Evaporative Emissions from Onroad Vehicles in MOVES3.R1

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Assessment and Standards Division
Office of Transportation and Air Quality
Office of Air and Radiation
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Table of Contents

1 Background

EPA's Office of Transportation and Air Quality (OTAQ) has developed the Motor Vehicle Emission Simulator (MOVES). The MOVES model estimates emissions for mobile sources covering a broad range of pollutants and allows multiple scale analysis. MOVES currently estimates emissions from cars, trucks and motorcycles.

Evaporative processes can account for a significant portion of gaseous hydrocarbon emissions from gasoline vehicles. Volatile hydrocarbons evaporate from the fuel system while a vehicle is refueling, parked or driving. MOVES does not include estimates for emissions from non-fuel sources such as window washer fluid, paint, plastics, and rubber. Evaporative processes differ from exhaust emissions because they don't directly involve combustion, which is the main process driving exhaust emissions. For this reason, evaporative emissions require a different modeling approach. In the previous MOBILE models and in certification test procedures, evaporative emissions were quantified by the test procedures used to measure them:

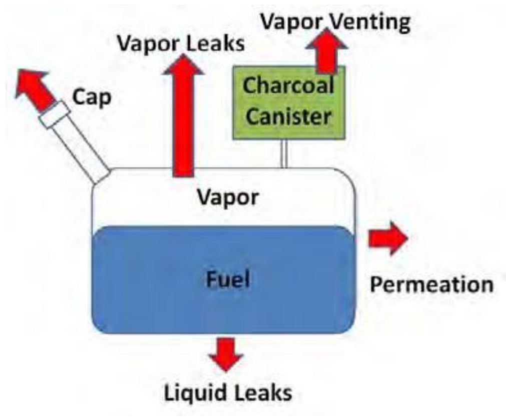
- **Running Loss** - Vapor lost during vehicle operation.
- **Hot Soak** - Vapor lost after turning off a vehicle.
- **Diurnal Cold Soak** - Vapor lost while parked at ambient temperature.
- **Refueling Loss** - Vapor lost and spillage occurring during refueling.

For MOVES, we instead model the underlying physical processes involved in evaporation of fuels. This "modal" approach characterizes the emissions by different emissions generation processes, each having its own engineering design characteristics and failure rates. This way, certain physical processes can be isolated, for example, ethanol has a unique effect on permeation, which occurs in all the above modes. The approach used in MOVES categorizes evaporative emissions based on the evaporative mechanism, using the following processes:

- **Permeation** - The migration of hydrocarbons through materials in the fuel system.
- **Tank Vapor Venting (TVV)** - Vapor generated in fuel system lost to the atmosphere, when not contained by evaporative emissions control system.
- **Liquid Leaks** - Liquid fuel leaking from the fuel system, ultimately evaporating.
- **Refueling Emissions** - Spillage and vapor displacement as a result of refueling.

Figure 1 illustrates the evaporative emission processes. Permeation occurs continuously through the tank walls, hoses, and seals. It is affected by fuel tank temperature and fuel properties.

Figure 1: Illustration of Evaporative Processes



These processes occur in each operating mode (Running Loss, Hot Soak, Cold Soak) used in the MOVES model. Each emission process can be modeled over a user-defined mix of operating modes, shown in Table 1. This makes for more accurate modeling of scenarios that do not replicate test procedures. The processed values for the evaporative emission processes used by MOVES are shown in Table 2.

Table 1: MOVES Evaporative Process Operating Modes

opModeID	Operating mode description
150	Hot Soaking
151	Cold Soaking
300	Engine Operation

Table 2: MOVES Evaporative Emission Processes

processID	Emission process description
11	Evap permeation
12	Evap vapor venting losses
13	Evap liquid leaks
18	Refueling displacement vapor losses
19	Refueling fuel spillage

Evaporative emissions are a function of many variables. In MOVES, these variables include:

- Ambient temperature
- Fuel Tank temperature
- Model year group (as a surrogate for technology and certification standard)
- Vehicle age
- Vehicle class
  - Passenger Vehicle
  - Motorcycle
  - Short/Long-haul Trucks
- Fuel Properties
  - Ethanol content
  - Reid Vapor Pressure (RVP)[a]
- Failure Modes
- Presence of inspection and maintenance (I/M) programs

