

# AN ON-BOARD EMISSIONS AND PERFORMANCE MEASUREMENT SYSTEM (OEPMS) FOR MEASURING CARBON MONOXIDE EMISSIONS DURING COLD STARTING

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## Final Report

*Prepared by:*

Jason P. Johnson  
And  
David B. Kittelson, Ph.D.

University of Minnesota  
Department of Mechanical Engineering  
Minneapolis, MN 55455

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# TABLE OF CONTENTS

CHAPTER 1	INTRODUCTION .....	1
CHAPTER 2	APPARATUS: THE OEPMS .....	5
CHAPTER 3	METHODS .....	11
CHAPTER 4	RESULTS .....	21
CHAPTER 5	CONCLUSION.....	31
REFERENCES	.....	33



## LIST OF TABLES

Table 3.1. Summary of test nomenclature, test dates, and test conditions.....	15
Table 3.2. Variables recorded by the OEPMS. ....	16
Table 4.1. Test ambient temperatures, test times, and times spent in control loops. ....	21
Table 4.2. Ratio of open-loop CO emitted to closed-loop CO emitted for diluted exhaust cold-start test.....	29
Table 4.3. Correlation coefficients for linear regression of CO mass emission rate and CO concentration versus non-zero throttle position. ....	30

# LIST OF FIGURES

Figure 2.1. OEPMS schematic. ....	6
Figure 2.2. Diagram of the diluting exhaust probe. ....	8
Figure 3.1. ECOM-AC CO gas calibration curve for standard gas concentrations. ....	12
Figure 3.2. Commute path map. ....	18
Figure 3.3. Plot of vehicle speed and CO mass flow vs. engine on time for a typical commute. ....	20
Figure 4.1. Plot of time spent in open-loop control vs. integrated average ambient temperature. ....	22
Figure 4.2. Logical model for passive ambient air dilution. ....	25
Figure 4.3. CO mass emitted during open-loop operation as a function of ambient temperature. ....	28

## EXECUTIVE SUMMARY

Over 80% of the emissions produced by spark-ignition (SI) automotive engines in a typical commute are produced during the first two minutes of operation. Of particular concern are emissions of carbon monoxide (CO), a pollutant regulated under the National Ambient Air Quality Standards (NAAQS) as administered by the United States Environmental Protection Agency (EPA). During start-up and the early phases of a commute, SI engines are operated under fuel-rich conditions that lead to incomplete combustion and the production of CO, as well as other pollutant gases. [1]

The problem of CO production during start-up is exacerbated by cold weather conditions, such as those experienced during Minnesota winters. More time is spent in fuel-rich conditions during cold weather, producing more CO. In addition, emission controls such as catalytic converters, which would otherwise remove CO from engine exhaust, are less effective in cold weather.

This study was undertaken in order to develop a system for measuring the CO exhaust emissions of a passenger automobile during a typical commute during cold weather in Minnesota. It provides a method for studying CO production in passenger automobiles with an eye toward overall reduction of CO emissions. In addition, the effect of magnetic-type block heaters on start-up emissions was studied.

A system, dubbed the On-board Emissions and Performance Measurement System (OEPMS), was developed for this purpose. The OEPMS consists of a laptop computer, a portable exhaust gas analyzer, a diluting tailpipe probe, an automotive scan tool for recording automobile performance variables, and various data acquisition and signal conditioning hardware. The OEPMS was installed into a 1990 model year

passenger car with 175,000 original miles and was driven under various commute conditions on Minnesota highways, freeways, and residential roads.

Tests with the OEPMS provided a wide range of results. First, it was shown that the time a car's engine spends operating under fuel-rich conditions was negatively related to the ambient temperature, as expected.

When operating at near stoichiometric fuel-air ratios over the test commute path, the mean value of CO mass emitted was 0.21 +/- 0.04 kg when measured undiluted and 0.20 +/- 0.06 when measured under ambient air dilution.

Emissions of CO were measured during start-up and fuel-rich operation with and without treatment with a magnetic-type block heater. When treated with a block heater, fuel-rich operation total mass emissions of CO under fuel-rich conditions were measured to be 0.19 +/- 0.20 kg. Due to large uncertainty, no significant effect of block heaters on reducing cold-start CO emissions was found.

In its current configuration, the OEPMS is ideal for research into on-road diesel engines that emit much lower levels of CO. By providing a reliable dilution system or a higher range CO analyzer, the OEPMS would be even more useful for research into spark ignition engines.

The OEPMS proved very durable and is easily adaptable to other vehicles for a wide-variety of testing. The OEPMS holds promise for future research into fuels, emissions reducing technologies, regulations, and commute habits in real-world situations. It is also an ideal tool for fleet maintenance and emissions compliance monitoring.

# CHAPTER 1

## INTRODUCTION

Over 80% of the emissions produced by spark-ignition automotive engines in a typical commute are produced during the first two minutes of operation. Under very low temperature conditions, such as those encountered in Minnesota during the winter, the fraction of emissions associated with the start and warm-up of the engine is even higher.

High carbon monoxide (CO) concentrations are a concern in many U.S. cities and are regulated under the National Ambient Air Quality Standards (NAAQS) which are administered by the United States Environmental Protection Agency (EPA). Ambient CO concentrations are especially high during the winter months, due in large part to the effect of extreme cold weather cold-starts on automobile emissions.

Qualitatively, starting an engine when its components (as measured by the engine's coolant temperature) are at or near ambient temperature and are below a characteristic temperature is known as a cold-start. Cold-starts are responsible for high CO emissions, particularly for cold ambient temperatures (defined as either 23.9 °C or – 6.7 °C under two versions of the Federal Test Procedure for cold-starts)

CO is produced primarily by vehicles with gasoline fueled, spark-ignition engines. During start-up, especially at low temperatures, a spark-ignition engine must be operated under fuel rich conditions. Operation under this fuel-rich condition is termed open-loop operation. Fuel-rich operation leads to incomplete combustion and excessive emissions of CO and other pollutant gases. [1]

When the engine reaches a characteristic operating condition, generally measured by coolant temperature, the engine begins to operate at a near-stoichiometric air to fuel ratio. This condition, termed closed-loop operation, results in more nearly complete combustion, reducing emissions of CO. The terms open-loop and closed-loop refer to the algorithms for control of the engine's air to fuel ratio.

