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Automobile Emissions: A Problem Based Learning Activity Using the Clean Air Act

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Abstract

A problem-based learning activity has been developed using automotive engineering and requirements of the Clean Air Act to examine complex environmental issues involving automobiles. After an introductory study, students sample the O_2, CO, NO, and NO_2 levels of automobile exhaust and analyze the results. The activity employs a constructivist approach and is appropriate for entry-level engineering classes. It can be modified for use in upper level engineering classes as well. To prepare for the emissions analysis lab, students study the composition of atmospheric gases, products of combustion, and the measurement of automotive emissions. The laboratory component is the actual sampling of engine exhaust from student selected automobiles using an exhaust emissions analyzer. Students use sample values of emission concentrations for O_2, CO, NO, and NO_2, combustion kinetics, and fluid dynamics to calculate the engine fuel flow rate, exhaust flow rate, and mass emission rates for CO and NO_X. This paper presents an overview of the introductory studies followed by a description of the automobile exhaust sampling activity. Representative sample data of automobile emissions are presented along with a discussion of the sampling results, a method for approximating pollutant mass emission rate levels, and comparison to EPA standards.

Introduction

Media coverage of environmental issues and global climate change occurs daily. Engineering students are continuously exposed to environmental topics and many are interested in pursuing environmental engineering careers. How can engineering educators incorporate contemporary issues in environmental engineering into the classroom? The activity described in this paper is designed to introduce students to automobile exhaust pollutant issues in a problem-based learning activity. The activity takes advantage of the growing availability and ease of use of portable emissions analyzers for exhaust testing. For the first part of the activity, students investigate the topic and associated issues. The second part of the activity is a laboratory component, consisting of sampling engine exhaust from student selected automobiles using an exhaust emissions analyzer. The analyzer includes a probe that is inserted into the exhaust stream from the tailpipe of a stationary automobile. Students collect concentrations of selected exhaust gases; in this case O_2, CO, NO, and NO_2. Calculations are performed to convert the concentrations in parts per million to mass emission rates in grams per mile or grams per brake horsepower-hour using estimates of the operating conditions of the engines, combustion kinetics, and fluid dynamics. The method for sampling and calculating levels of exhaust gases used in this in this activity is an approximation. It does not represent EPA test guidelines and is not considered a standardized method. But it does provide students the opportunity for useful experience that is needed to develop and guide understanding of the topic along with experience in making assumptions and estimates for rapid problem solving. For the third part of the activity, students are asked to develop their own problem to examine such as testing additional vehicles or examining the difference between emissions from cold and hot engines.

Course Framework

This activity has been developed for Introduction to Mechanical Engineering at Kansas State University, a course that allows students to explore different facets of the mechanical engineering field. Introduction to Mechanical Engineering is a freshman/sophomore level class with a normal enrollment of around 150 students. In addition to whole class activities and lecture, students are placed into groups of ten to twelve students, and each group rotates at different times through a variety of research institutes and laboratories associated with the Department of Mechanical Engineering. This rotation allows students to work in small groups while experiencing research and processes in a particular sub-field of mechanical engineering. For an introduction to environmental engineering applications, students visit the National Gas Machinery Laboratory of Kansas State University to investigate exhaust emissions. The activity described in this paper has been developed to provide both a problem solving and a laboratory activity on exhaust emissions. The students spend three two hour sessions on the activity. During the first session, the students are introduced to the technology and perform the initial problem development and discussion portions of the activity. During the second session, the students perform the laboratory, collecting the data using the emissions analyzer. During the third session, students analyze the data and discuss the results. Student comments about the activity have been highly favorable. The class is offered only in the fall and a study to evaluate the effectiveness of the activity for engagement and learning is planned for fall 2010.