Both ambient temperature and engine operation cause increases in fuel tank temperature. An increase in fuel tank temperature generates more vapor in the tank. Activated charcoal canisters are a control technology commonly used to adsorb the generated vapor. During engine operation, the canister is purged periodically and the captured vapor is diverted to the engine and burned as fuel. The emission certification standards for a vehicle (associated with model year and vehicle class) influence the capacity of the canister system. When the generated vapor exceeds the capacity of the canister, the vapor is vented to the atmosphere. This can occur when a fuel undergoes a large ambient temperature increase, or if a fuel with higher volatility is used, or when a vehicle canister collects vapor for many days without purging. In calculating vapor venting, MOVES accounts for co-mingling ethanol and non-ethanol gasoline, and for RVP weathering of in-use fuel. Details on these Tank Fuel Generator calculations are provided in Appendix B.

Fuel systems can develop liquid and vapor leaks that circumvent the vehicle emissions control system. Some inspection and maintenance (I/M) programs explicitly intend to identify vehicles in need of evaporative system repairs. Some states also implement Stage II programs at gas stations to capture the vapors released during refueling. These programs capture refueling vapor with technology installed at the pump rather than internal to the vehicle.

The model year groups for evaporative emissions are shown in Table 3. They reflect evaporative emission standards and related technological improvements. Early controls included the introduction of activated charcoal canisters for controlling fuel vapor emissions. Later controls included fuel tanks and hoses built with more advanced materials less prone to

[a] The MOVES fuel supply table provides the characteristics of gasoline sold in each county and month. For vapor venting calculations, the MOVES Tank Fuel Generator uses the fuel supply information to account for the effects of “comingling” ethanol with non-ethanol gasoline and for the “weathering” effect on RVP for in-use fuel. See appendix for details.

permeation. Also, reduction of fittings and connections became an important consideration for vapor mitigation.

Table 3: Model Year Groups for Evaporative Emissions in MOVES

Model year group	Evaporative 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
2004-2015	Tier 2, LEV II
2016-2017	40% Tier 3
2018-2019	60% Tier 3
2020-2021	80% Tier 3
2022+	Tier 3

This report documents the evaporative emission rates measured in terms of total hydrocarbons (THC). Total hydrocarbon gases are defined as the measurement of gaseous hydrocarbons by a flame ionization detector (FID). Evaporative emissions also contain oxygenated hydrocarbons such as alcohols and aldehydes.

MOVES estimates organic gas aggregate species (e.g., Volatile Organic Compounds, Total Organic Gases) from the THC emissions as documented in the speciation report.[1] MOVES estimates specific hydrocarbon species as fractions of VOC and TOG emissions. Eight important mobile source air toxics (MSATs), including benzene and ethanol, are calculated from evaporative VOC emissions as documented in the air toxics report.[2] Evaporative emissions are not directly affected by the combustion process, and does not estimate any emissions from combustion products. Table 4 contains a list of the evaporative pollutants calculated by MOVES. MOVES calculates additional chemical mechanism species from evaporative emissions used for air quality modeling as documented in the speciation report.[1]

The data used for this evaporative analysis was collected on light-duty gasoline vehicles but were also applied to heavy-duty gasoline vehicles since heavy-duty gasoline data was not available at time of analysis.

Table 4: MOVES Evaporative Pollutants

pollutantID	pollutantName	NEIPollutantCod	shortName
1	Total FID Hydrocarbons	HC	THC
20	Benzene	71432	Benzene
21	Ethanol		ETOH
40	2,2,4-Trimethylpentane	540841	2,2,4-Trimethylpentane
41	Ethyl Benzene	218019	Ethyl Benzene
42	Hexane	206440	Hexane
45	Toluene	85018	Toluene
46	Xylene	123386	Xylene
79	Non-Methane Hydrocarbons	NMHC	NMHC
80	Non-Methane Organic Gases	NMOG	NMOG
86	Total Organic Gases	TOG	TOG
87	Volatile Organic Compounds	VOC	VOC
185	Naphthalene gas	91203	Naphthalene Gas

Due to the low vapor pressure of diesel fuel, it is assumed that there are no evaporative emission losses except from refueling spillage.

At the time of this analysis, there was no relevant evaporative emissions data for compressed natural gas (CNG) vehicles. CNG fuel systems and refueling procedures are significantly different from those of liquid petroleum-based fuels. For the current release of MOVES, all evaporative emission rates for CNG vehicles are set at zero.

