Temperature and RVP Effects on Diurnal Emissions for Nonroad Engine Modeling

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Purpose

This report documents how the EPA NONROAD emission inventory model accounts for the effects of temperature and RVP on diurnal evaporative emissions.

Background

The EPA NONROAD model estimates diurnal evaporative emissions from gasoline-fueled engines. Evaporative emissions from diesel-fueled engines are considered negligible due to the extremely low volatility of diesel fuel and, therefore, are not included in the NONROAD model.

Evaporative emissions from most gasoline-fueled engines are very sensitive to the volatility of the fuel (typically expressed as Reid Vapor Pressure or RVP) as well as the temperatures that the fuel experiences. In highway vehicles, this sensitivity is mitigated to some degree by the carbon canister evaporative control systems that have been used for many years, but such control systems are not currently used on nonroad equipment.

Modeling of uncontrolled evaporative emissions has been attempted in a variety of ways. The EPA MOBILE model for highway vehicles uses an algorithm based on the Wade equation [1, 2]. This is based on the "Ideal Gas Law" which models pressure, temperature, and volume assuming simplified "ideal" behavior, and the equation also includes a compressibility factor to account for the non-ideal nature of hydrocarbon vapor. There has also been some limited testing of nonroad engines, such as lawn mower fuel tanks, to gather diurnal evaporative emission data, but little or none of this testing has addressed variation of the fuel's base temperature and RVP, so it is of little value for the purposes of this analysis.

Approach

The basic mechanisms of fuel evaporation are the same regardless of whether the engine/fuel system is a highway vehicle or a nonroad engine. They both use fuel tanks, fuel lines, and carburetors or fuel injection systems to deliver the fuel to the engine. In terms of their evaporative emissions, the major difference between highway vehicles and nonroad engines is that highway vehicles in the U.S. have been required to use evaporative control systems, such as carbon canisters, to minimize evaporative losses. Thus, test data from controlled vehicles would not be applicable to nonroad engines, but the principles and test data concerning uncontrolled evaporative emissions from highway vehicles should be reasonably applicable to nonroad engines.

Two existing models of RVP and temperature effects on diurnal emissions were investigated and considered: the California ARB OFFROAD model and the US EPA MOBILE highway vehicle emissions model. The EPA model used for development of the national Phase 1 small spark ignition engine rule was not considered in this evaluation since it did not include any calculation of RVP or temperature effects on evaporative emissions.

Both the ARB OFFROAD model and MOBILE calculate diurnal emissions by adjusting from base conditions of 9.0 psi RVP and an ambient temperature rise from 60F - 84F during the day (average temperature of 75F) to the RVP and ambient temperature range being modeled. However, there are substantial differences in the effects of temperature in the two models. In MOBILE, a day with an average temperature of 90F instead of 75F results in twice as much diurnal emissions, whereas in ARB's OFFROAD model the 90F day would increase diurnal emissions by a factor of 3. According to the ARB model documentation, their equation was derived from EPA highway vehicle data that included both carbureted and fuel injected vehicles, which means that the vehicles were probably equipped with carbon canister evaporative control systems. The use of such data could account for the greater rate of increase in diurnal losses with temperature, since carbon canisters would be more likely to experience "breakthrough" due to the much greater vapor generation rate at high temperature. Although the controlled vehicles would probably show lower absolute emissions, they would have a larger percentage increase in emissions with temperature, when compared with uncontrolled vehicles. Thus, EPA does not consider the approach used in the ARB OFFROAD model to adjust evaporative emissions for RVP and temperature to be appropriate for nonroad engines. By contrast, the approach used in the EPA MOBILE model does not rely on emission data from highway vehicles to estimate evaporative emissions from nonroad engines. For this reason, EPA has chosen to rely on the approach used in the EPA MOBILE model for uncontrolled engines to estimate evaporative emissions from nonroad engines.

