

RVP and Temperature Corrections for Nonroad Engine Modeling

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Assessment and Standards Division
Office of Transportation and Air Quality
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technical information and to inform the public of technical developments which
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Purpose

This report documents how the draft EPA NONROAD2004 emission inventory model accounts for the effects of temperature and RVP on diurnal evaporative emissions, as well as temperature effects on four-stroke exhaust emissions. RVP and temperature also effect vapor displacement, which is covered in NR-013a, "Refueling Emissions for Nonroad Engine Modeling."

Background

The draft EPA NONROAD2004 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 MOBILE5b 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.

In addition to effects on diurnal emissions, NONROAD also includes effects of ambient temperature on exhaust emissions. This has been true in every release of the model including the 1997 beta, but it was inadvertently omitted in the previous version of this technical report. The method used in NONROAD is taken directly from the MOBILE5b highway vehicle emission factor model. Only effects on 4-stroke gasoline engine exhaust hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) are included. We are not aware of any data that could be used to estimate temperature effects on the other pollutants in NONROAD, so no such effects are currently modeled.

Approach

Temperature and RVP Effects on Diurnal Evaporative Emissions

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 MOBILE5b 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 MOBILE5b 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 MOBILE5b, 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 MOBILE5b 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 MOBILE5b 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 MOBILE5b 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 MOBILE5b model's diurnal calculations to adjust the base nonroad diurnal emissions for temperature and RVP. By applying this code from the MOBILE5b 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.

Temperature Effects on Four-Stroke Exhaust Emissions

The details of the temperature correction method from the MOBILE5b model are as follows:

$$TCF = EXP [A * (T_{ambient} - 75)]$$

where:

TCF = multiplicative Temperature Correction Factor

T_{ambient} = Ambient Temperature, in degrees Fahrenheit

"A" = The coefficient "A" is taken from MOBILE5b for "Bag 2" effects on uncontrolled light-duty gasoline vehicles (LDGV's). "Bag 2" refers to the hot stabilized portion of the test sequence, so no cold-start effects are present. The value of "A" in the above equation depends on high or low temperature (relative to 75F) and on pollutant (HC/CO/NO_x). Values for A are:

"A"	T _{ambient} <75	T _{ambient} >75
HC (4-stroke)	- 0.00240	+0.00132
CO (4-stroke)	+0.00158	+0.00375
NO _x (4-stroke)	- 0.00892	- 0.00873

For two-stroke engines, conditions differ significantly from those of on-road motor vehicles. Therefore, the 4-stroke corrections from MOBILE5b are not applied to 2-stroke or diesel engines in NONROAD. Due to lack of data for these engine types, temperature effects on

exhaust emissions from 2-stroke and diesel engines are not currently included in the draft version of NONROAD2004.

Summary and Recommendations

Due to its applicability to current nonroad engines without evaporative emission controls, the algorithm used in EPA's MOBILE5b model to predict the effects of ambient temperature and fuel RVP on evaporative emissions from uncontrolled highway vehicles was chosen for use in NONROAD. 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 MOBILE5b that performs this adjustment is attached as an appendix.

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, "Basic Evaporative Emission Rates for Nonroad Engine Modeling, NR-0012a".

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   function: CALUDI
C
C Local array subscripts :
C
C AIRPRE(2)  -  AIRPRE ( IREJN )
C FUEL(2)    -  FUEL   ( JV )
C VAPOR(2)   -  VAPOR  ( JV )
C
C Local variable / array dictionary:
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 FUEL       R        incremental fuel tank temperature in degrees Fahrenheit
C GTP        R        grams of HC loss for temperature pair FUEL
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 FUEL (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 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
C   COMMON /REGION/ FEET(2), IREJN, ALT, INITPR
C
C   DIMENSION AIRPRE(2), FUEL(2), VAPOR(2)
C
C   DATA AIRPRE/14.696,12.5/,PI/3.14159/
C
C   UDISUM=0.0
C
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
C   DENSTY=6.4-0.01977*RVPW
C
C   Calculate vapor space under given percent of fuel tank filled.
C
C   VSPACE=2.4062-0.02139*FILLED
C
C   Calculate vapor pressure at 100 (VP100) for given RVPW.
C
C   VP100=1.0223*RVPW
C   *   + (0.0357*RVPW)/(1.0-0.0368*RVPW)
C
C   Calculate A100 according to VP100.
C
C   IF(VP100.LT.14.18) GOTO 10
C   C=80.861
C   X=0.11*COS((4.0*VP100-9.0)*PI/14.0)
C   *   +5.4*ALOG(VP100)
C   GOTO 20
C
C 10 C=66.561
C   X=0.12*COS((VP100-6.0)*PI/4.0)
C   *   -0.21*SIN(2.0*PI/7.5*(VP100-4.0))
C
C 20 A100=C-12.822*VP100
C   *   +1.3291*VP100**2
C   *   -0.07991*VP100**3
C   *   +1.9017E-03*VP100**4-X
C
C   Initialize fuel tank temperature pair.
C
C   FUEL(1)=TMIN
C   FUEL(2)=FUEL(1)+1.0
C   IF(FUEL(2).GT.TMAX) FUEL(2)=TMAX
C
C   Iteration starts here.
C
C 30 CONTINUE
C
C   Calculate molecular weight.

```



```

C      WMOLEC=69.69-1.274*RVPW
C      *      +0.059*(FUELT(1)+FUELT(2))/2.0
C
C      Calculate vapor pressures.
C
C      DO 40 JV=1,2
C      A=A100+(100.0-FUELT(JV))
C      *      *((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
C
C      cgwilson -----
C
C      The following change made to write an error message ---
C
C      cgwilson      IF(A.LT.0.0) CALL QUITER(A,JV,97,INERR)
C
C      IF(A.LT.0.0) then
C          write(*,'(/,1X,2A)') 'ERROR: Calculating the temperature ',
C      &          'adjustment factors for diurnal emissions.'
C          write(*,'(9X,2A)') 'Check parameters in /OPTIONS/ packet ',
C      &          'of the options file.'
C      endif
C
C      cgwilson -----
C
C
C      VAPOR(JV)=14.696
C      *      -0.53059*A
C      *      +7.6961E-03*A**2
C      *      -5.4907E-05*A**3
C      *      +1.7044E-07*A**4
C      40 CONTINUE
C
C      Apply Wade equation.
C
C      TP1=VSPACE*118040.0*DENSTY/(690.0-4.0*WMOLEC)
C      TP2=VAPOR(1)/(AIRPRE(IREJN)-VAPOR(1))
C      *      +VAPOR(2)/(AIRPRE(IREJN)-VAPOR(2))
C      TP3=(AIRPRE(IREJN)-VAPOR(1))/(FUELT(1)+460.0)
C      *      - (AIRPRE(IREJN)-VAPOR(2))/(FUELT(2)+460.0)
C      GTP=TP1*TP2*TP3
C
C      UDISUM=UDISUM+GTP
C
C      FUELT(1)=FUELT(1)+1.0
C      FUELT(2)=FUELT(2)+1.0
C      IF(FUELT(2).GT.TMAX) FUELT(2)=TMAX
C      IF(FUELT(1).LT.TMAX) GOTO 30
C
C      99 CALUDI=UDISUM
C
C      RETURN
C      END

```