We significantly updated the evaporative emission calculations and rates in MOVES2014 based on updated emissions data, failure rates, and vehicle activity in MOVES2014. Because of the significant updates, the MOVES2014 version of this report was subject to peer review under EPA's peer review guidelines. More information about this peer review, including peer reviewer comments and EPA response is available on the web.[3]

Evaporative emission inputs for MOVES2014 were also reviewed by the Coordinating Research Council.[4] Based on our evaluation, most of the issues pointed out in the CRC report are expected to have very little impact on the magnitude of the evaporative emissions computed by MOVES. However, we continue to look for opportunities to improve how MOVES estimates evaporative emissions.

Updates for MOVES3 and MOVES3R.1 changed the calculation of refueling emissions as explained in Section 3.6 below. Peer review of the Section 3.6 was conducted as part of this update.[b]

As explained in the MOVES Population and Activity report[5], the activity associated with evaporative emissions remains the same as in MOVES2014.

[b] Document provided for peer review had the wrong equation for displaced vapor rate, Equation 3-18. See EPA response to comments for more information.

2 Test Programs and Data Collection

The modeling of evaporative emissions in MOVES is based on data from a large number of studies (Table 5). Over a decade of research greatly modernized evaporative emissions modeling. New test procedures provided modal emissions data that greatly advanced the state of the science. For example, the CRC E-77 test programs[6,7,8,9] measured permeation emissions separately from vapor emissions. Implanted leak testing from these studies along with further field research provided the first large database regarding the prevalence and severity of evaporative leaks and other mal- functions. The studies applied an innovative sampling design which preferentially recruited high emissions vehicles with the aid of infrared ultraviolet remote sensing devices. The field studies used a portable test cell (PSHED) to measure in-use hot soak emissions on a large number of vehicles. Findings from these studies were introduced in MOVES2014 with the explicit modeling of vapor leaks.[10,11].

Appendix A has a more detailed summary of these test programs.

Table 5: Evaporative Emission Research Programs

Program		# of Vehicles
CRC E-9	Measurement of Diurnal Emissions from In-Use Vehicles[12]	151
CRC E-35	Measurement of Running Loss Emissions in In-Use Vehicles[13]	150
CRC E-41	Evaporative Emissions from Late-Model In-Use Vehicles[14,15]	50
CRC E-65	Fuel Permeation from Automotive Systems[16]	10
CRC E-65-3	Fuel Permeation from Automotive Systems: E0, E6, E10, and E85[17]	10
CRC E-77	Vehicle Evaporative Emission Mechanisms: A Pilot Study[6]	8
CRC E-77-2	Enhanced Evaporative Emission Vehicles[7]	8
CRC E-77-2b	Aging Enhanced Evaporative Emission Vehicles[8]	16
CRC E-77-2c	Aging Enhanced Evaporative Emission Vehicles with E20 Fuel[9]	16
High Evap field studies[10, 11]		Thousands
Fourteen Day Diurnal study[18]		5
Running Loss Testing with Implanted Leaks[19]		5
API Leakage Study[20]		Not Avail.
API Gas Cap Study[21]		Not Avail.
EPA Compliance Testing[22]		Thousands

