Development of Evaporative Emissions Calculations for the Motor Vehicle Emissions Simulator (Draft MOVES2009)

Draft Report

United States
Environmental Protection
Agency

Development of Evaporative Emissions Calculations for the Motor Vehicle Emissions Simulator (Draft MOVES2009)

Draft Report

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

United States
Environmental Protection
Agency

EPA-420-P-09-006
August 2009

Table of Contents

1 Background

Evaporative emissions account for a significant portion of the total gaseous hydrocarbon inventory. Its processes are unique and require a unique modeling approach. For a long time, evaporative emissions were thought of being quantifiable in three distinct modes and subsequent test procedures: running loss (during vehicle operation), diurnal/resting loss (stabilized parked emissions), and hot soak (parked emissions immediately after vehicle operation). However, it has become evident that different factors, such as ambient temperature and fuel type for example, affect evaporative emissions more noticeably in the emissions processes, rather than the aforementioned three modes. Evaporative emissions can be broken up into three main processes:

- Permeation – the migration of hydrocarbons through elastomers in a vehicle's fuel system
- Tank Vapor Venting – expulsion into the atmosphere of fuel vapor generated from evaporation of fuel in the fuel system
- Liquid Leaks – fuel, in liquid form, leaking from the fuel tank or fuel system, which then evaporates into the atmosphere

These three processes occur and can be addressed in each mode. Therefore, we can measure and/or calculate permeation, tank vapor venting, and liquid leaks in each of the three testing regimes prevalent in major evaporative emissions test programs. Then, we can relate the emissions from each of the processes to different factors that occur independently of modes. This makes for easier, more accurate modeling of scenarios that do not perfectly replicate the test procedures.

The factors that affect permeation, vapor venting, and leaks that we considered were:

- Ambient temperature
- Fuel tank temperature
- Model year
- Age
- Vehicle class
- Fuel (ethanol %, RVP)
- Failure modes
- Presence of I/M

The model year groups used for evaporative emissions are shown in Table 1. They depend on evaporative emission standards and related technological improvement designed to control evaporative emissions.

Table 1 describes the model year group stratifications used for MOVES analysis.

Model year group	Emissions standard or technology level
1971-1977	Pre-control
1978-1995	Early control
1996	80% early control, 20% enhanced evap.
1997	60% early control, 40% enhanced evap.
1998	10% early control, 90% enhanced evap.
1999-2003	100% Enhanced evap.
2004 and later	Tier 2, LEV II

2 Data Sources

- CRC E-9 – Measurement of Diurnal Emissions from In-Use Vehicles[1]

- CRC E-35 – Measurement of Running Loss Emissions in In-Use Vehicles[2 3]
- CRC E-41 – Evaporative Emissions from Late-Model In-Use Vehicles[4 5]
- CRC E-65 – Fuel Permeation from Automotive Systems[6]
- CRC E-65-3 – Fuel Permeation from Automotive Systems: E0, E6, E10, and E85[7]
- BAR Gas Cap Study
- API Gas Cap Study
- EPA Compliance Testing

Appendix A has a summary of most of the test programs mentioned above.

3 Design and Analysis

We found fuel tank temperature to be the driver of the two transient emissions processes, permeation and vapor venting. Determining fuel tank temperature was critical in predicting emissions in each of these Operating Modes. Fuel tank temperature is dependent on the daily ambient temperature profile, times that the vehicle is operating, and the model year of the vehicle. Then, we can use the calculated fuel tank temperature profile to calculate permeation and vapor venting. Other factors were included as needed. Liquid leaks were not dependent on temperature. This section will first describe the Fuel Tank Temperature Generator, and then explain how we used the fuel tank temperature to determine emission rates for each of the emissions processes.

3.1 Fuel Tank Temperature Generator

This section explains how to generate fuel tank temperature through time for a given day's ambient temperature profile and a vehicle's trip times. Generating fuel tank temperature allows for the calculation of permeation and vapor venting, two major fuel-related evaporative emissions processes. As a result, this algorithm is instrumental in modeling evaporative emissions in MOVES.

3.1.1 Input parameters

- Hourly ambient temperature profile
- Key on and key off times
- HourDayID (day and hour) of first KeyON
- Vehicle Type (LDT/LDV)
- Pre-enhanced or enhanced evaporative emissions control system

MOVES defines these input parameters via the sampleVehicleTrip and zoneMonthHour tables and the sourceBinID variable.

3.1.2 General steps

1) Input parameters must be defined.
2) Fuel tank temperature is computed up to the start of the first trip, assuming that the vehicle has been parked for a long time (overnight). This is done through the block diagram in
3) Figure 1 below, which represents the differential equation in equation 1. All soaks (hot and cold) are calculated using this portion of the algorithm.
4) Next, for each trip, the fuel tank temperature is computed for the operation period and the corresponding soak period after the key off for that trip. It computes fuel tank temperature until the start of the next trip (next key on), at which point this step is repeated, or until the end of the day. The fuel tank temperature during operation is calculated using equations (3) and (4). The fuel tank temperature during hot soak is

calculated as for cold soak (equation 2b), but with the initial temperature (T_i) changed to the temperature at the end of each trip, and the time interval modified to accommodate the key on/off times.