CO is usually removed by oxidation to carbon dioxide ( $\text{CO}_2$ ) within the exhaust catalytic converter. Contributing to the problem of increased CO emissions during cold-start is the function of typical catalysts. Generally, the catalytic converter does not function until it reaches a certain characteristic temperature, called the catalyst light-off temperature. This temperature is generally between 200 and 350 °C. [1] During a cold-start at a cold ambient temperature (such as those experienced during a Minnesota winter), the catalyst does not immediately reach its light-off temperature. The excess emissions during the fuel-rich start-up and warm-up periods of operation pass into the atmosphere untreated. While outside the scope of this study, future research utilizing the methods presented herein could provide valuable information regarding the function of catalysts in extreme cold weather.

Much laboratory research has been conducted on the effect of ambient temperature on the emissions of spark-ignition engines or on cold-start emissions control strategies. Much of this research has been focused on hydrocarbon (HC) emissions, though CO emissions and oxides of nitrogen ( $\text{NO}_x$ ) emissions have also been widely studied. [2][3][4][5][6] Significant research has also been conducted in the laboratory on entire vehicles using refrigerated test cells. It is not known, however, whether these tests

are adequate simulations of actual automobile commutes, especially commutes conducted during the extreme cold that can be experienced in Minnesota.

Recent research has turned to on-board emissions measurements using actual automobile commutes on the open-road.[7] This study seeks to expand that research. It will also be used to evaluate on-board emissions sensing technologies for use in Minnesota during extreme cold and other conditions.

Additionally, the effect of block heaters on emissions will be evaluated. Previous studies have indicated that block heaters can be an effective means for reducing emissions of CO and other pollutants.[8][9] One study indicated that a block heater can reduce CO emissions during cold-start by 60%. [9]

The main focus of this research was to design and construct a system capable of making on-board emissions and performance measurements on a spark ignition engine, passenger automobile. The system was designed with many concepts in mind, including the following:

- Portability from one vehicle to another
- Simplicity
- Ease of installation, requiring minimal modification of the test vehicle
- Ability to be used in a fleet situation
- Ability to track relative changes in an individual vehicle, due to research or maintenance needs
- Durability
- Performance in cold-weather characteristic of winter in Minnesota

As a test of the usefulness of this system, dubbed the On-board Emissions and Performance Measurement System (OEPMS), it was used to examine cold weather emissions of CO. Exhaust emissions of CO were measured at the automobile tailpipe using the OEPMS during cold start conditions over a typical suburban commute path. A comparison was made of CO emissions between open-loop (start-up) and closed-loop operation.

In addition, CO emissions during closed-loop operation were related to throttle position, a surrogate for acceleration. This analysis may be useful in identifying causes of CO "hot-spots", localized increases in ambient CO levels that may be found on freeway on and off ramps and near freeway interchanges.

As an additional test, the effectiveness of magnetic-type block heaters in reducing start-up CO emissions was examined.

## **CHAPTER 2**

### **APPARATUS: THE OEPMS**

The test vehicle used in the evaluation of the OEPMS and in the emissions research was a 1990 passenger car with a 2.5L TBI engine and approximately 175,000 original miles. This vehicle is representative of older cars that may be high emitters of CO. The vehicle passed Minnesota's inspection maintenance test for CO. It is equipped with a factory standard catalytic converter.

The OEPMS itself consists of 5 parts:

1. A Dell Latitude Cpi Laptop Computer running Windows 98 and National Instruments LabView
2. An ECOM-AC portable exhaust gas analyzer
3. A diluting exhaust probe
4. A ProLink 9000 automotive scan tool
5. A National Instruments SCXI signal conditioning and data acquisition system

A schematic of the system is shown in figure 2.1.

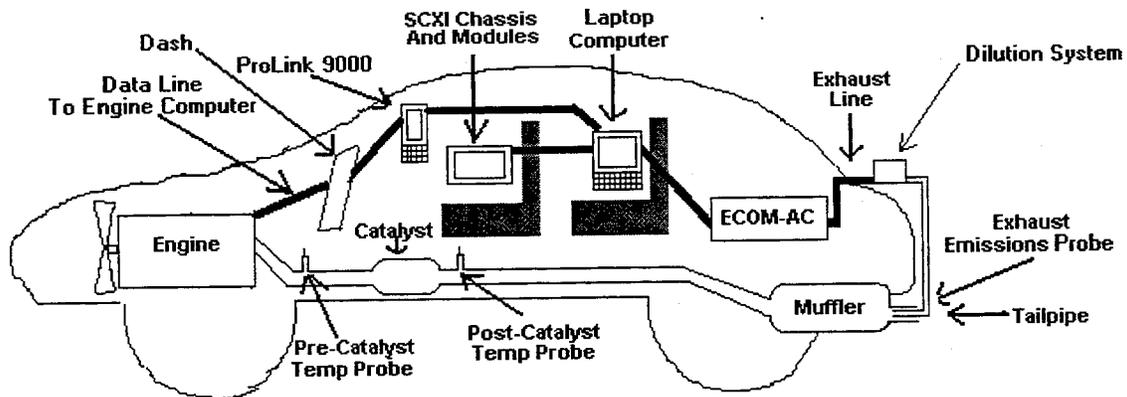


Figure 2.1. OEPMS schematic.

The control center of OEPMS is a Dell Latitude Cpi laptop computer, with a 266 MHz Pentium II processor running the Windows 98 operating system. It is equipped with 3 serial ports and 1 parallel port for device communications.

The computer runs a data logger program written in the LabView software package from National Instruments. LabView was chosen for ease of programming, suitability to task, and transparent integration with data acquisition devices. The data logger program written for the OEPMS communicated with two RS-232 devices (serial port devices) and with the SCXI system, a parallel port device. Data from these three devices was written to disk at the maximum sampling rate, approximately once every 5 seconds. The data was analyzed offline at a later time using Microsoft Excel and Microsoft Access. The data logging computer is physically located on the passenger seat of the test vehicle.

The second part of the OEPMS is the ECOM-AC portable exhaust gas analyzer. The ECOM-AC utilizes electrochemical cells to measure oxygen ( $O_2$ ) and CO

concentrations in the exhaust sample. Concentration of O<sub>2</sub> is measured to a precision of +/- 0.1% with an accuracy of 2% of the reading. CO is measured on a parts per million basis with two separate sensors, one low range sensor with a 0-4000 ppm range and one high range sensor with a range of up to 65500 ppm, with precision of 1 ppm and an accuracy of 4% of reading.