3 Design, Analysis and MOVES Inputs

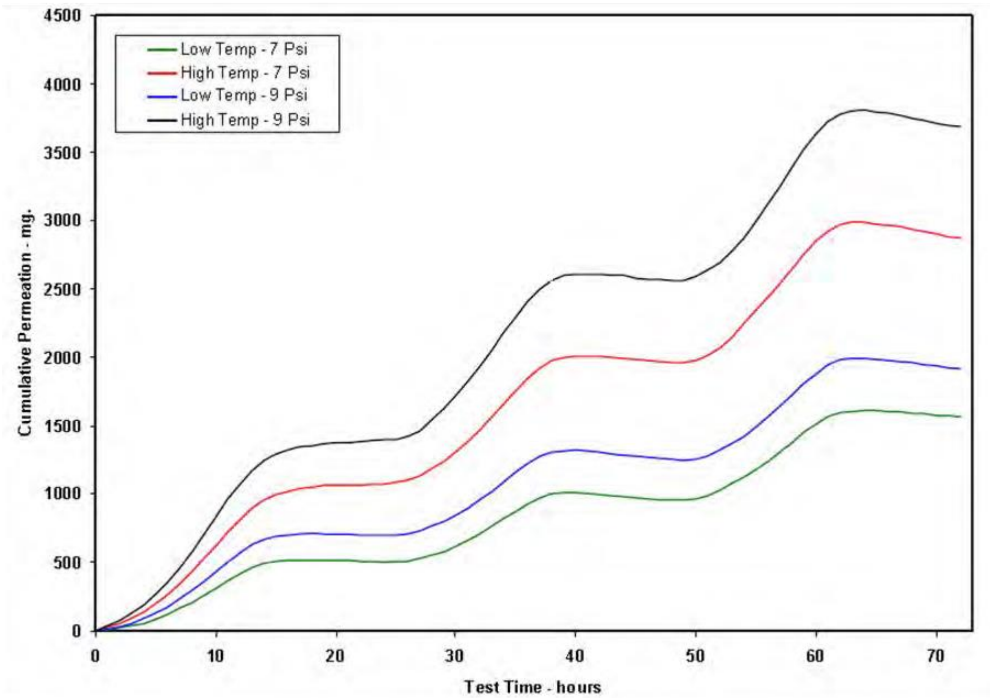
This chapter provides detailed information on how evaporative emissions in MOVES are calculated, and the analysis used to determine appropriate default inputs for the model.

As emission standards have tightened, fuel system materials and connections have become more efficient at containing fuel vapors. Purge systems and canister technologies have also advanced, resulting in less vented emissions. Fuel tank temperature is an important consideration in modeling permeation and vapor emissions. However, liquid leaks occur regardless and are not dependent on temperature.

3.1 *Fuel Tank Temperature Generator*

Fuel tank temperature is closely correlated with permeation and vapor venting as observed in the CRC E-77 pilot testing program [6]. This program tested ten vehicles in model years 1992 through 2007. The results showed that fuel temperature strongly influences evaporative emissions in all testing regimes. Fuel tank temperature is dependent on the daily ambient temperature profile and vehicle operation patterns. Modern vehicles (enhanced-evap, 1996 & later) do not recirculate fuel from the engine to the fuel tank and therefore have a lower temperature rise than older vehicles during operation. In Figure 2, the permeation emissions are plotted over a 3-day California diurnal tests with (65-105°F) as the low temperature range and 85-120°F as the high temperature range. Both the effects of temperature and fuel volatility can be observed.

Figure 2: Permeation Temperature and RVP effects



The MOVES "Fuel Tank Temperature Generator" calculates fuel temperature (also referred to as fuel tank temperature) for a given ambient temperature profile and vehicle trip schedule based on the vehicle type and model year. Different equations are used depending on the operating mode of the vehicle: running, hot soak, or cold soak. Fuel tanks are warmer during running operation than the ambient temperature. The routing of hot exhaust, vehicle speed, and airflow can all affect tank temperature. Immediately after the engine is turned off, the vehicle is in a hot-soak condition, and the fuel tank begins to cool to ambient temperature. In cold soak mode, the vehicle has reached ambient temperature.

Input parameters for the fuel tank temperature generator are:

- Hourly ambient temperature profile (zoneMonthHour table)
- Key on and key off times (sampleVehicleTrip table)
- Day and hour of first KeyON (hourDay table)
- Vehicle Type (Light-duty vehicle, Light-duty truck, Heavy-duty gas truck and Motorcycles)
- Pre-enhanced or enhanced evaporative emissions control system

The MOVES algorithm iterates through a set of "typical" vehicle trips based on information from instrumented vehicles. This data is stored in two tables in the MOVES default database.

SampleVehicleDay lists a sample population of vehicles, each with an identifier (vehID), an indication of vehicle type (sourceTypeID), and an indication (dayID) of whether the vehicle is part of the weekend or weekday vehicle population. To represent vehicles that may sit unused for multiple days, some vehicles in this table do not have any trips. The second table, SampleVehicleTrip, lists the trips in a day made by each of the vehicles in the SampleVehicleDay table. It records the vehID, dayID, a trip number (tripID), the hour of the trip(hourID), the trip number of the prior trip (priorTripID), and the times at which the engine was turned on and off for the trip. The keyOnTime and keyOffTime are recorded in minutes since midnight of the day of the trip. For more information on the activity data used to determine the time of keyOn and keyOff events, see the MOVES technical report on vehicle populations and activity [5] and supporting contractor reports [23], [24].