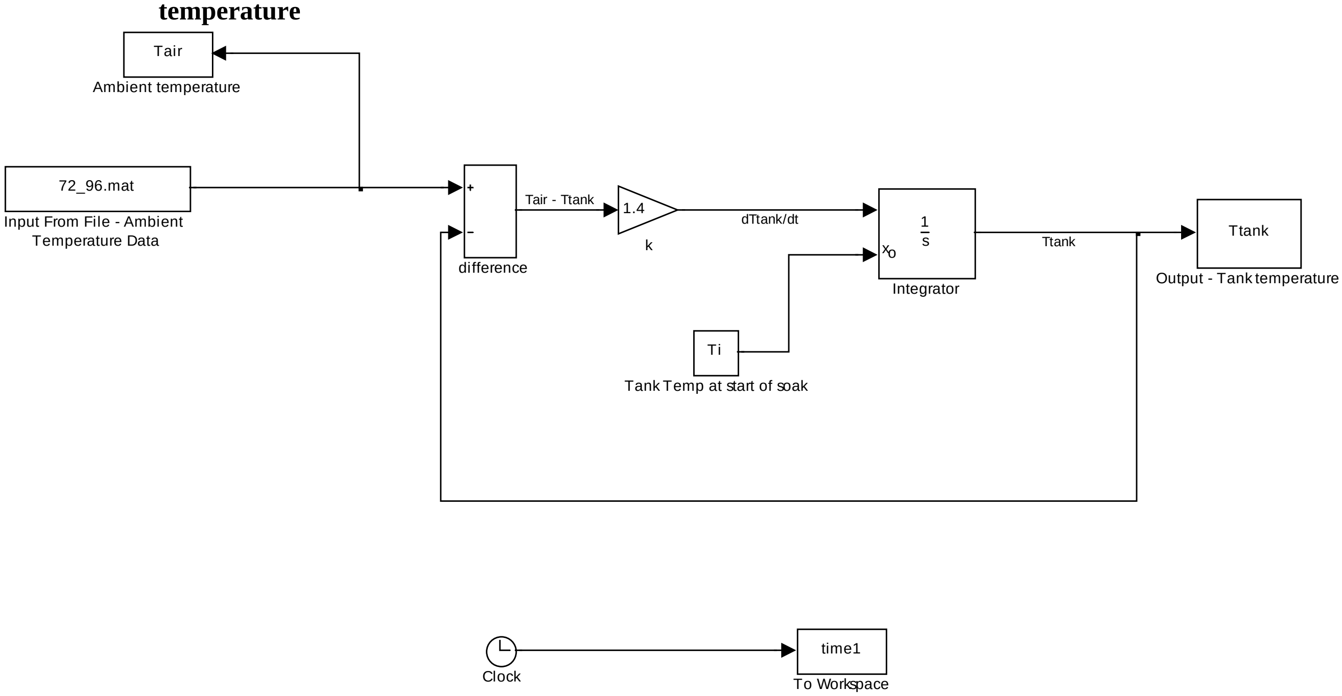
3.1.2.1 Calculating soak temperatures (as a function of ambient temperature)

The following equation was used to model tank temperature as a function of ambient temperature. This was used for hot and cold soaks.

$$\frac{dT_{Tank}}{dt} = k(T_{air} - T_{Tank}), \qquad (1)$$

where T_{tank} is the fuel tank temperature, T_{air} is the ambient temperature, and k is a constant proportionality factor (k = 1.4). The value of k was verified by trial and error against EPA compliance data. There was no distinction made between hot soak and cold soak calculations. We assumed that during either soak, the only factor affecting fuel tank temperature was the ambient temperature profile and the fuel tank temperature at the start of the soak. The block diagram below simplifies the equation into several mathematical steps, which are explained below.

Figure 1 – Simulink® block diagram of the relation between ambient temperature and fuel tank temperature



The time periods for which this part of the algorithm is used depends on the key on and key off times. Since this equation can be used only for cold soaks and hot soaks (all parked conditions), it applies for the following time intervals only:

- from the start of the day to the first trip,
- from all key off to key on times, and
- from the last key off to the end of the day.

Mathematical steps

1) At time $t_0 = 0$ or KeyOFF (start of soak), $T_{tank} = T_i$. This value will either be the ambient temperature (at the very start of the model) or the fuel tank temperature at the end of a trip.

2) Then, for all $t > 0$ or KeyOFF, the next tank temperature is calculated in this manner:

$$(T_{Tank})_{n+1} = \left[\sum_{j=0}^{n} k(T_{air} - T_{Tank})_j \, \Delta t \right] + T_i \qquad \text{(2a)} \quad \text{or}$$

$$(T_{Tank})_{n+1} = T_{Tank\,n} + k(T_{air} - T_{Tank})_n \, \Delta t \qquad \text{(2b)}$$

$(T_{air} - T_{tank})$ is a function of time. Since analytical integration is too complicated (the input ambient temperature data is in a table), numerical integration should be used to perform this step. The method of numerical integration varies based on the accuracy desired. The above method represents the Euler method, one of the simplest methods of integration. The less accurate the method, the smaller the time step Δt should be, to improve the solution. MOVES uses a Δt of 15 minutes, which is accurate enough for our modeling purposes.

3.1.2.2 Calculating fuel tank temperatures during operation

Operation periods (trips) are relatively short compared to the length of the day or modeling period. Therefore, even though the fuel tank temperature profile during operation is not exactly linear, assuming a linear increase in temperature makes calculations easier without compromising accuracy. However, the increase in temperature ΔT_{tank} depends on the temperature at the start of operation. It also depends on vehicle type. The convention used in this algorithm is that ΔT_{tank} applies over a 4300 second period, which is the length of the running loss test performed by manufacturers for certification. To find ΔT_{tank}, we must first find ΔT_{tank95}, the average increase in tank temperature at a standard 4300 second @ 95F running loss test.

- If the vehicle is evap-enhanced, then ΔT_{tank95} = 24F [8]
- If the vehicle is pre-enhanced, the vehicle type affects ΔT_{tank95}.
  - If LDV, then ΔT_{tank95} = 35F.
  - If LDT, then ΔT_{tank95} = 29F.

We can use these values for ΔT_{tank95} for 95F to calculate the ΔT_{tank} for other starting fuel tank temperatures (other trips) using the following equation:

$$\Delta T_{Tank} = 0.352\,(95 - T_{Tank,KeyON}) + \Delta T_{Tank\,95} \qquad \text{(3)}$$ [9]

Since this gives us the increase in tank temperature, we can create a simple linear function that models fuel tank temperature for each trip.

$$T_{Tank} = \frac{\Delta T_{Tank}}{4300/3600}(t - t_{keyON}) + T_{Tank,KeyON} \qquad \text{(4)}$$

The 4300/3600 appears, as the running loss test done by manufacturers is 4300 seconds long, and we convert that to hours maintain consistency in the algorithm.