If necessary the ECOM-AC can measure exhaust concentrations of nitric oxide (NO), nitrogen dioxide (NO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), and unburned hydrocarbons (HC), in some cases with optional analyzer upgrades.

During testing, the ECOM-AC is located in the trunk compartment of the test vehicle. It is cabled to the data logging laptop computer, communicating continually by streaming data through an RS-232 serial port.

A stand-alone ECOM-AC has been tested for use in underground mines as a maintenance diagnosis and compliance-checking tool. [10] Cold start testing has shown that the ECOM-AC's range for CO measurements may be too low for accurate measurement of cold start emissions in SI automobiles. Dilution has solved this problem, but dilution increases the difficulty of making measurements and also increases measurement error. As currently configured, without dilution, the OEPMS with the ECOM-AC is ideal for diesel powered vehicles, which emit lower levels of CO. The availability of higher range CO analyzers should be examined for any future implementations of the OEPMS in SI automobiles. Alternately, a dilution ratio controlled compressed air dilution system could be implemented.

The ECOM-AC draws sample from the exhaust pipe through the third part of the OEPMS, a diluting exhaust probe. The diluting exhaust probe is a three-foot section of

stainless steel tubing, bent into an 'L' shape and inserted into the tailpipe. The end of this tubing is fitted with 2 needle valves and a 'T' fitting. One valve controls the inflow of exhaust and the other controls the inflow of ambient dilution air. Sample is drawn from a nipple in the 'T' fitting through a particulate filter and a rubber sample line to the analyzer. The exhaust gas sample reaches the ECOM-AC as a mixed sample of ambient dilution air and direct-sampled automobile exhaust. A diagram of the exhaust probe is shown below in Figure 2.2.

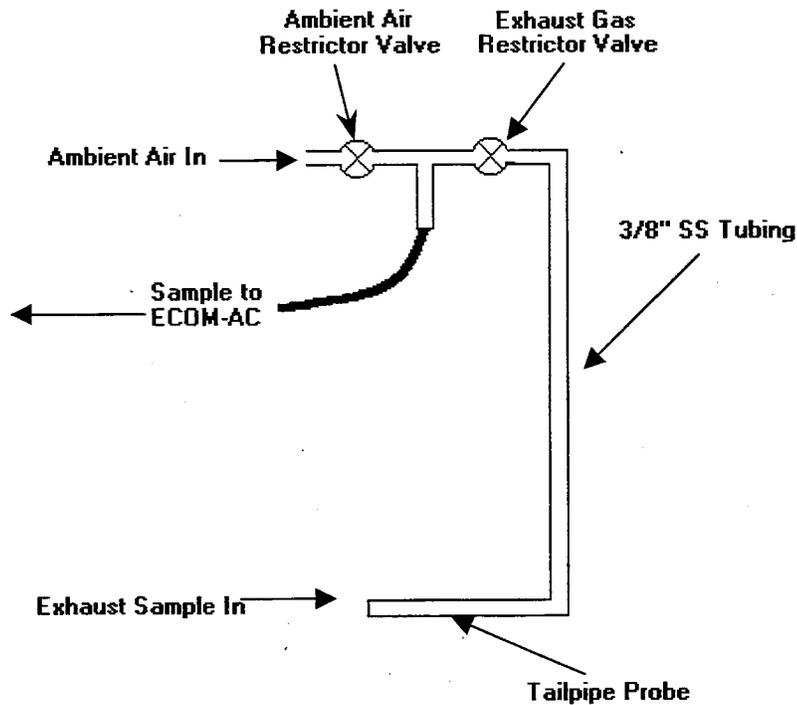


Figure 2.2. Diagram of the diluting exhaust probe.

Dilution ratio is measured on a cycle-averaged basis and is calculated from sample O<sub>2</sub> concentration and the assumption of a constant atmospheric O<sub>2</sub> concentration for a given test.

The fourth part of the OEPMS is ProLink 9000 automotive scan tool. This device reads the live performance data of the automobile's engine microprocessor. The ProLink 9000 can output up to 16 data variables at one time, including engine speed (in RPM), vehicle speed, intake manifold pressure (MAP), intake manifold temperature (MAT) and control loop status, among others.

The output is via a four-line RS-232 serial port, using the VT-100 terminal protocol. The datalogging computer receives this data via one of its serial ports.

The ProLink 9000 was not part of the original design of the OEPMS, but has proven its most critical component for meeting the previously outlined design requirements. It is portable from one vehicle to another, is simple to use, and is familiar to maintenance personnel. When combined with a datalogger, an emissions analyzer, the diluting exhaust probe, and a vehicle with serial performance data (OBD II compliant automobiles, etc.) the scan tool forms a cross-platform OEPMS ideal for fleet situations, research, and maintenance.

The final part of the OEPMS, the SCXI system, consists of various signal-conditioning modules that are placed into electronic chassis. Conditioned signals are passed along an electronic bus to an analog-to-digital converter module. This module in turn communicates digital voltage measurements to the computer over a parallel port connection. The modularity of this system makes it easy to use, highly flexible, and very useful for many types of data acquisition needs.

In the current configuration, the SCXI system is configured to measure up to 32 thermocouple type signals. Four such signals are currently being measured, all

thermocouples for temperature measurements not available from the ProLink 9000.

These four temperatures are:

1. Ambient temperature, measured at the passenger side roof support
2. Exhaust temperature, measured by a probe in the tailpipe
3. Exhaust upstream of the catalyst, in a custom welded and machined port
4. Exhaust downstream of the catalyst, also in a custom welded and machined port

The ports created for the catalyst monitoring thermocouple represent the only permanent modifications to the test vehicle. These ports were added to monitor variables that proved to be outside the scope of this research. Future implementations of the OEPMS may eliminate the need for the SCXI system or could be configured to monitor as of yet unidentified transducers.

The current OEPMS has proved durable throughout multiple tests. It is easily adaptable to fleets and is available for wide variety of on-board testing. This OEPMS can serve as a template system used to check automobile emissions, maintain automobiles, diagnose maintenance problems, and to reduce pollution. By the addition of the SCXI system, the OEPMS can be adapted to a wide variety of research needs.