Coefficients for the Fuel Tank Temperature Generator are recorded in MOVES in the tankTemperatureGroups and tankTemperatureRise tables.

3.1.1 *Fuel Tank Temperature for Hot and Cold Soaks*

Equation 3-1 is used to model tank temperature as a function of ambient temperature.

Equation 3-1

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

T_{Tank} is the fuel tank temperature, T_{air} is the ambient temperature, and k is a constant proportionality factor (k = 1.4 hr^{-1}). The value of k was established from EPA compliance data on 77 vehicles that underwent a 2-day diurnal test and had a 1-hour hot soak (See Appendix A). No distinction was made between hot and cold soak for this derivation. We assumed that during any soak, the only factor driving change in the fuel tank temperature was the difference between the tank temperature and the ambient temperature.

This equation only applies during parked conditions, which include the following time intervals:

- From the start of the day (midnight) until the first trip (keyOnTime)
- From a keyOffTime until the next keyOnTime
- From the final keyOffTime time until the end of the day

Mathematical steps:

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

2. Then, for all t >0 and keyOffTime, the next tank temperature is calculated by integrating numerically[c] over the function for temperature change, using Equation 3-2.

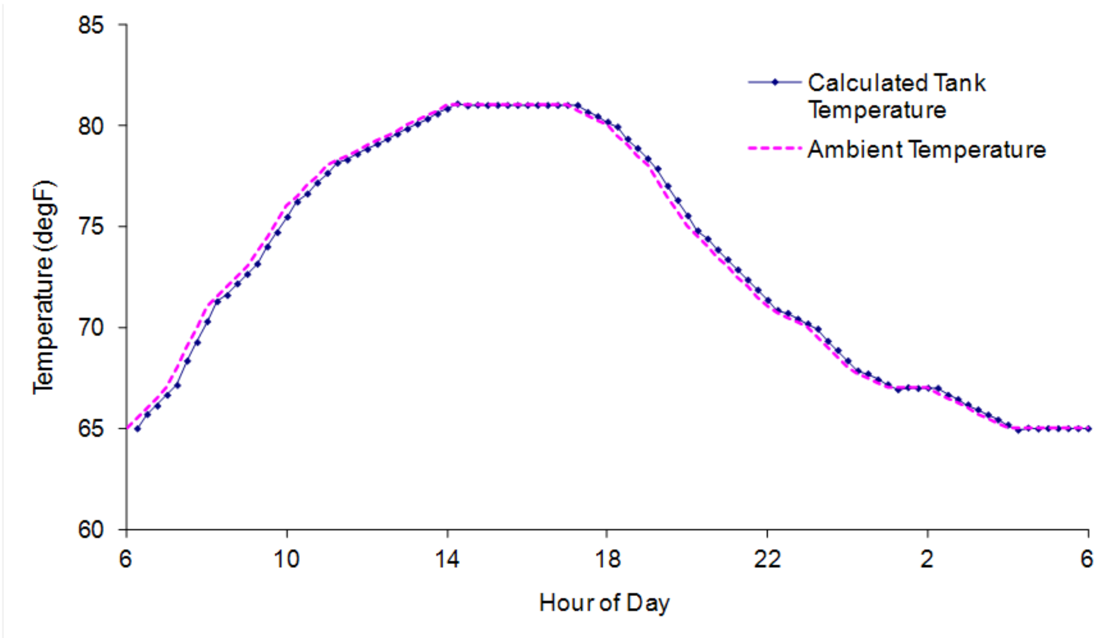
$(T_{Tank})_{n+1} = T_{Tank} + k(T_{air} - T_{Tank})\Delta t$	**Equation 3-2**

where:

T_{Tank} = Tank temperature
T_{air} = Ambient air temperature
t = Time
k = Temperature constant (1.4 hr^{-1})

Figure 3 demonstrates the Euler approximation for calculating the tank temperature based on ambient temperature.

Figure 3: Example Day Modeled with Euler Method



[c] Numerical integration is used to perform this step using the Euler method, one of the simplest methods of integration. The smaller the time step Δt, the more accurate the solution. MOVES uses a Δt of 15 minutes, which is accurate enough for our modeling purposes without causing tremendous strain on computing resources.