Assumptions:

- The first trip is assumed to start halfway into the hour stated in the first trip's HourDayID.
- We assumed the effect of the ambient temperature or change in ambient temperature during a trip was negligible compared to the effect of operation.
- The KeyON tank temperatures will be known by way of the calculations of the tank temperatures from the previous soak.

3.2 Permeation

3.2.1 Base Rates

We first determined base rates for permeation. We define these rates as the non-leak hydrocarbon gram-per-hour emission rate during the last six hours of a 72-96-72°F diurnal test (also known as resting loss). In these six hours, the emissions rate and the ambient and fuel tank temperatures are relatively stable or constant, leading us to believe that the constant permeation process is the only emissions process occurring. We stratified these rates by model year group and age group. The base permeation rates are in Table 2. Separate inputs were created from model years 1996-1998 to account for the 20/40/90% phase-in of enhanced evaporative emissions standards.

Table 2 – Base permeation rates at 72 F

Model year group	Age group	Base permeation rate [g/hr]
1971-1977	10-14	0.192
	15-19	0.229
	20+	0.311
1978-1995	0-3	0.0554
	4-5	0.0554
	6-7	0.0913
	8-9	0.0913
	10-14	0.124
	15-19	0.148
	20+	0.201
1996	0-3	0.046
	4-5	0.046
	6-7	0.075
	8-9	0.075
	10-14	0.101
	15-19	0.120
	20+	0.163
1997	0-3	0.037
	4-5	0.037
	6-7	0.059
	8-9	0.059
	10-14	0.079
	15-19	0.093
	20+	0.125
1998	0-3	0.015
	4-5	0.015
	6-7	0.018
	8-9	0.018
	10-14	0.022
	15-19	0.024
	20+	0.029
1999-2003	0-3	0.0102
	4-5	0.0102
	6-7	0.0102
	8-9	0.0102
	10-14	0.0102
	15-19	0.0102
	20+	0.0102

3.2.2 Temperature adjustment

Use following equation for temperature-adjusted permeation rate for each hour not in the last six hours of a diurnal:

$$P_{adj} = P_{base}\, e^{0.0385\,(T_{Tank} - T_{base})} \qquad (5)$$

where P_{base} is the base permeation rate calculated by averaging the last six hours of emissions, T_{tank} is the tank temperature, and T_{base} is the base temperature for a given temperature cycle (e.g. 72 for a 72-86-72 diurnal test). This is derived from the E-65 permeation study which found that permeation rate doubles for every 18 degrees F. In MOVES the base permeation rates are calculated at 72 F.

3.2.3 Fuel Adjustment

E10 affects evaporative emissions from gasoline vehicles due to the increased volatility of E10 blends, the increased permeation of fuel vapors through tanks and hoses, and the increased vapor emissions due to the lower molecular weight of E10. Each of these effects were modeled using the draft MOVES model, which separates permeation emissions from vapor venting emissions to allow better accounting for these different processes.

Fuel effects on permeation were developed from CRC's E-65 and E-65-3 programs, which measured evaporative emissions from ten fuel systems that were removed from the vehicles on E0, E5.7, and E10 fuels; fuel systems were removed to ensure that all evaporative emissions measured were from permeation of the fuel through the different components of the fuel system. For this analysis, we separated the evaporative enhanced vehicles from the pre-enhanced vehicles. Enhanced evaporative vehicles began being phased in from 1996 through 1999 and needed to meet a 2.0 g standard over a 24-hour diurnal test. Pre-enhanced vehicles needed to meet 2.0 g over a 1-hour simulated diurnal. We estimated the ethanol effect by calculating the percent increase in average emissions over the 65-105-65 deg F diurnal cycle from each of the two groups of vehicles. To determine the effect of ethanol blend, we first averaged the E5.7 and E10 results (where both fuels were tested) for each vehicle to obtain its mean ethanol permeation rate. We then averaged each vehicle's mean permeation rate on E0. The percent difference between the ethanol rate and the E0 rate was input into MOVES as the fuel adjustment. Due to the phase in from 1996 to 1999 (20/40/90/100 %), the two fuel adjustments must be properly weighted for those model years. The fuel adjustment in MOVES is based on a variable called fuelModelYearID. Table 3 shows the fuel adjustments used for E5 through E10 for the fuelModelYearID's used in MOVES.

Table 3 – Increase in emissions due to ethanol levels of 5 to 10% compared to E0 (gasoline)

Model years (via fuelModelYearID in MOVES)	Percent increase due to ethanol (E5 through E10)
1995 and earlier	37.3
1996	69.4
1997-2000	175
2001 and later	198

We plan to revisit our permeation emissions estimates with the release CRC E-77 and E-77-2b studies.

3.3 Tank Vapor Venting

The following explains how vapor venting rates were calculated for each of the operating modes. For cold soak, MOVES first finds the amount of vapor generated in the tank as a function of fuel tank temperature and RVP. Then, it determines how much of this vapor is released into the atmosphere based on several criteria, such as model year and fill pipe pressure test result. The temperatures will have been generated by the fuel tank temperature generator, and the RVP will have been generated by the MOVES tank fuel generator. This cannot apply for when vapor is not generated (when fuel tank temperature is not increasing), such as during a hot soak, but is released. For these situations, we have aggregated TVV rates after subtracting out permeation and leaks from the test results. Also, due to the availability of test data for running loss and the short length of trips, we determined TVV rates during operation the same way we did for hot soak.

3.3.1 Cold Soak

1) For each diurnal test, we calculated fuel tank temperature at each hour using the fuel tank temperature algorithm.
2) After calculating base permeation rate for each vehicle (average of last six hours of HC evaporative emissions), we used the fuel tank temperature adjustment with the temperatures calculated in step 1 to calculate the permeation for each hour. The fuel tank temperature is determined through the fuel tank temperature algorithm for MOVES diurnals.
3) We filtered/reduced data set such that each test met the following requirements:
    a. Non-leakers
    b. “As received” vehicles (no retests)
    c. Hours where tank temperature increased from previous hour
    d. Pressure test result must be pass, fail, or blank only (no dashes, slashes, “I”, etc.)
4) We subtracted permeation from HC for each hour to get tank vapor venting (*TVV*) rate
5) We summed TVV from beginning of diurnal to each hour to get Cumulative TVV.
6) We then determined Tank Vapor Generated (TVG) from hour 1 to hour *x* for each hour that the fuel tank temperature is rising.

$$TVG = Ae^{B*RVP}(e^{CT_x} - e^{CT_2}) \text{ [grams/gal] } (6)$$ [10]

where A, B, and C are constants listed below in Table 4, and T_x is the temperature at hour *x*.