## CHAPTER 3 METHODS

With the OEPMS constructed as described above, tests were undertaken to quantify cold-start emissions of CO during cold-weather conditions indicative of Minnesota winters. The effectiveness of magnetic-type block heaters in reducing cold start emissions was also evaluated.

As a first step, the ECOM-AC was upgraded with a CO analyzer capable of ranges up to 65500 ppm. This analyzer was factory calibrated with standard gases. The analyzer also performs electronic zero and calibration during its 3 minute start-up period after power-on.

Observations during testing have called into question the factory calibration of the analyzer. After the completion of testing, a zero and span calibration was performed on the CO sensor. For a CO 49900 ppm standard gas sample, the ECOM-AC measured a value of 51000 ppm, within the accuracy of the CO sensor. A ten point calibration of the CO analyzer was then performed. The results of this calibration are graphed below in figure 3.1.

### ECOM-AC CO Gas Calibration

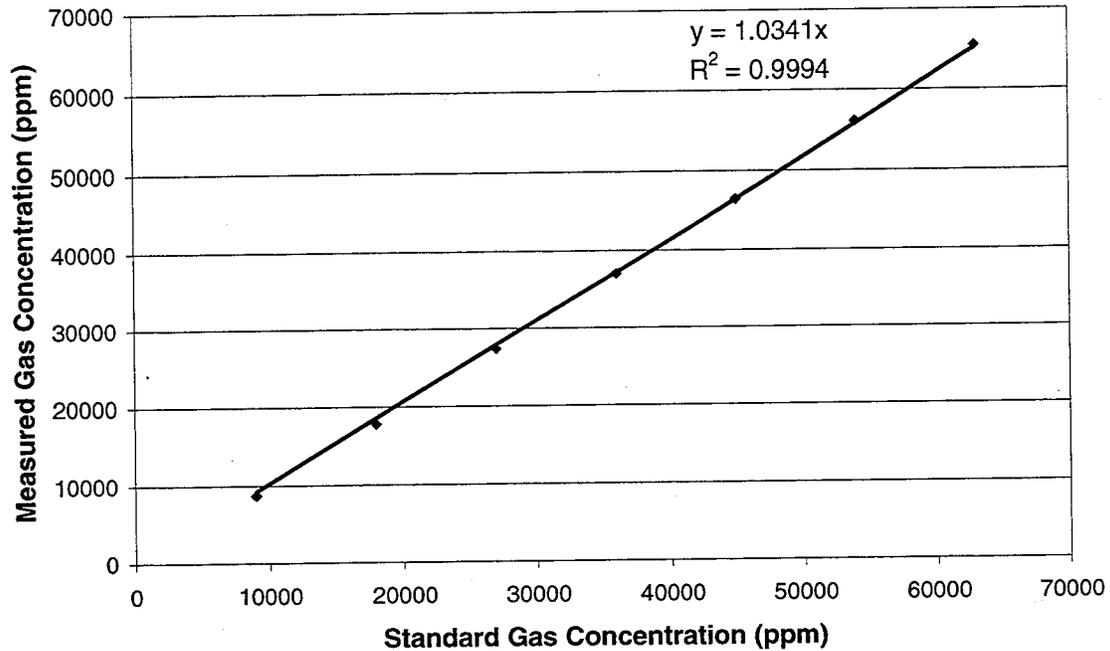


Figure 3.1. ECOM-AC CO gas calibration curve for standard gas concentrations.

A proportional least-squares fit of the data showed that the ECOM-AC measured the concentrations of the standard gases to within 3.41%. This value is less than the stated accuracy of the instrument, 4 to 5% of the reading. The ECOM-AC was compared to conventional exhaust gas analyzers as part of research conducted by Matthew Spears, then of the CDR, for the U.S. Department of the Interior and the National Institute of Occupational Health and Safety entitled "An Emissions-Assisted Maintenance Procedure (EAMP) for Diesel-Powered Equipment". His comparison concluded that measurements made by the ECOM-AC agree with laboratory-based non-dispersive infrared (NDIR) CO measuring instruments with a reduced  $X^2$  of 0.65. [10]

In this study, the reduced  $X^2$  test was used to determine whether two distributions measured for discrete values of an independent variable were significantly different from one another. A reduced  $X^2$  is expected to have a value near 1 and is a measure of goodness of fit. The reduced  $X^2$  statistic is calculated according to the following general formula.

$$X^2_{reduced} = \sum_{j=1}^n \frac{[g(x_j) - h(x_j)]^2}{\sigma^2(g) + \sigma^2(h)} / \nu$$

Where  $X^2_{reduced}$  is the reduced  $X^2$  statistic,  $n$  is the number of discrete measurements of the two distributions under comparison that were made,  $j$  is the summation index,  $h(x_j)$  is the value of one distribution measured at the value  $x_j$  of the independent variable,  $g(x_j)$  is the value of the second distribution measured at  $x_j$ ,  $\sigma(g)$  is the standard error of  $g(x)$  at  $x_j$ ,  $\sigma(h)$  is the standard error of  $h(x)$  at  $x_j$ , and  $\nu$  is the number of degrees of freedom. [11]

A test matrix for characterizing cold start emissions and evaluating the effectiveness of magnetic-type block heaters in reducing CO emissions was defined. For the purposes of this research, a cold-start was defined as an engine start with a coolant temperature at or near ambient temperature, after a minimum 6 hours cool down from the last engine on condition, with ambient conditions less than 15 °C. In the case of block heater tests, cold-start is defined as above with the possibility that coolant temperature may be heated to greater than ambient.

Tests were performed under one of four conditions. They are as follows:

1. Cold-start commutes, emissions measured undiluted
2. Cold-start commutes, emissions measure with passive ambient air dilution

3. Cold-start commutes after treatment with a magnetic-type block heater, emissions measured undiluted
4. Cold-start commutes after treatment with a magnetic-type block heater, emissions measured with passive ambient air dilution.

Three tests were made under condition one and one test was made under condition two. At this time, the decision was made to add diluted conditions two and four, as the ECOM-AC was unable to measure peak levels of CO emissions during cold-start.

Three tests under condition two were performed, followed by a fourth test under condition one. This test was used as an additional measure of exhaust oxygen concentration under extreme cold weather conditions, for use in dilution ratio calculations. Finally, three tests under condition three were conducted.