3.1.2 *Fuel Tank Temperature while Running*

Vehicle trips are short compared to the length of the day. Therefore, we assume a linear temperature increase during a trip to improve model performance with minimal compromise to accuracy.

In this algorithm, to determine ΔT_{tank}, the increase in tank temperature for an arbitrary trip length with arbitrary starting tank temperature, we must first find ΔT_{tank95}, the average increase in tank temperature during a standard 4300 second, 95°F running loss test. The algorithm models the increase in fuel tank temperature using the tank temperature at KeyOnTime, the amount of running time and the vehicle type and technology. Newer technologies reduce the heat transferred to the fuel tank. The MOVES ΔT_{tank95} temperatures are as follows:

- If the vehicle is pre-enhanced (model year pre-1996), vehicle type affects ΔT_{tank95}: [13]

$$\text{LDV } \Delta T_{tank95} = 35^{\circ}\text{F}$$
$$\text{LDT } \Delta T_{tank95} = 29^{\circ}\text{F}$$

- If the vehicle is evap-enhanced (model year 1996+):

$$\Delta T_{tank95} = 24^{\circ}\text{F}$$

These values are used to calculate the change in temperature for a 4300 second test ($\Delta T_{tank4300}$) for arbitrary starting fuel tank temperatures using Equation 3-8

$\Delta T_{Tank4300} = 0.352(95 - T_{Tank,KeyON}) + \Delta T_{Tank95}$	**Equation 3-3**

The parameters in Equation 3 are derived from regression analyses of light-duty vehicles driving the running loss drive cycle with varied starting temperatures [25]. The lower the initial tank temperature, the larger the increase over a given drive cycle.

The average ratio of fuel temperature increase to initial fuel temperature is -0.352. This gives us the increase in tank temperature, so we can create a linear function that models fuel tank temperature for each trip.

$\Delta T_{Tank4300} = 0.352(95 - T_{Tank,KeyON}) + \Delta T_{Tank95}$	**Equation 3-4**

The parameters in Equation 3 are derived from regression analyses of light-duty vehicles driving the running loss drive cycle with varied starting temperatures [26]. The lower the initial tank temperature, the larger the increase over a given drive cycle.

The average ratio of fuel temperature increase to initial fuel temperature is -0.352. This gives us the increase in tank temperature, so we can create a linear function that models fuel tank temperature for each trip.

$\Delta T_{Tank4300} = 0.352(95 - T_{Tank,KeyON}) + \Delta T_{Tank95}$	**Equation 3-5**

The parameters in Equation 3 are derived from regression analyses of light-duty vehicles driving the running loss drive cycle with varied starting temperatures [27]. The lower the initial tank temperature, the larger the increase over a given drive cycle.

The average ratio of fuel temperature increase to initial fuel temperature is -0.352. This gives us the increase in tank temperature, so we can create a linear function that models fuel tank temperature for each trip.

3.1.3 ***Fuel Tank Temperature while Running***

Vehicle trips are short compared to the length of the day. Therefore, we assume a linear temperature increase during a trip to improve model performance with minimal compromise to accuracy.

In this algorithm, to determine ΔT_{tank}, the increase in tank temperature for an arbitrary trip length with arbitrary starting tank temperature, we must first find ΔT_{tank95}, the average increase in tank temperature during a standard 4300 second, 95°F running loss test. The algorithm models the increase in fuel tank temperature using the tank temperature at KeyOnTime, the amount of running time and the vehicle type and technology. Newer technologies reduce the heat transferred to the fuel tank. The MOVES ΔT_{tank95} temperatures are as follows:

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- If the vehicle is evap-enhanced (model year 1996+):

$$\Delta T_{tank95} = 24^{\circ}\text{F}$$

These values are used to calculate the change in temperature for a 4300 second test ($\Delta T_{tank4300}$) for arbitrary starting fuel tank temperatures using Equation 3-8

$\Delta T_{Tank4300} = 0.352(95 - T_{Tank,KeyON}) + \Delta T_{Tank95}$	**Equation 3-6**

The parameters in Equation 3 are derived from regression analyses of light-duty vehicles driving the running loss drive cycle with varied starting temperatures [28]. The lower the initial tank temperature, the larger the increase over a given drive cycle.

The average ratio of fuel temperature increase to initial fuel temperature is -0.352. This gives us the increase in tank temperature, so we can create a linear function that models fuel tank temperature for each trip.