Table 4 – TVG constants for equation 7.

	Gasoline		E10	
Constant	**Sea Level**	**Denver alt.**	**Sea Level**	**Denver alt.**
A	0.00817	0.00518	0.00875	0.00665
B	0.2357	0.2649	0.2056	0.2228
C	0.0409	0.0461	0.0430	0.0474

TVG is the amount of vapor generated in the tank. We will establish a relationship between Cumulative *TVV* and *TVG* for inputs into MOVES.

7) We constructed quadratic curves (zero intercept) of *CumTVV* vs. *TVG*, stratifying by model year group, age group, and pressure test result.

$$CumTVV = a_1 TVG + a_2 TVG^2 \qquad (7)$$

Having the zero-intercept ensures that the (0, 0) is a point on the quadratic curve. In other words, it implies that at 0 *TVG*, there is no tank vapor venting, which is an accurate physical assumption.

Curves were generated for model year groups 1971-1977 (ages 15+), 1978-1995 (ages 0-19), and 1996-2003 (ages 0-9). We also stratified by pressure test result. In failing vehicles, more of the vapor that is generated in the fuel system will be vented than in passing vehicles, where the evaporative emission controls should be functioning properly. The remainder of the coefficients was found by extrapolation or previously determined relationships. The coefficients of variation (CVs) were calculated by dividing the standard error of the sample (calculated by SPSS) by the mean for each coefficient in the quadratic equation.

8) After failure frequencies (*F*) were generated from pressure, gas cap, and OBD test results from the Phoenix I/M program (see section *3.3.3 Inspection/Maintenance (I/M) Program effects*), aggregate coefficients were calculated:

$$a_{x,agg} = a_{x,fail} F + a_{x,pass} (1-F) , \qquad (8)$$

where x = 1 or 2, corresponding to quadratic equation 8.

9) Since the aggregate coefficients were determined using the failure rates, which are essentially weighting factors, the standard errors of the aggregate coefficients are calculated:

$$s_{\bar{y},a_{x,agg}} = \sqrt{F^2 s^2_{\bar{y},a_{x,fail}} + (1-F)^2 s^2_{\bar{y},a_{x,pass}}} \qquad (9)$$

As a result, the CV's for the aggregate coefficients are calculated:

$$CV_{a_{x,agg}} = \frac{1}{a_{x,agg}} \sqrt{F^2 a^2_{x,fail} CV^2_{a_{x,fail}} + (1-F)^2 a^2_{x,pass} CV^2_{a_{x,pass}}} \qquad (10)$$

Table 5 shows the I/M coefficients resulting from the analysis. Ratios between age groups were used to extrapolate for the 10-14 age group in the 1971-1977 model year groups, and older age groups where data did not exist were forced to have the same coefficients as their preceding age groups. The passing coefficients for the 2004 and later model year group were reduced by 32% from the 1999-2003 model year group, which reflects a reduction in the evaporative emissions standard from enhanced-evap to Tier 2/LEV II. Separate model year groups are created for 1996 through 1998 due to the phasing of enhanced evaporative standards. These three groups are only different weightings of the 1978-1995 and 1999-2003 model year groups based on the 20/40/90% phase-in for 1996/1997/1998. Similarly, though not shown, is a table that was developed for non-I/M vehicles using non-I/M failure frequencies calculated from the Phoenix I/M data set.

Table 5 – I/M coefficients for equation 7. The aggregate columns are the inputs in the MOVES model for I/M coefficients in the cumTVVCoeffs table.

model year group	age group	a_1			a_2		
		pass	fail	aggregate	pass	fail	aggregate
1971-1977	10-14	1.227	11.314	1.941	2.175	0.402	2.049
	15-19	5.406	9.254	5.835	2.331	3.117	2.419
	20+	5.406	9.254	6.127	2.331	3.117	2.479
1978-1995	0-3	1.578	3.073	1.589	0.440	1.338	0.446
	4-5	1.578	3.073	1.604	0.440	1.338	0.455
	6-7	1.578	3.073	1.610	0.440	1.338	0.459
	8-9	1.578	3.073	1.623	0.440	1.338	0.466
	10-14	0.849	11.314	1.283	2.095	0.402	2.025
	15-19	3.743	9.254	4.120	2.246	3.117	2.305
	20+	3.743	9.254	4.376	2.246	3.117	2.346
1996	0-3	1.339	3.073	1.354	0.344	1.338	0.352
	4-5	1.339	3.073	1.362	0.344	1.338	0.357
	6-7	1.339	3.073	1.376	0.344	1.338	0.365
	8-9	1.339	3.073	1.392	0.344	1.338	0.374
	10-14	0.756	9.666	1.124	1.668	0.589	1.624
	15-19	3.071	8.017	3.399	1.789	2.762	1.853
	20+	3.071	8.017	3.530	1.789	2.762	1.879
1997	0-3	1.100	3.073	1.120	0.248	1.338	0.259
	4-5	1.100	3.073	1.129	0.248	1.338	0.264
	6-7	1.100	3.073	1.146	0.248	1.338	0.273
	8-9	1.100	3.073	1.163	0.248	1.338	0.283
	10-14	0.663	8.018	0.976	1.241	0.776	1.222
	15-19	2.399	6.781	2.686	1.332	2.406	1.402