The following table summarizes the order of the testing and gives test names and conditions. The naming follows the "XXX##" scheme, where "XXX" denotes test conditions and "##" is a number describing the order of the test within a given test condition. "UT" describes an untreated test (no block heater), whereas "TT" describes a treated test (block heater was used.) The prefix "D" denotes that dilution was used.

Test Name	DATE	Dilution	Block Heater?
UT 01	09-Dec-98	Undiluted	No
UT 02	10-Dec-98	Undiluted	No
UT 03	11-Dec-98	Undiluted	No
TT 01	12-Dec-98	Undiluted	Yes
DUT 01	22-Dec-98	Diluted	No
DUT 02	22-Dec-98	Diluted	No
DUT 03	23-Dec-98	Diluted	No
UT 04	26-Dec-98	Undiluted	No
DTT 01	27-Dec-98	Diluted	Yes
DTT 02	28-Dec-98	Diluted	Yes
DTT 03	29-Dec-98	Diluted	Yes

Table 3.1. Summary of test nomenclature, test dates, and test conditions.

Various performance and emissions variables were recorded during testing. The following chart summarizes recorded variables and their sources (devices acting as transducers.)

Source			
Computer	ProLink 9000	ECOM-AC	SCXI System
Date	Air Fuel Ratio	O2 (%)	Ambient Temperature
Time	Barometric Pressure (kPa)	CO (PPM)	Exhaust Temperature
	Coolant Temperature (C)		Catalyst Upstream Temperature
	Spark Advance (Deg)		Catalyst Downstream Temperature
	Designated Idle RPM		
	Engine On Time		
	Engine Speed (RPM)		
	Loop Status		
	MAP (kPa)		
	MAT (C)		
	Oxygen Sensor Voltage (mV)		
	Injector Pulse Width (ms)		
	Throttle Position (%)		
	Vacuum Pressure (kPa)		
	Vehicle Speed (MPH)		

Table 3.2. Variables recorded by the OEPMS.

The tests were made and data was taken according to a defined protocol. This step-by-step process is outlined as follows.

1. The exhaust probe is inserted into the tail pipe and is secured to the test vehicle

2. The ECOM-AC is placed in the trunk and its sample line is connected to the exhaust probe.
3. The ECOM-AC, SCXI system, and the ProLink 9000 are powered on.
4. The ECOM-AC runs through its self-calibration period of three minutes.
5. The ProLink 9000 is programmed to provide the necessary data output via an RS-232 serial port.
6. The data logging laptop is booted. The LabView data logging software is started. An abbreviated data file is checked to insure that all devices are communicating properly.
7. If testing with treatment by the magnetic-type block heater, the heater is removed.
8. The engine is started.
9. The automobile is allowed to run at idle for 30 seconds.
10. The commute path is driven.
11. At the end of the commute path, the engine is shut down. The test ends with the shut down of the engine.

The commute path was chosen to represent the researchers' view of a typical commute. A map of this commute is shown in figure 3.2.



The commute begins on residential roads and highways. It proceeds to an interstate on-ramp, followed by interstate driving (on I-694). The commute path reaches a freeway interchange (between I-35W and I-694) and then proceeds along another interstate. This interstate gives way to a city highway (Minnesota 55). Side roads lead to the final destination, the Center for Diesel Research facility in South Minneapolis. The commute ends immediately upon arrival.

The on-ramps, off-ramps, and interchanges that are part of this commute show the effects of rapid acceleration on CO emissions. Residential roads at the start of this tests are typical of roads driven during the cold-start, open-loop phase of driving. Interstate cruising is common to many commutes and gives an indication of steady-state CO emissions during driving.

The following chart, figure 3.3, showing a typical test result illustrates the commute path. Vehicle speed is plotted against time elapsed from the start of the tests. Typical mass emissions of CO are plotted as well. The different commute phases are also labeled.

## CHAPTER 4 RESULTS

The following chart summarizes the test conditions for each set of data taken.

Average ambient temperature, times spent in each control mode (open-loop and closed-loop), and total test times for each test are shown in the following chart.

Test Name	Ambient Temp (C)	Time in Open-loop (s)	Time in Closed-loop (s)	Total Test Time (s)
DTT 01	-2.8	123	1900	2023
DTT 02	4.0	111	2125	2236
DTT 03	-14.1	165	2003	2168
DUT 02	-10.8	132	2051	2183
DUT 03	-8.9	152	2037	2189
TT 01	8.9	104	1923	2027
UT 01	4.3	112	1959	2071
UT 02	4.4	114	2119	2233
UT 03	4.0	103	2061	2164
UT 04	-8.3	149	1861	2010
DUT 01	-13.7	67	2091	2158

Table 4.1. Test ambient temperatures, test times, and times spent in control loops.

The relationship between time spent in open-loop control to ambient temperature is plotted in Figure 4.1. Test DUT01 is an outlying point, perhaps due to engine starting difficulties experienced during this test. After elimination of this point, linear regression

analysis indicates a negative relationship amongst these two variables with a correlation coefficient of 0.86.