Problem-Based Learning

Problem-Based Learning, PBL, is a constructivist learning approach that is used to stimulate and improve learning by presenting problems about topics of interest to students. Learning is shaped by direct experience and is most effective when students are presented with a compelling problem.[1, 2] The problem-based learning approach allows students to study a problem of interest in a team-based setting. A PBL study is student directed with opportunity for discussion, and often the students rather than the instructor select the problem. Much of the new information is acquired through student research with the instructor acting as a facilitator. The goal of the activity is to acquire new skills and collaboratively build knowledge about a topic. Collaborative knowledge building occurs when team members work together to construct, improve, and expand knowledge.[3] This type of activity requires an engaging topic along with student directed research and discussion. As knowledge building proceeds, questions and proposed answers to the problem emerge within the student teams.[4]

Learning Objectives

The learning objectives for this activity exist in two domains: 1) developing collaborative problem solving abilities, and 2) developing a working knowledge of language and skills of the topic. Learning and the ability to solve problems depend on “exploration of alternatives”.[1] Much of the purpose of education in an increasingly technological world is to transmit the skills and language of that complex world to students.[1] Students are asked to collaboratively explore the topic, make assumptions, and use them for reasonable estimates. Students use their assumptions and estimates in mathematical calculations. In the process of exploring the topic, students will develop a working knowledge base about compressible fluids, dimensional analysis of units, and the language and terminology associated with gases and exhaust emissions.

Initial Problem and Discussion

As an introductory activity, a class discussion takes place about concentrations of gases in the atmosphere and combustion engine exhaust. Students are asked about their previous knowledge of atmospheric gases, pollutants and automobile emissions. Following a typical PBL model, students are divided into teams and asked to research the effects of automobile exhaust pollutants on human health. The results of their research are presented to their peers and each team constructs an exam question based on their research. Suggested questions to be answered by student research are:

1. What are the identities and concentrations of atmospheric pollutants caused by automobile exhaust?
2. What are the effects of those pollutants on humans?
3. What are allowable levels of engine exhaust emissions and according to the Clean Air Act?
4. How are engine exhaust emissions measured?

Students should determine that pollutants from vehicle exhaust include carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter along with air toxics such as benzene and toluene. A brief description of the effects of automobile pollutants can be found at the U. S. Environmental Protection Agency website.[6] In the section on regulations, allowable levels of exhaust pollutants are measured in grams per mile (gm/mile) for light duty vehicles, (cars and small trucks) and grams per brake horsepower-hr (gm/bhp-hr) for heavy-duty vehicles.[9, 10]

Pollutant Levels

For the purposes of this paper, only levels of CO and NO_X are examined. NO_X is defined as the combined levels of NO and NO_2. Current allowable levels of CO and NO_X can be retrieved from the Electronic Code of Federal Regulations, Title 40, Protection of the Environment.[7] However, to simplify the search required for this activity, allowable levels are selected from the EPA website for comparison purposes only. The levels selected are for cars (light duty vehicles, LDV) classified as transitional low emission vehicles (TLEV) with allowable levels of 3.4 gm/mile CO and 0.4 gm/mile NO_X.[9] Allowable levels selected for comparison with diesel engines are 15.5 gm/bhp-hr CO and 10.7 gm/bhp-hr NO_X.[10]

Data Collection

The process of continuous emission testing with a portable analyzer is explained and students are asked to select vehicles to bring to the lab for exhaust emissions testing. Ideally, students should select automobiles varying in age and engine size to be able to consider varying levels of emissions. Before the vehicles are tested, students are asked to make comparative predictions about pollutant concentrations in the exhaust of the vehicles based on their engine types and age.

The exhaust emissions analyzer used in this activity is an ECOM America analyzer owned by Kansas State University's National Gas Machinery Laboratory (NGML). The analyzer includes a probe that students hold in the exhaust stream to measure concentrations of O_2, CO, NO, and NO_2 in parts per million (ppm). Engineers from NGML instruct the students in use of the analyzer, collection of data, and interpretation of results. To avoid lowering emission concentrations due to dilution of the exhaust stream, the analyzer probe is held as close to the tail pipe as possible. The vehicle operator is directed to accelerate the engine to approximately 2000 RPM to simulate engine load. A cold engine will produce higher concentrations of CO while a warm engine will produce higher concentrations of NO_X; therefore, engines are allowed to warm up before testing is commenced. Sample values are collected multiple times from each vehicle. Data included in Table 1 consist of the emission results from a 2001 Chevrolet Cavalier, a 1992 Buick Le Sabre, and an M35 (military surplus) truck with LD (diesel) engine.