	20+	2.399	6.781	2.791	1.332	2.406	1.428
1998	0-3	0.502	3.073	0.538	0.009	1.338	0.027
	4-5	0.502	3.073	0.553	0.009	1.338	0.035
	6-7	0.502	3.073	0.575	0.009	1.338	0.046
	8-9	0.502	3.073	0.596	0.009	1.338	0.057
	10-14	0.429	3.897	0.589	0.174	1.244	0.223
	15-19	0.719	3.691	0.907	0.189	1.516	0.273
	20+	0.719	3.691	0.959	0.189	1.516	0.296
1999-2003	0-3	0.383	3.073	0.422	-0.039	1.338	-0.019
	4-5	0.383	3.073	0.438	-0.039	1.338	-0.011
	6-7	0.383	3.073	0.461	-0.039	1.338	0.001
	8-9	0.383	3.073	0.483	-0.039	1.338	0.012
	10-14	0.383	3.073	0.508	-0.039	1.338	0.025
	15-19	0.383	3.073	0.552	-0.039	1.338	0.048
	20+	0.383	3.073	0.595	-0.039	1.338	0.070
2004 and later	0-3	0.124	3.073	0.151	-0.013	1.338	-0.001
	4-5	0.124	3.073	0.161	-0.013	1.338	0.004
	6-7	0.124	3.073	0.175	-0.013	1.338	0.010
	8-9	0.124	3.073	0.187	-0.013	1.338	0.016
	10-14	0.124	3.073	0.203	-0.013	1.338	0.023
	15-19	0.124	3.073	0.229	-0.013	1.338	0.035
	20+	0.124	3.073	0.255	-0.013	1.338	0.047

3.3.2 Hot Soak

1) First we found the temperature at the start of the soak for each hot soak test. This is done by adding on the temperature increase experienced during an LA-4 running loss test cycle (1372 seconds), since the vehicle is put through this test before entering the soak chamber. These temperature rises depend on the fuel tank temperature at the start of the LA-4 test (ambient). To calculate hot soak start temperature T_{start}, see section *3.1.2.2 Calculating fuel tank temperatures during operation*.

2) We then found the average temperature in that hour:

$$T_{avg} = \frac{1}{k}(T_{start} - T_{air})(1 - e^{-k}) + T_{air} \qquad (11)$$

This is derived from the average value of a function over an interval (in this case, between 0 and 1 hour after the start of the hot soak). As stated in the Fuel Temperature algorithm, k = 1.4.

3) We used this average temperature to determine the average permeation rate during the hot soak via the permeation temperature adjustment using the 72F base permeation rates determine by model year group and age group.

4) We filtered/reduced the data set such that each test met the following requirements:
   a. Non-leakers (emissions less than 10.0 grams[11]; taken from M6.EVP.009_2.4; Since hot soak emissions are measured after one hour, the total emissions is "equal" to its g/hr rate)
   b. "As received" vehicles (no retests)
   c. Pressure test result must be pass, fail, or blank only (no dashes, slashes, "I", etc.)

5) We subtracted permeation from HC for each hour to get tank vapor venting (*TVV*) rate

6) We averaged TVV rates by model year group, age group, and pressure test result, shown in

Table 6 – Average hot soak tank vapor venting rates in g/hr by model year group, age group, and pressure test result.

Model year group	Age group	Pressure test result	TVV rate
1971-1977	20+	F	6.17
	20+	P	2
1978-1995	0-5	Both	1.25
	0-5	P	0.56
	0-9	F	2.37
	6-9	Both	1.75
	6-9	P	1.38
	10-14	Both	5.13
	10-14	F	3.41
	10-14	P	1.76
	15-19	F	4.51
	15-19	P	2.99
1996-2003	all	Both	0.1073

7) Like with cold soak, aggregate rates were found using failure rates involving pressure, gas cap, and OBD tests for non-I/M and I/M. Table 7 below does not reflect the most updated I/M analysis explained in section *3.3.3 Inspection/Maintenance (I/M) Program effects* (unlike the cold soak coefficients in Table 5) or the enhanced evaporative phase-in, so these numbers will be updated for the final version of MOVES.

Table 7 – Example of non-I/M hot soak tank vapor venting rates

Model year group	Age group	TVV rate [g/hr]
1971-1977	10-14	3.099
	15-19	5.149
	20+	5.455
1978-1995	0-3	0.627
	4-5	0.627
	6-7	1.451
	8-9	1.471
	10-14	2.082
	15-19	3.492
	20+	3.817
1996-2003	0-3	0.124
	4-5	0.124
	6-7	0.150
	8-9	0.168
	10-14	0.250
	15-19	0.383
	20+	0.611
2004 and later	0-3	0.060
	4-5	0.060
	6-7	0.086
	8-9	0.105
	10-14	0.187
	15-19	0.323
	20+	0.553

3.3.3 Inspection/Maintenance (I/M) Program effects

Our assumption in MOVES is that tank vapor venting is the only evaporative process where the effects of I/M are realized. The types of evaporative tests performed in I/M programs (gas cap test, fill pipe pressure test, OBD scans) do not affect permeation or liquid leaks.

In order to develop I/M and non-I/M tank vapor venting rates, we used available data from I/M programs to determine the failure frequencies of evaporative control systems. These frequencies were then used to combine the cumulative tank vapor venting coefficients for failing vehicles and those for passing vehicles (determined from the TVV analysis). Details of each of the four programs are in Table 8 below.