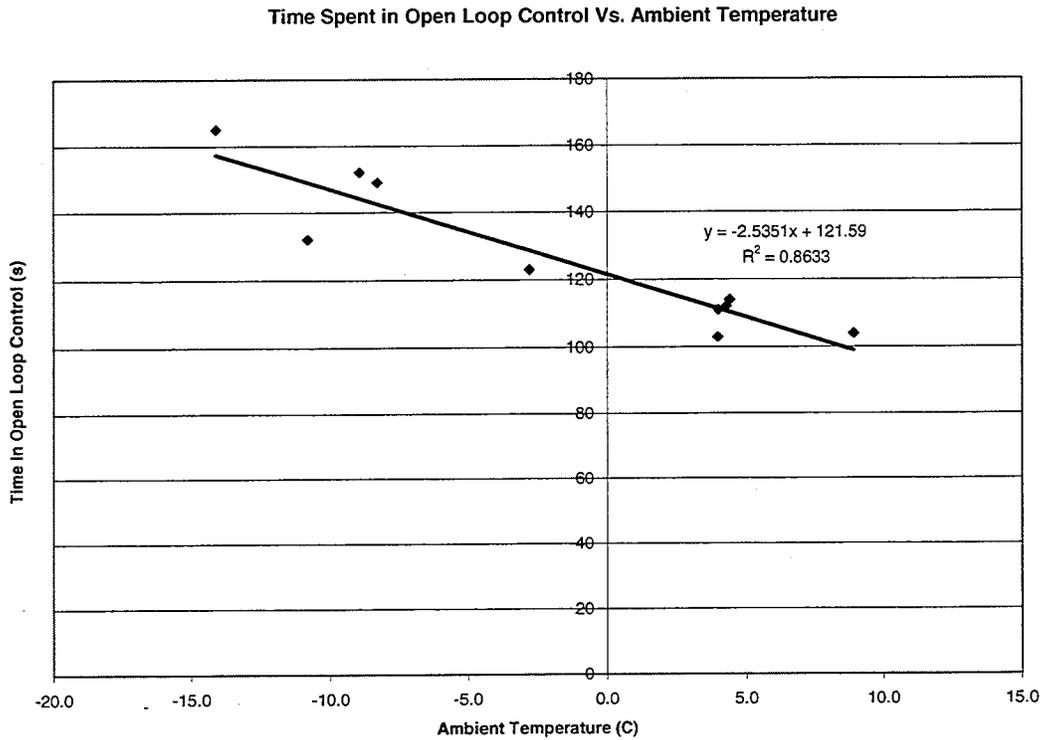


Figure 4.1. Plot of time spent in open-loop control vs. integrated average ambient temperature.

Carbon monoxide concentration is measured by the ECOM-AC. The quantity of interest is CO mass rate of emissions, integrated to give total mass of CO emitted. In order to determine this quantity, the mass flow of exhaust must be calculated.

Mass flow exhaust is based on measurements of intake manifold pressure (MAP), intake manifold air temperature (MAT), and air to fuel ratio. The calculation is also based on physical constants characteristic of the engine and on thermodynamic assumptions about the function of the engine. This calculation proceeds as follows.

$$Q_E = Q_F + Q_A$$

Where  $Q_E$  is mass flow of exhaust,  $Q_F$  is mass flow of fuel, and  $Q_A$  is mass flow of air.

This step assumes that mass flow into engine in the form of fuel and air is conserved.

Mass exhaust flow can be determined entirely from a measure of mass air flow by the following relationship.

$$Q_E = (1 + 1/R_{AF}) Q_A$$

Where  $R_{AF}$  is the air-to-fuel ratio.

$$E_v = \left(1 + \frac{1}{r-1}\right) \left(1 - \left(\frac{P_E}{P_M}\right)^{\frac{1}{g}}\right) \left(\frac{P_m}{P_B}\right) \left(\frac{1}{(1 + (M_e / M)(1 / R_{AF}))(C_{FE})}\right) \left(\frac{T_M}{T_C}\right)$$

Where  $r=8.5$  (the engine compressions ratio),  $P_E$  is exhaust pressure, assumed to be 115 kPa,  $P_B$  is the barometric pressure,  $P_M$  is the manifold pressure,  $g$  is a thermodynamic constant equal to 1.28,  $M_e$  and  $M$  are characteristic molecular mass constants equal to 29 and 114 respectively,  $C_{FE}$  is the fuel evaporation constant, equal to 0.5,  $T_M$  is the manifold temperature, and  $T_c$  is the cylinder pressure, assumed to be 315 K, and  $E_v$  is the volumetric efficiency.

Volumetric efficiency is the measure of the ratio of air taken in by the engine during a cycle to the engine's displacement over that cycle. Air density,  $\rho_A$ , is given by

$$\rho_A = \frac{P_M}{(0.285T_M)}$$

Finally air flow,  $Q_A$ , and hence exhaust mass flow is given by the following:

$$Q_A = \rho_A E_v \left( \frac{V_D}{6000} \right) \theta_e$$

Where  $V_D$  is engine volume displacement (2.5L), and  $\theta_e$  is engine speed in RPM.

With the passive dilution system used in this testing, some independent measure of dilution ratio had to be made. Without flow and pressure measurements available for the sampling system, we came to rely on measures of  $O_2$  concentration in the sample.

From undiluted tests, an average operating oxygen level is found. The ambient  $O_2$  level is measured at the beginning of a diluted test, before the engine is started. The average measured  $O_2$  level for a diluted test is also calculated. From these three values, the average dilution ratio for a given test can be found.

The calculation of the dilution ratio is based on mass conservation, as described in the pictorial model found in figure 4.2.  $Q$  denotes mass flow and  $C$  denotes concentration.

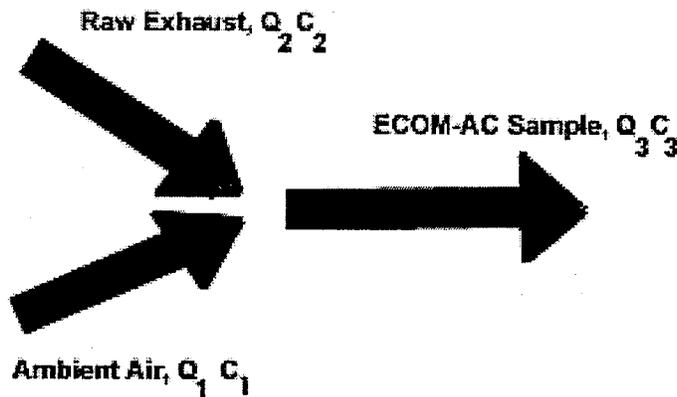


Figure 4.2. Logical model for passive ambient air dilution

The calculation proceeds as follows:

$$Q_1 + Q_2 = Q_3$$

$$\text{Dilution Ratio} = Q_3/Q_1 = (Q_2/Q_1) + 1$$

$$C_1 Q_1 + C_2 Q_2 = C_3 Q_3$$

$$\text{Dilution Ratio} = (Q_2 - Q_1)/(Q_2 - Q_3)$$

With exhaust flow and dilution ratio calculated, the determination of total mass of CO emitted can proceed. Measured concentration of CO is multiplied by the average dilution ratio to give an exhaust concentration of CO. This concentration is multiplied by mass flow rate of exhaust and the ratio of CO molecular mass to average exhaust molecular mass to give a mass flow rate of CO. Integrating over time yields the total mass of CO emitted during the test cycle. Simple numerical integration was used to determine this value. This calculation is given below.

$$Q_{co} = (DilutionRatio)(C_{co})(Q_e)(M_{co}/M_e)$$

Where  $Q_{co}$  is the mass flow rate of CO,  $D$  is the dilution ratio,  $C_{co}$  is the measured concentration of CO on a volume basis,  $Q_e$  is the mass flow rate of exhaust,  $M_{co}$  is the molecular mass of CO, 28.0, and  $M_e$  is the average molecular mass of the exhaust, calculated to be 28.8. [12]

The total mass of CO emitted during closed-loop operation was determined for undiluted tests. Both heater-treated and untreated tests were included, since closed-loop operation should be the same in both cases. The mean value of CO emitted during closed-loop operation is 0.20 +/- 0.04 kg .

