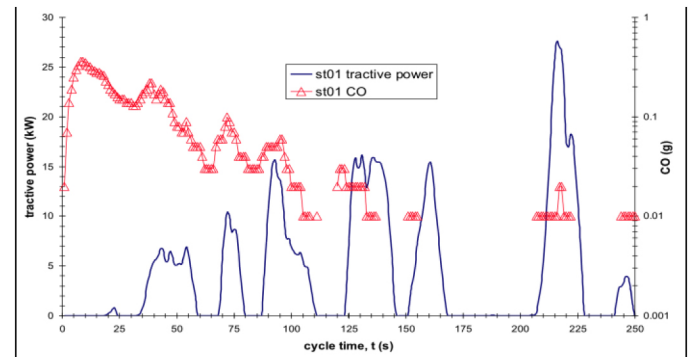


Figure 3. Evolution of CO emissions as a function of cycle time from a dynamometer cold start ST01 emissions test of a light duty vehicle. Except for the initial key-on and idle portion (from 0 to about 20 seconds) of the test, the CO emissions can be correlated with positive tractive power events. The additional feature is the steady decrease in emissions with increasing vehicle operation (cycle) time.

As mentioned above, there is a 10 minute soak period before the bag 3 portion of the FTP cycle is started which allows the catalyst and engine to cool. Hence, the difference between the cold start and hot start portions of the FTP should be corrected upwards to make a more accurate comparison between the FTP and ST01 cold start minus hot start emissions. This correction can be estimated by using the HR 505 which is a cycle identical to the FTP bag 3 except the vehicle is preconditioned to ensure the catalyst is heated to its most efficient operational temperature before starting the actual driving. FTP cold start (bag1) minus hot start (bag3) CO emissions were compared to the FTP cold start (bag1) minus the EPA's hot running (HR) 505 second cycle CO emissions. These CO emissions from the FTP bag1, bag3, and HR505 cycles for 88 light duty cars with model years ranging between 1983 and 1998 were extracted from the EPA's MSOD. For each of the 88 vehicles, the ratio between the total cold start minus hot start emissions from FTP and HR505 were calculated

$$\frac{\text{bag1} - \text{HR505}}{\text{bag1} - \text{bag3}} \quad (1)$$

and then graphed as a histogram. Mean values of the ratio of the differences had values between 0.03 and 0.14 depending on the range of the ratio chosen in the histogram. Hence, estimating the cold start minus hot start emissions using the FTP bag1-bag3 difference is conservatively 5% low. Total cold start emissions for the ST01 and FTP cycles are about 13.1 grams and 17.4 grams, respectively. Accordingly, the cold start minus hot start portion of the FTP cycle CO emissions could be corrected to about 18.3 grams. How this should be apportioned in regard to the cycle time will be discussed below.

Until the converter is heated to an efficient operational temperature, the power consumption portion of the emission spikes are greater than what occur during the hot running vehicle operation. Throughout this time the catalyst is being