Table 8- Description of evaporative characteristics of I/M programs available for analysis [12]

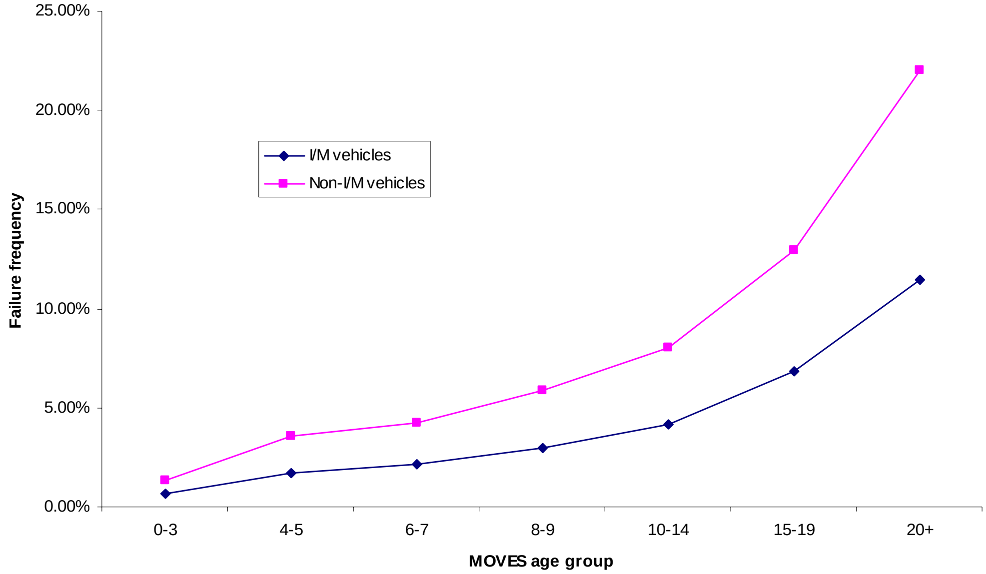
	Gas cap test	OBD	Pressure test	Frequency	Network	Calendar years
Colorado	*Y*	*Advisory only*	*N*	*Biennial*	*Hybrid*	*2003-2006*
N. Carolina	*N*	*Y*	*N*	*Annual*	*Decentralized*	*2002-2006*
Phoenix	*Y*	*Y*	*Y*	*Biennial*	*Centralized*	*2002-2006*
Tucson	*Y*	*Y*	*N*	*Annual*	*Centralized*	*2002-2006*

Since the Phoenix program contained the most extensive amount of data, we used it to develop reference I/M evaporative failure frequency. The Tucson, Colorado, and North Carolina data were used to adjust the Phoenix numbers for differences in I/M programs.

The Phoenix evaporative I/M program used gas cap tests on all vehicles, OBD scans on OBD-equipped vehicles, and fill pipe pressure tests on pre-OBD vehicles. The OBD codes used to determine evaporative failures were P0440, P0442, P0445, P0446, and P0447 for all vehicle makes and additionally P1456 and P1457 for Honda and Acura vehicles. Vehicles that had one or more of these faults were flagged as failing vehicles, analogous to pre-OBD vehicles that failed the pressure test. Very few vehicles failed both the gas cap test and the pressure/OBD test. Therefore, our total number of failures was the sum of gas cap and pressure/OBD failures.

To determine failure frequencies for I/M areas, from the Phoenix data, we looked at the initial and final results for each vehicle in a given I/M cycle. For passing vehicles, the initial test and the final tests were one and the same. We averaged the initial and final failure frequencies (weighted equally) to calculate an overall I/M failure frequency by model year group and age group. Using the initial failure frequencies alone would neglect the effect of repair that most failing vehicles would be required to undergo, and using the final failure frequencies alone would neglect the existence of the failing vehicles driving around in the fleet in the first place. To determine non-I/M failure frequencies, we restricted our sample in the Phoenix data to those vehicles with license plates from states that do not have an I/M program anywhere. Figure 2 gives an example of how failure frequencies increase with age. Shown are frequencies for model years 1978-1995, where data was extrapolated for the youngest age groups.

Figure 2 – Evaporative failure frequencies for I/M and non-I/M vehicles in the Phoenix area. This figure shows model years 1978 to 1995.



The Tucson data was used to determine the effect of program frequency (annual vs. biennial). For OBD vehicles, Tucson performs gas cap and OBD tests annually, while Phoenix performs them biennially. Therefore, we were able to develop failure frequencies for annual programs by analyzing the Tucson data. We applied the ratio between Tucson and Phoenix to determine the failure frequencies for where we did not have data (e.g. pre-OBD vehicles).

The North Carolina data was used to determine non-I/M failure frequencies for OBD tests. In North Carolina, expansion of I/M program has led to counties where many vehicles were tested under the I/M program for the first time. Vehicles were flagged as non-I/M tests if they were tested:

- before the official start of the I/M program,
- in a new I/M county and were registered in that same county, or
- in a new I/M county and were registered in a non-I/M county or a county that did not start I/M within the last year.

We compared those failure frequencies to those for vehicles tested in older I/M areas, where vehicles were previously tested. From the North Carolina data, the average ratio of non-I/M to I/M OBD failure frequencies is 1.6. This ratio was then applied to the Phoenix OBD and pressure test failure frequencies to determine non-I/M failure frequencies.

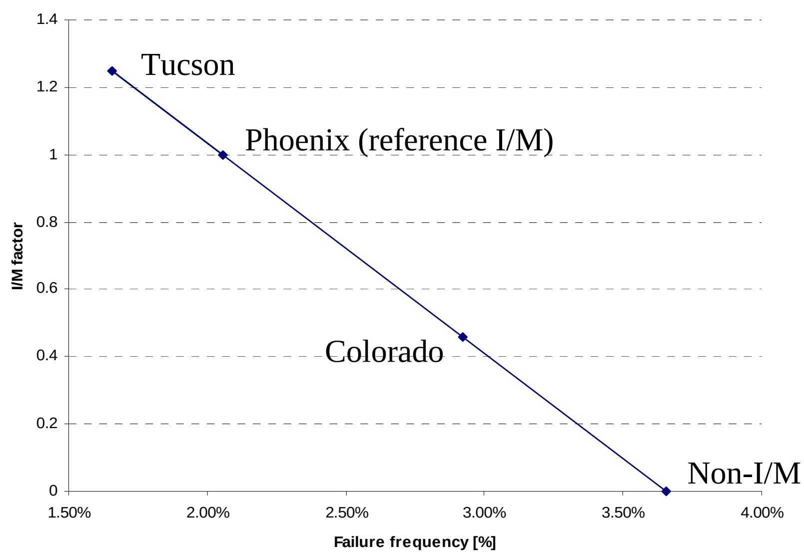
The Colorado data was used to determine non-I/M failure frequencies for gas cap tests. In Colorado, the I/M data comes mostly from the Denver and Boulder metropolitan areas. Many residents are new to this area, with many having moved in from non-I/M areas in Colorado or non-I/M states. Vehicles were flagged as non-I/M tests if their registration state was a 100% non-I/M state, or if the registration county was a non-I/M county in Colorado. We compared the failure rates of the flagged vehicles to those of the full tested fleet. The ratio of these two frequencies was then applied to the Phoenix gas cap failure frequencies to determine non-I/M failure frequencies. Colorado OBD data was not used, since OBD in Colorado is only advisory, and does not pass or fail a vehicle.