The EPA MOBILE model 's diurnal evaporative calculations are divided into three separate parts: (a) a base diurnal emission rate based on test data at standard test conditions: 9.0 psi RVP and a 60F - 84F temperature rise, (b) adjustment of these uncontrolled emissions to the temperature and RVP of interest, and (c) modification of results to account for the control system and possible tampering. As described above, the MOBILE model uses basic chemistry theory to model the variation in uncontrolled diurnal emissions with RVP and temperature. Thus, for purposes of the NONROAD model, it is fairly straightforward to use the appropriate portion of code directly from the MOBILE model's diurnal calculations to adjust the base nonroad diurnal emissions for temperature and RVP. By applying this code from the MOBILE model, the absence of evaporative control systems can be reflected properly in the calculations.

This approach provides consistency between the NONROAD model and other current models, but it does not rule out possible changes to the method in a future version of the NONROAD model based on analysis of any newer data or comparison with updated versions of other models that may become available.

Summary and Recommendations

Due to its applicability to current nonroad engines without evaporative emission controls, the algorithm used in EPA's MOBILE5 model to predict the effects of ambient temperature and fuel RVP on evaporative emissions from uncontrolled highway vehicles was chosen for use in the EPA NONROAD model. This algorithm is applied as an adjustment factor to the base emission rate, expressed as grams per day per gallon of fuel tank capacity, for a given type of engine to adjust from the base RVP and temperature conditions to the RVP and ambient temperatures being modeled. The FORTRAN subroutine from MOBILE5 that performs this adjustment is attached.

The base diurnal emission rates for different equipment types come from limited testing that has been done of nonroad equipment. The documentation of these base emission rates is contained in a separate report.

References

[1] "Factors Influencing Vehicle Evaporative Emissions," D.T. Wade, Esso Research and Engineering Co., Society of Automotive Engineers paper SAE 670126, 1967.

[2] "Mathematical Models for Prediction of Fuel Tank Carburetor Evaporation," W.J. Koehl, Jr., Mobile Research and Development Corp., Society of Automotive Engineers paper SAE 690506, 1969.

[3] "MOBILE5b" Emission Factor Model, U. S. EPA, Office of Mobile Sources, Assessment and Modeling Division, 1997.