3.1.4 *Fuel Tank Temperature while Running*

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- If the vehicle is pre-enhanced (model year pre-1996), vehicle type affects ΔT_{tank95}: [13]

  LDV $\Delta T_{tank95} = 35°F$
  LDT $\Delta T_{tank95} = 29°F$

- If the vehicle is evap-enhanced (model year 1996+):

  $\Delta T_{tank95} = 24°F$

These values are used to calculate the change in temperature for a 4300 second test ($\Delta T_{tank4300}$) for arbitrary starting fuel tank temperatures using Equation 3-8

$\Delta T_{Tank4300} = 0.352(95 - T_{Tank,KeyON}) + \Delta T_{Tank95}$	**Equation 3-7**

The parameters in Equation 3 are derived from regression analyses of light-duty vehicles driving the running loss drive cycle with varied starting temperatures [29]. The lower the initial tank temperature, the larger the increase over a given drive cycle.

The average ratio of fuel temperature increase to initial fuel temperature is -0.352. This gives us the increase in tank temperature, so we can create a linear function that models fuel tank temperature for each trip.

3.1.5 ***Fuel Tank Temperature while Running***

Vehicle trips are short compared to the length of the day. Therefore, we assume a linear temperature increase during a trip to improve model performance with minimal compromise to accuracy.

In this algorithm, to determine ΔT_{tank}, the increase in tank temperature for an arbitrary trip length with arbitrary starting tank temperature, we must first find ΔT_{tank95}, the average increase in tank temperature during a standard 4300 second, 95°F running loss test. The algorithm models the increase in fuel tank temperature using the tank temperature at KeyOnTime, the amount of running time and the vehicle type and technology. Newer technologies reduce the heat transferred to the fuel tank. The MOVES ΔT_{tank95} temperatures are as follows:

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$\Delta T_{Tank4300} = 0.352(95 - T_{Tank,KeyON}) + \Delta T_{Tank95}$	**Equation 3-8**

The parameters in Equation 3 are derived from regression analyses of light-duty vehicles driving the running loss drive cycle with varied starting temperatures [30]. The lower the initial tank temperature, the larger the increase over a given drive cycle.

The average ratio of fuel temperature increase to initial fuel temperature is -0.352. This gives us the increase in tank temperature, so we can create a linear function that models fuel tank temperature for each trip.

$T_{Tank} = \frac{\Delta T_{Tank4300}}{4300/3600}(t - t_{keyON}) + T_{Tank,KeyON}$	**Equation 3-9**

Where:

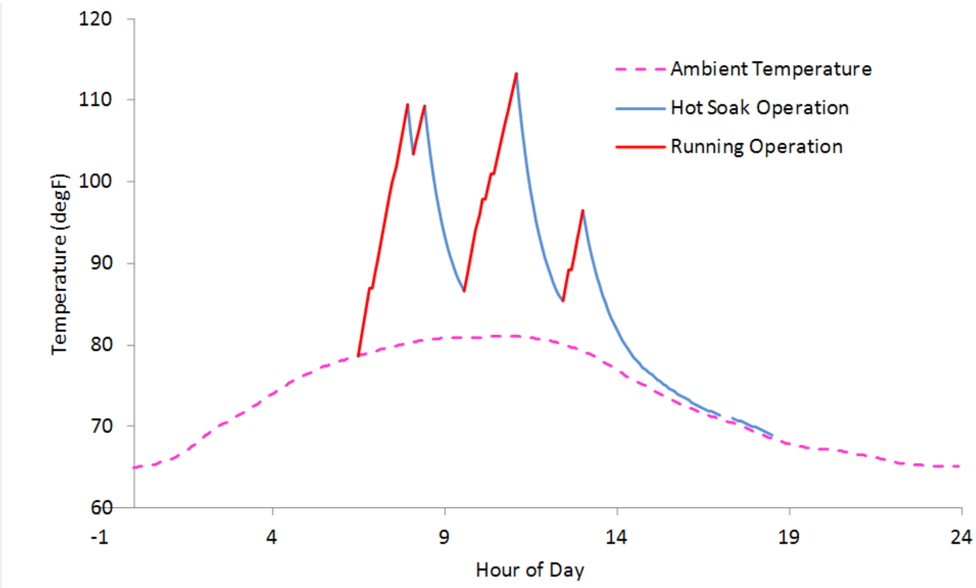
T_{Tank} = Tank temperature

t = Time

t_{keyON} = Time of engine start

The 4300/3600 in the Equation 4 denominator converts seconds to hours (4300 seconds in the running loss certification test), maintaining temporal consistency in the algorithm. The resultant tank temperatures for an example temperature cycle are illustrated in Figure 4. Running operation is shown as a red line, and hot soak operation is shown as a blue line