From the Colorado data, the average ratio of non-I/M to I/M gas cap failure frequencies is 2.2. This ratio was then applied to the gas cap failure frequencies to determine non-I/M failure frequencies.

IM factor

The IM factor lets MOVES interpolate and extrapolate the non-I/M emission rates and the I/M emission rates depending on the characteristics of the I/M program in each county. Our reference program, Phoenix, was given an IM factor of 1. The non-I/M rates were given an IM factor of 0. For each model year group and age group stratification, we used the failure frequencies determined from the analysis described above to calculate IM factors for the diverse types of evaporative I/M programs. Figure 3 illustrates how the I/M factor is influenced by the types of evaporative tests conducted in I/M programs. We modeled the estimated failure frequency linearly with the I/M factor, with Phoenix, our reference program, always receiving a value of 1, and our non-I/M failure frequency always receiving a value of 0. Different programs move along the line, as determined by the analysis from above, based on which evaporative tests they choose to use. The figure is an example using model year group 1999-2003 and age group 4-5. For these vehicles, Tucson's OBD and gas cap tests are annual, compared to Phoenix's biennial requirement, which gives Tucson a lower failure frequency and a higher I/M factor. Colorado's frequency is biennial, like Pheonix's, but its OBD test is non-enforcing. As a result, their data shows a higher failure frequency, which results in a lower I/M factor.

Figure 3 – Example of how we calculated the I/M adjustment factor. This figure applies for model years 1999-2003 ages 4-5.



3.3.4 Running Loss

1) For each vehicle, we calculated fuel tank temperature at the end of the running loss test using the fuel tank temperature algorithm (see section *3.1.2.2 Calculating fuel tank temperatures during operation*). The running loss test performed was the typical 4375-second LA-4 – NYCC – NYCC – LA-4 sequence, with two minute idle periods following the first LA-4, the second NYCC, and the final LA-4 (CRC E-41).
2) We found the average temperature during the test by assuming a linear increase in temperature during the test. Thus, the average was calculated by averaging the start temperature of the test and the final temperature of the test found in step 1.

3) We used this average temperature to determine the average permeation rate during the hot soak via the permeation temperature adjustment using the 72F base permeation rates determine by model year, age.
4) We calculated gram/hour rates by dividing total emissions by the duration of the running loss test (4300 seconds)
5) We filtered/reduced the data set such that each test met the following requirements:
    a. Non-leakers (emissions less than 137.2 g/hour; taken from M6.EVP.009_2.4)
    b. "As received" vehicles (no retests)
    c. Pressure test result must be pass, fail, or blank only (no dashes, slashes, "I", etc.)
6) Subtract permeation from HC for each hour to get tank vapor venting (*TVV*) rate
7) After analysis of TVV data, we found that the best way to stratify running loss TVV was by model year only. Table 9 shows the results of the analysis.

Table 9 – Final running loss tank vapor venting emission rates.

Model year group	TVV mean [g/hr]
1971-1977	12.59
1978-1995	11.6
1996-2003	0.72
2004 and later	0.23

8) Since model year group is the only stratification, the running loss TVV rates are not affected by the failure rates. Therefore, the I/M and non-I/M rates are the same and equal to the table above.

3.4 Liquid Leaks

Liquid leaks are the final evaporative emissions process discussed in this document. To calculate the average leaking rate, we used the leaking vehicles excluded from the previous analysis for tank vapor venting. We estimated permeation and tank vapor venting on these vehicles using the methods described above. We assumed the remainder of emissions to be caused by liquid leaks. We averaged these emissions by the three different modes, shown in Table 10.

Table 10 – Emission rates for liquid leakers by mode.

Mode	Liquid leak rate
Cold Soak	9.85 g/hr
Hot Soak	19.0 g/hr
Operating	178 g/hr

The rates in Table 10 must be multiplied by the percentage of leakers in the fleet to get an average liquid leaking emission rate. For this we relied on the studies by BAR and API. Our estimates of the percentage of liquid leakers are shown in
Table **11**. On average, we assume that most leaks do not occur until vehicles are 15 years or older.

Table 11 – Percentage of liquid leakers by age.

Age group	Percentage of leakers in fleet
0-9	0.09 %
10-14	0.25 %
15-19	0.77 %
20+	2.38 %

Combining Table 10 and Table 11, we get Table 12, which shows the liquid leaking rate of the entire fleet. We assume that this rate does not change with model year nor is it affected by I/M.

Table 12 – Final liquid leak rates in g/hr by age group and mode.

Age group	Cold soak	Hot soak	Operating
0-9	0.009	0.017	0.158
10-14	0.025	0.048	0.450
15-19	0.075	0.145	1.36
20+	0.235	0.452	4.23

Appendix A - Notes on Evaporative Emission Data

Parameters: Vehicle Numbers, Test #, Ambient Temperature, RVP, Model Year, Fuel System, Purge, Pressure, Canister, Gram HC, Retest

E-41 CRC Late Model In-Use Evap. Emission Hot Soak Study (1998):

- 50 vehicles (30 passenger cars and 20 light duty trucks)
- Age: 1992 to 1997 model year
- Average RVP: 6.5 psi
- Diurnal Temperature: 72 to 96F
- Fuel System: Port Fuel Injection, Throttle Body Injection
- Vehicle fuel tank drained and refilled to 40% of capacity with Federal Evaporative Emission Test Fuel
- Driving schedule will be a full LA-4-NYCC-NYCC-LA4 sequence, with two minute idle periods following the first LA-4, the second NYCC, and the final LA-4.
- Hydrocarbon readings will be taken continuously throughout the running loss test.
- Cumulative mass emissions will be reported at one minute intervals.
- Ambient Temperature in running loss enclosure: 95F