Table 1: Measured emission concentrations (E_{conc})

	Sample #	O_2 (ppm)	CO (ppm)	NO (ppm)	NO_2 (ppm)
1992 Buick Le Sabre	1	16.9	5964	9.0	2.4
	2	19.8	3205	2.0	1.8
	3	19.0	2965	4.0	1.4
	4	18.3	5227	6.0	0.8
2001 Chevrolet Cavalier	1	19.6	80	0	0.5
	2	19.4	55	0	0.5
	3	19.4	43	0	0.3
Diesel Truck	1	19.4	293	153	74.4
	2	19.1	373	190	108.4
	3	19.4	320	154	108.2

Data Analysis and Calculations

Students record the concentrations of pollutants in the exhaust emission in parts per million (ppm) using the analyzer. Table 1 allows students to compare pollutant emission concentrations between vehicles, but comparison to EPA standards requires that the pollutant concentrations be converted to grams per mile or grams per brake horsepower-hour. Students are guided through calculations to determine approximate pollutant levels in terms of grams per mile (gm/mile) or grams per brake horsepower-hour (gm/bhp-hr). The method for sampling and calculating levels of exhaust gases used in this in this activity does not represent EPA test guidelines and is not considered a standardized method. But it does allow students the opportunity for useful experience that is needed to develop and guide understanding of the topic along with experience in making assumptions and estimates for rapid problem solving. Values selected for use in the calculations are included in Table 2.

Table 2: Selected Calculation Values

	Gasoline	Diesel
Higher heating value, *HHV* (Btu/lb)	20007	19676
Fuel economy, estimated *MPG* (mile/gallon)	19 (Buick) 23 (Chevrolet)	10
Selected speed, *MPH* (mile/hr)	60	50
Fuel Density, ρ_{fuel} (lb/gal)	6.073	7.09
O_2 F-factor, F_{O2} ($ft^3/10^6$-Btu)	9190	9190
Brake Horsepower, estimated (bhp)	--	300

To facilitate the problem solving activity and reduce the cognitive load, students are guided through the calculations by engineers from NGML.[5] The problem solving steps are shown below.

1. Students are first asked to determine the approximate fuel flow rate ($\dot{m}_{fuel}$) in lb/hr of each vehicle using estimated engine fuel economy (*MPG*) and selected engine speed (*MPH*). Using the density of the fuel, gasoline or diesel, the fuel flow rate can be calculated with the following equation:

   $$\dot{m}_{fuel} = \frac{\rho_{fuel} \times MPH}{MPG}$$

   Students are expected to find the density of the fuel, select the speed, and estimate the fuel economy, in addition to utilizing the appropriate dimensional analysis.

2. Students are then guided through the calculation for the volumetric exhaust flow rate (Q_{exh}), in ft^3/hr using an equation adapted from Method 19 of the Clean Air Act:[8]

   $$Q_{exh} = \dot{m}_{fuel} \times HHV \times F_{O_2} \times \left(\frac{20.9}{20.9 - \%O_2}\right)$$

   The percentage of oxygen in standard air is 20.9%. Students find the higher heating value (*HHV*) of each fuel, in Btu/lb and convert the O_2 emission concentration in parts per million (ppm) from Table 1 to volume percent ($\%O_2$). Engineers from NGML provide the O_2 F-factor for each fuel (F_{O_2}).

3. Finally, students calculate approximate mass emission rates (E_{mass}) in gm/mile, using the volumetric exhaust flow rate (Q_{exh}) from step 2, concentrations of pollutants in ppm collected with the exhaust emission analyzer (E_{conc}), the selected speed (MPH) from Table 1, and a gas density factor (ρ_E) in gm/ft^3-ppm in Table 3.

Table 3: Method 19 Gas density factor

	CO	NO_X
Gas density factor, ρ_E (gm/ft^3-ppm)	3.293×10^{-5}	5.416×10^{-5}

$$E_{mass} = \frac{Q_{exh} \times E_{conc} \times \rho_E}{MPH}$$

4. The mass emission rate of the diesel engine ($E_{mass\ D}$) is found using the estimated brake horsepower (bhp) from Table 2:

$$E_{mass\ D} = \frac{Q_{exh} \times E_{conc} \times \rho_E}{bhp}$$

The calculated mass emission rates are recorded in Table 4 and Table 5.