Linear regression analysis, plotting CO mass emitted versus ambient temperature showed not significant relationship with a correlation coefficient of 0.03.

This same analysis of closed-loop CO emissions was performed for tests under dilution conditions. The mean value of CO emitted during closed-loop under diluted conditions was 0.19 +/- 0.08 kg. Taken together, the mean value of closed-loop CO emitted was 0.20 +/- 0.06 kg. Again, linear regression analysis showed no significant relationship between mass of CO emitted during closed-loop operation and ambient temperature with a correlation coefficient of 0.10.

Under diluted conditions, open-loop mass emissions of CO were also quantified. The average value of total CO mass emitted was 0.19 +/- 0.20 for untreated tests and 0.16 +/- 0.23 kg for treated tests. These large standard deviations illustrate the extreme variability of cold start emissions. A Student's t-test analysis of these values indicates no significant difference between treated and untreated cold-start emissions. Clearly, this is due to large standard deviations. Further research under more controlled ambient conditions is necessary.

The Student's t-test is used to determine whether or not two measured mean values are significantly different from one another for a given level of confidence, in this case, 95%. Significance at 95% is given when the t test statistic exceeds the so-called t-critical value, which can be found in tables of t-critical values in any statistics text. The form of the t test statistic is given by the following equations.

$$t = \frac{x_1 - x_x}{\sqrt{s_p^2 \left( \frac{1}{n_1} + \frac{1}{n_2} \right)}}$$

$$s_p^2 = \left( \frac{n_1 - 1}{n_1 + n_2 - 2} \right) s_1^2 + \left( \frac{n_2 - 1}{n_1 + n_2 - 2} \right) s_2^2$$

Where t is the test statistic,  $x_1$  and  $x_x$  are the test values,  $s_1$  and  $s_2$  are their corresponding standard errors,  $s_p$  is a pooled common error, and  $n_1$  and  $n_2$  are the number of measurements leading to means  $x_1$  and  $x_2$  respectively.

The values for individual tests (both treated and untreated cases together) were plotted versus integrated average ambient temperature, as seen in Figure 4.3. Linear regression analysis showed no significant relationship with a correlation coefficient of 0.08.

CO Mass Emitted During Open Loop Operation Vs. Ambient Temperature

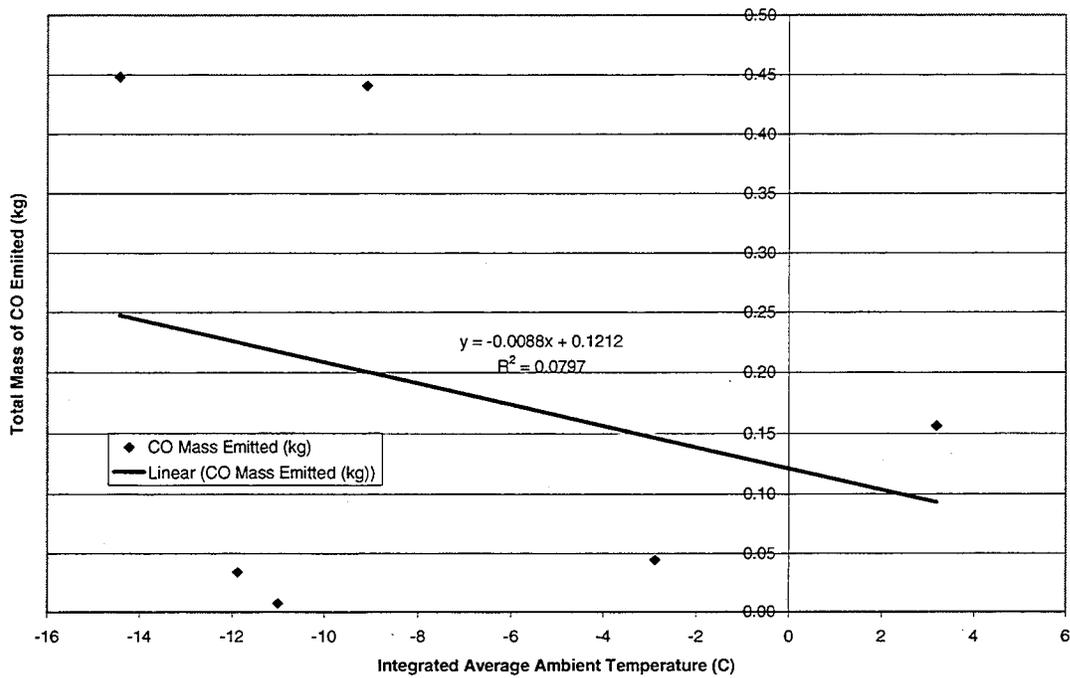


Figure 4.3. CO mass emitted during open-loop operation as a function of ambient temperature

Calculations of CO emitted during diluted tests proved extremely variable, likely due in part to the passive nature of the dilution system. Since the ratio of open-loop to closed-loop CO emissions during these tests is independent of dilution ratio, a comparison of these ratios was conducted. Table 4 lists the values for each test. The mean value for untreated tests was  $1.1 \pm 0.9$  and the average value of treated tests was  $0.7 \pm 1.0$ . Taken together, this ratio is  $0.9 \pm 0.8$ .

Test Name	Ratio of Open-loop CO Mass Emitted to Closed-loop Mass of CO Emitted
DTT 01	0.73
DTT 02	0.52
DTT 03	2.10
DUT 01	0.04
DUT 02	0.18
DUT 03	1.88

Table 4.2. Ratio of open-loop CO emitted to closed-loop CO emitted for diluted exhaust cold-start test.

This analysis indicates that a magnetic-type block heater shows no significant effect in changing the ratio of open-loop to closed-loop CO emissions, within the uncertainties of this test. Further, the large uncertainties illustrate the very chaotic and uncontrolled nature of CO emissions during open-loop operation under cold weather conditions. However, these tests do show that cold-start emissions do contribute a rather sizable fraction of the total CO emitted during a typical commute.