E-9 CRC Real Time Diurnal Study (1996):

- 151 vehicles (51 vehicles from MY 1971 through 1977, 50 vehicles from MY1980 through 1985, 50 vehicles from MY 1986 through 1991)
- Odometers range from 39,000 to 439,000 miles
- Fuel tank volume was 15% of the rated capacity
- RVP: 6.62 psi (average sum of 47 vehicles)
- Diurnal temperature: 72 to 96F
- Fuel System: Port Fuel Injection, Carburetor, Throttle Body Injection

CRC E-35 Running Loss Study (1997)

- 150 vehicles
- Ambient Temperature in running loss enclosure: 95F
- RVP: 6.8 psi
- Fuel System: Port Fuel Injection, Carburetor, Throttle Body Injection

EPA Compliance Data:

- 2-Day Test
- Length of the hot soak: 1 hour
- 77 vehicles
- RVP: average 8.81 psi
- Ambient Temperature:
- Federal Standard (72 to 96 F) Diurnal
- Cal. (65 to 105 F) Diurnal
- Hot Soak: 81.67F

Fuel System: Port Fuel Injection

Unleaded Cert Fuel			CARB Phase II Fuel		
Sulfur	RVP	Date	Sulfur	RVP	Date
wt %			wt %		
0.0048	9.04	Jul-98	0.0023	6.92	Aug-99
0.0045	9.2	Dec-98	0.0023	6.92	May-00
0.0063	9.04	Aug-99	0.0038	6.92	Jan-01
0.0048	8.99	May-00	0.0033	6.92	Oct-02
0.0042	9.05	Sep-01	0.0036	6.77	Mar-04
0.003	9.12	Dec-01			
0.003	9.12	Dec-02			
0.0031	8.8	May-03			
0.0035	8.91	Apr-04			
0.0027	8.95	Jun-04			

MSOD (Mobile Source Observation Database):

Hot Soak: 1 hour hot soak evaporative test
FTP: Federal test procedure (19.53 mph), also referred to as the UDDP schedule
NYCC: New York City Cycle Test (7.04 mph)
BL_1A: 1 hour Breathing Loss Evap. Test – Gas Cap left "On"
BL_1B: 1 hour Breathing Loss Evap. Test – Canister as recd.
ST01: Engine Start cycle test
4HD: 4 hour Diurnal test
24RTD: 24 Hour Real Time Diurnal
33RTD: 33 Hour Real Time Diurnal
72RTD: 72 Hour Real Time Diurnal
3Rest: 3 Hour Resting Loss Evap. Emission Test (follows 1 HR Hot Soak)
CY6084: Real time diurnal temperature pattern: range 60 to 84 F
CY7296: Real time diurnal temperature pattern: range 72 to 96 F
CY8210: Real time diurnal temperature pattern: range 82 to 102 F
DIURBL: Standard temperature rise for 1 hour diurnal or breathing loss evaporative emission test
F505: Bag 1 of federal test procedure (25.55 mph)
ASM: Acceleration Simulation Mode Test Procedure
ATD: Ambient Temperature diurnal evaporative Test, shed temp constant, vehicle begins 24 degree cooler

[1] CRC Report No. 610, Project E-9. Measurement of Diurnal Emissions from In-Use Vehicles. September 1998. http://www.crcao.com/reports/emission/e9.htm.

[2] CRC Report No. 611. Project E-35. Measurement of Running Loss Emissions from In-Use Vehicles. Automotive Testing Laboratories. Februrary 1998. http://www.crcao.com/reports/emission/e35.htm.

[3] CRC Report No. 612. Project E-35. Running Loss Emissions from In-Use Vehicles. Harold Haskew and Associates, Inc. Februrary 1999. http://www.crcao.com/reports/emission/e35.htm.

[4] CRC Report No. 622. Project E-41-1. Real World Evaporative Testing of Late-Model In-Use Vehicles. October 1999. http://www.crcao.com/reports/emission/e41.htm.

[5] CRC Report No. 622. Project E-41-2. Evaporative Emissions from Late-Model In-Use Vehicles. October 1999. http://www.crcao.com/reports/emission/e41.htm.

[6] Haskew, Harold M., Thomas F. Liberty and Dennis McClement, "Fuel Permeation from Automotive Systems," Final Report, for the Coordinating Research Council and the California Air Resources Board, CRC Project E-65, September 2004. http://www.crcao.com/reports/recentstudies2004/E65%20Final%20Report%209%202%2004.pdf. Available in Docket EPA-HQ-OAR-2005-0161.

[7] Haskew, Harold M., Thomas F. Liberty and Dennis McClement, "Fuel Permeation from Automotive Systems: E0, E6, E10, E20, and E85" Final Report, for the Coordinating Research Council and the California Air Resources Board, CRC Project E-65-3, December 2006. http://www.crcao.com/reports/recentstudies2006/E-65-3/CRC%20E-65-3%20Final%20Report.pdf

[8] Certification fuel tank temperature profiles of top selling passenger cars and light-duty trucks provided by manufacturers.

[9] T. Cam, K. Cullen, and S. L. Baldus, Running Loss Temperature Profile, *SAE. 930078*, Society of Automotive Engineers, Warrendale, Pa., 1993;

[10] R.S. Reddy, Prediction of fuel vapour generation from a vehicle fuel tank as a function of fuel RVP and temperature, *SAE 892089*, 1989.

[11] Landman, Larry C. U.S. EPA MOBILE6 Technical Document M6.EVP.009. Evaporative Emissions of Gross Liquid Leakers in MOBILE6 (EPA420-R-01-024). April 2001. http://www.epa.gov/otaq/models/mobile6/r01024.pdf.

[12] Sierra Research Report No. SR2005-12-03. United States Motor Vehicle Inspection and Maintenance (I/M) Programs. December 2005.