Attachment (CALUDI source code from MOBILE5b)

```
      FUNCTION CALUDI(RVPW,TMIN,TMAX,FILLED)
C
C  CALUDI uses passed in fuel RVP levels, minimum and maximum fuel tank
C  temperatures and fleet average percent of fuel tank filled to estimate
C  an Uncontrolled Diurnal emission rate.
C
C  Called by LOCAL
C
C  Calls QUITER.
C
C  Input on call:
C
C    parameter list:
C    RVPW,TMIN,TMAX,FILLED
C
C    common blocks:
C    /REGION/ IREJN
C
C  Output on return:
C
C    function: CALUDI
C
C  Local array subscripts :
C
C  AIRPRE(2)  -  AIRPRE ( IREJN )
C  FUELT(2)   -  FUELT  ( JV )
C  VAPOR(2)   -  VAPOR  ( JV )
C
C  Local variable / array dictionary:
C
C  Name   Type              Description
C  ------ ----  ----------------------------------------------------
C  A       R    coefficient used to calculate VAPOR(I)
C  AIRPRE  R    air pressure
C  A100    R    coefficient used to calculate A
C  C       R    constant, used to calculate A100
C  DENSTY  R    fuel density, a function of RVPW
C  FILLED  R    percent of fuel tank filled
C  FUELT   R    incremental fuel tank temperature in degrees Fahrenheit
C  GTP     R    grams of HC loss for temperature pair FUELT
C  PI      R    Greek pi = ratio of circumference of a circle to its diameter.
C               Used in computing X.
C  RVPW    R    fuel RVPs used to compute the components of the Wade Index
C  TMAX    R    maximum temperature
C  TMIN    R    minimum temperature
C  TP1     R    first coefficient for Wade equation
C  TP2     R    second coefficient for Wade equation
C  TP3     R    third coefficient for Wade equation
C  UDISUM  R    incremental and, eventually, total Uncontrolled Diurnal rate
C  VAPOR   R    vapor pressure at FUELT (2 temperatures, 1 degree apart)
C  VP100   R    vapor pressure at 100F, a function of RVPW
C  VSPACE  R    vapor space in cubic feet, a function of FILLED
```

```
C  WMOLEC  R    molecular weight, a function of RVPW and fuel temp
C  X       R    coefficient used to calculate A100, a function of VP100
C
C  Notes:
C
C  CALUDI is the sum of HC loss at each fuel temperature increment under the
C  input conditions.
C  CALUDI temperature range "cuts" code changed for MOBILE4.1 so as to
C  not lose the last difference pair due to round off.  Also added an
C  immediate return if TMIN=TMAX.
C
      INCLUDE 'REGION.I'
C
      DIMENSION AIRPRE(2),FUELT(2),VAPOR(2)
C
      DATA AIRPRE/14.696,12.5/,PI/3.14159/
C
      UDISUM=0.0
C
      IF(TMIN.EQ.TMAX) GOTO 99
C
C  To calculate the CALUDI value, first compute several parameters and then
C  move stepwise through the fuel tank temperature range, adding each
C  degree difference pair's contribution to the sum UDI of the grams HC
C  loss over the entire range.
C
C  Calculate fuel density for given RVPW.
C
      DENSTY=6.4-0.01977*RVPW
C
C   Calculate vapor space under given percent of fuel tank filled.
C
      VSPACE=2.4062-0.02139*FILLED
C
C  Calculate vapor pressure at 100 (VP100) for given RVPW.
C
      VP100=1.0223*RVPW
     *    +(0.0357*RVPW)/(1.0-0.0368*RVPW)
C
C  Calculate A100 according to VP100.
C
      IF(VP100.LT.14.18) GOTO 10
      C=80.861
      X=0.11*COS((4.0*VP100-9.0)*PI/14.0)
     *  +5.4*ALOG(VP100)
      GOTO 20
C
   10 C=66.561
      X=0.12*COS((VP100-6.0)*PI/4.0)
     * -0.21*SIN(2.0*PI/7.5*(VP100-4.0))
C
   20 A100=C-12.822*VP100
```

```
     *      +1.3291*VP100**2
     *      -0.07991*VP100**3
     *      +1.9017E-03*VP100**4-X
C
C  Initialize fuel tank temperature pair.
C
      FUELT(1)=TMIN
      FUELT(2)=FUELT(1)+1.0
      IF(FUELT(2).GT.TMAX) FUELT(2)=TMAX
C
C  Iteration starts here.
C
   30 CONTINUE
C
C  Calculate molecular weight.
C
      WMOLEC=69.69-1.274*RVPW
     *         +0.059*(FUELT(1)+FUELT(2))/2.0
C
C  Calculate vapor pressures.
C
      DO 40 JV=1,2
      A=A100+(100.0-FUELT(JV))
     *      *((262.0/(A100/6.0+560.0))-0.01328)
C
C  pass JV's A  < 0.0  =>  CALUDI < 0.0  =>  diurnal evap < 0.0  =>  fatal error
C  Technically, high RVPW (in A100) and high temperature (in FUELT(JV)) does not
C  make sense anyway: the gas tank would blow up.
C
      IF(A.LT.0.0) CALL QUITER(A,JV,97,INERR)
C
      VAPOR(JV)=14.696
     *        -0.53059*A
     *        +7.6961E-03*A**2
     *        -5.4907E-05*A**3
     *        +1.7044E-07*A**4
   40 CONTINUE
C
C  Apply Wade equation.
C
      TP1=VSPACE*118040.0*DENSTY/(690.0-4.0*WMOLEC)
      TP2=VAPOR(1)/(AIRPRE(IREJN)-VAPOR(1))
     *   +VAPOR(2)/(AIRPRE(IREJN)-VAPOR(2))
      TP3=(AIRPRE(IREJN)-VAPOR(1))/(FUELT(1)+460.0)
     *   -(AIRPRE(IREJN)-VAPOR(2))/(FUELT(2)+460.0)
      GTP=TP1*TP2*TP3
C
      UDISUM=UDISUM+GTP
C
      FUELT(1)=FUELT(1)+1.0
      FUELT(2)=FUELT(2)+1.0
      IF(FUELT(2).GT.TMAX) FUELT(2)=TMAX
```

```
      IF(FUELT(1).LT.TMAX) GOTO 30
C
   99 CALUDI=UDISUM
C
      RETURN
      END
```