Table 4: Calculated Gasoline Engine Results

	Sample #	$\dot{m}_{fuel}$ (lb/hr)	Q_{exh} (ft^3/hr)	E_{mass} CO (gm/mile)	E_{mass} NO_X (gm/mile)
1992 Buick Le Sabre	1	19.18	3526	11.54	0.036
	2	19.18	3526	6.20	0.012
	3	19.18	3526	5.74	0.017
	4	19.18	3526	10.12	0.022
2001 Chevrolet Cavalier	1	15.84	2912	0.13	0.001
	2	15.84	2912	0.088	0.001
	3	15.84	2912	0.069	0.001

Table 5: Calculated Diesel Engine Results

	Sample #	$\dot{m}_{fuel}$ (lb/hr)	Q_{exh} (ft^3/hr)	$E_{mass\ D}$ CO (gm/bhp-hr)	$E_{mass\ D}$ NO_X (gm/bhp-hr)
Diesel Truck	1	35.45	6410	0.206	0.263
	2	35.45	6410	0.262	0.345
	3	35.45	6410	0.225	0.303

Discussion of Data

In the case of the vehicles with measured emission concentrations (E_{conc}) shown in Table 1, a reasonable prediction prior to the data collection is that the Chevrolet would have the lowest concentrations of all pollutants due to the age and emission control technology and that the diesel truck would have the highest levels. Examination of the data from Table 1 show that while the lowest concentrations of NO and NO_2 are from the Chevrolet and the highest are from the diesel truck, the highest concentrations of CO are from the Buick. This provides an opportunity for discussion of the operation of the catalytic converter in cars and how age and maintenance issues can affect emissions in cars. The high concentrations of CO from the Buick likely were due to either a problem with the catalytic converter or other mechanical problems within the engine. In cars built after 1996, a warning light from the on board detection system alerts the driver to problems with the environmental system, but that technology was not present on the 1992 Buick.

The inclusion of the diesel engine presents the opportunity for discussion of the different pollutant emission rules that apply to diesels. It also allows for discussion or student research about the differences between the diesel engines and gasoline engines. Students have often experienced the heavy exhaust produced by diesel engines but are unfamiliar with the differences in performance and the need for higher torque associated with the diesel engine. In this particular result, pollutant concentrations for the diesel are low considering the age of the truck. Repairs had been made to the truck engine to improve performance including replacement of piston rings and addition of an oxidation catalyst. Maintenance and refurbishing the diesel engine improved the engine performance and decreased pollutant emissions. Maintenance performed on the other two vehicles could improve their performance as well.

The calculated CO and NO_X levels, E_{mass} and $E_{mass\ D}$ from Table 4 and Table 5 can be compared with the previously selected allowable levels of pollutants from the EPA website.[9, 10] A comparison shows that calculated pollutant emissions from the three selected vehicles are below the allowable levels except for the CO levels in the Buick. For the Buick, the lowest sample value of 5.74 gm/mile CO is higher than the selected allowable level of 3.4 gm/mile for LDV/TLEV.[9]

Extension Activities

After the students complete the lab analysis, questions are posed. What should a responsible car owner do if their car is producing pollutants above the allowable levels? Should the owners of higher emission-producing vehicles buy new lower emission cars? What should society as a whole consider as responsible options for reducing automobile emissions? Class discussions can include the issues associated with replacing older vehicles with newer vehicles and/or electric cars. Students can discuss solutions to automobile emissions and their relationship to environmental problems and economics associated with the manufacture of cars, electric car technology, and the petroleum industry. At this point an extension of the activity would be to allow students to develop their own problem solving activities. Students can sample additional vehicles or compare emission concentrations for different engine conditions such as engines at start up compared to engines that have been running.

Future Research

This activity has been used in an initial mechanical engineering class as an introduction to environmental science. To assess the effectiveness of the activity, students will be given surveys to assess engagement and pre and post assessments of conceptual understanding. After analysis of surveys and assessments, we intend to make assessment results, additional data sets, and sample calculations available for other engineering educators.

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