During periods of closed-loop acceleration, CO exhaust concentration spikes were observed. An attempt was made to relate acceleration to an increase in CO emissions. Throttle position was measured as a surrogate for acceleration in three undiluted exhaust tests, UT03, UT04, and TT01. Linear regression analyses were performed on closed-loop CO emissions data, on a mass basis and on a concentration basis. No significant trends

were found, based on values of correlation coefficient. A table listing these values is shown below.

Correlation Coefficients for CO Vs. Throttle Position		
Test Name	Based on CO Concentration	Based on CO Mass Emitted
UT 03	0.01	0.13
UT 04	0.02	0.16
TT 01	0.01	0.2

Table 4.3. Correlation coefficients for linear regression of CO mass emission rate and CO concentration versus non-zero throttle position.

## CHAPTER 5 CONCLUSION

This research has provided a method for measuring CO emissions under real world conditions, including cold-starts. We have measured the ratio of CO mass emitted during open-loop operation to closed-loop operation for this specific commute and automobile to be  $0.9 \pm 0.8$ . This value was measured for a vehicle entering the end of its life span with little or no emissions reducing maintenance performed. Higher closed-loop emissions of CO may account for this lower than expected ratio. The inherent variability of open-loop, cold start emission accounts for the uncertainty of this measurement. We found no correlation between throttle position and CO emissions over the course of this commute.

While the magnetic-type block heater proved anecdotally useful for starting the test vehicle in cold weather, it could not be shown that such a heater has a significant effect in reducing cold-start CO emissions. It is clear that more testing is needed to determine whether or not magnetic-type block heaters significantly reduce cold-start CO emissions.

Unseasonably warm weather and wide swings in ambient temperature during testing made it unlikely that any CO reduction effects, if any had been observed, could be correlated with the effect of treatment with the magnetic-type block heater. The magnetic heater did not significantly increase engine coolant temperature prior to start-up. It is likely that other types of block heaters that directly heat engine coolant would reduce the time an engine spends in open-loop control, thus reducing mass emissions of CO. Further research into methods for reducing cold-start emissions is warranted.

The mean value of closed-loop CO emitted was 0.21 +/- 0.06 kg. This result was very consistent between undiluted and diluted measurements and is likely a reliable value characteristic of the accuracy of the method.

Due in large part to the variability of cold start, open-loop emissions, no significant relationship between these emissions and ambient temperature was measured. Further research is necessary to combat variability and to determine the nature of this relationship.

The major goal of this research was to design, build, and test the effectiveness of the OEPMS. That goal has been accomplished. In addition, the research has suggested that further refinements of the OEPMS are desirable. This research has also suggested ways in which the OEPMS could be utilized in the future.

The OEPMS can be used to identify the causes of CO "hot-spots". These "hot-spots", if their existence is established by future research, may include areas of acceleration such as is found near on-ramps, off-ramps, and freeway interchanges. They may also include areas of automobile start-ups-- enclosed spaces such as parking garages.

The OEPMS holds promise for future research into fuels, emissions reducing technologies, regulations, and commute habits in real-world situations, not in laboratories where artifacts may be introduced.

The OEPMS is also ideal for fleet maintenance and emissions compliance monitoring. Many of its subsystems are already familiar to maintenance personnel and the OEPMS' emissions sensing capabilities only add to the tools in their arsenal. Future iterations of the OEPMS can only simplify its design and increase its usefulness in the fight to reduce automobile pollution.

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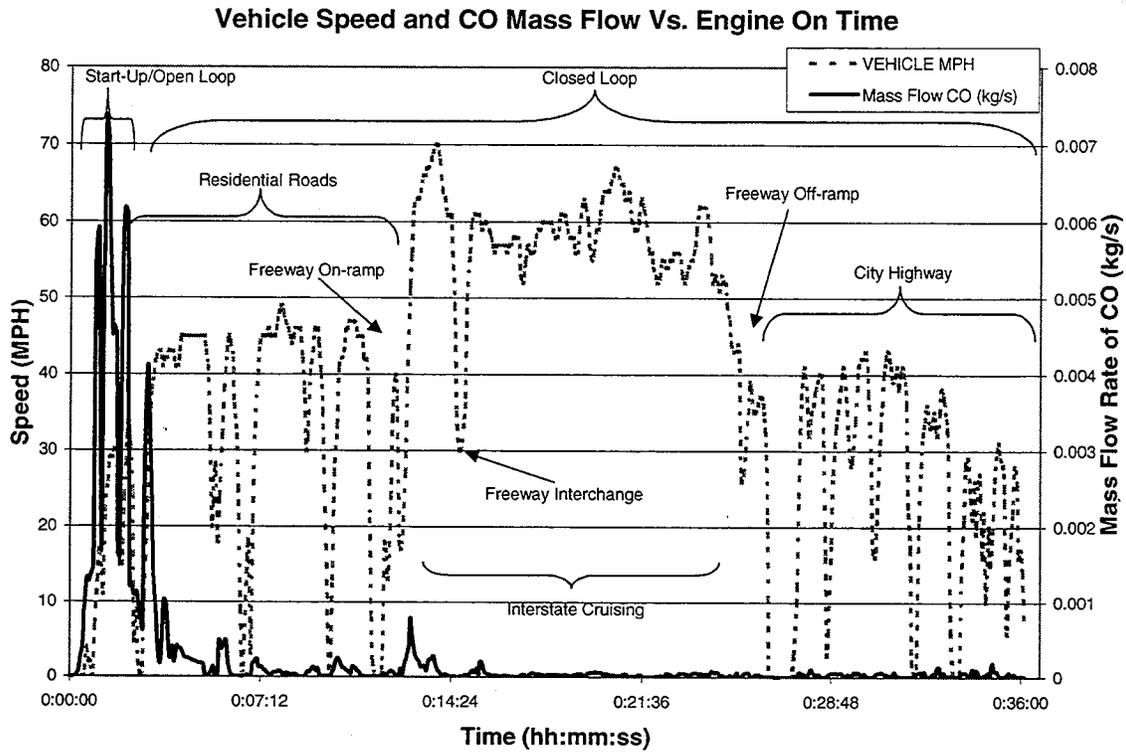


Figure 3.3. Plot of vehicle speed and CO mass flow vs. engine on time for a typical commute.