Figure 4: Modeled Vehicle Tank Temperature During a Day of Operation



Assumptions:

- The first trip is assumed to start halfway into the hour stated in the first trip's HourDayID.
- The effect of a change in ambient temperature during a trip is negligible compared to the temperature change caused by operation.
- The KeyOn tank temperature is known from calculation of tank temperature from the previous soak.

3.2 ***Permeation***

Permeation emissions are specific hydrocarbon compounds that escape through micro-pores in pipes, fittings, fuel tanks, and other vehicle components (typically made of plastic or rubber). They differ from leaks in that they occur on the molecular level and do not represent a mechanical/material failure in a specific location. In MOVES, base permeation rates are estimated and then adjusted to the modelled tank temperatures and fuel properties.

The base rates in MOVES represent rates for gasoline with no ethanol. As detailed in Section 3.2.2, while keeping other fuel properties constant, the presence of ethanol increases permeation emissions approximately two-fold.

For model years before 1999, permeation base rates are developed using the mg/hour emission data from the last six hours of a 72-96-72˚F diurnal test (also known as cold soak/resting loss) The diurnal tests were measured on the federal cycle (72F-96˚F) for the CRC E-9 and E-41 programs [12, 14, 15]. Together, these two programs tested a total of 151 vehicles with model years ranging from 1971 to 1997. The final six hours of the diurnal are an appropriate surrogate for a permeation-only test because the emission rate, ambient temperature, and fuel temperature are relatively stable or constant. Permeation should be the only evaporative process occurring. The rates were developed for distinct model year and age groups. Model years 1996-1998 are represented individually to reflect the phase-in of Enhanced Evaporative Emissions Standards (20 percent Enhanced Evap in 1996, 40 percent in 1997, 90 percent in 1998).

For the 1999 – 2003 model years (full implementation of the Enhanced Evaporative Emissions Standards) and the 2004 – 2015 model years (Tier 2 Evaporative Emissions Standards) the E-77-2 Static test data was analyzed using the 86^{o} F tests for non-leaking vehicles, corrected to 72^{o}F. We used the Static test for these vehicles because the last six hours of Diurnal test was a surrogate to represent permeation rates in the older vehicle data, but the static test is intended to measure permeation and only permeation. The values in MOVES are based on 54 tests in the 1999-2003 model year group taken from EPA's Compliance Testing Program. Later data from the E-77 programs served to validate the Tier 2 permeation base rates already used in MOVES. The E-77-2 data points expanded the range of the age groups but the data was not sufficient to differentiate the estimates for the age and model year groupings, thus, we kept the 0.0102 rate for all ages of both 1999-2003 and 2004+. Table 6 summarizes the data, analysis and resulting emission rates for model years 1999-and-later for the number of tests within each age group to understand how these decisions were made. There were three vehicles in the 0-3 age group for model year 2004+ that had an average of 0.003 but ten vehicles in the next age group had essentially the same average emissions rate of 0.01. Assuming there is deterioration for these vehicles, averaging all ages into one group made sense to characterize the fleet without data to support finer age groups.

The Tier 3 evap standards apply starting in model year 2017, and phase in over model years 2016-2022, with early allowances. The Tier 3 permeation standard reflects a 40 percent reduction from the previous standard and the introduction of 10 percent ethanol to the certification fuel discussed earlier.

Permeation base rates are presented in Table 7. These rates are recorded in the MOVES emissionRateByAge table.

Table 6: Permeation Analysis for 1999 – 2003 and 2004 and later Model Years

		Previous Data (Compliance data)					Decision for MOVES2014
Model Year	Age	# of tests	MOVES2010	# of E-77 tests	E-77 avg rate	weighted avg of ALL	Enhanced Evap
1999-2003	0-3	52	0.0102			0.0102	0.0102
	4-5	0	0.0102			0.0102	
	6-7	2	0.0102	7	0.021	0.0186	
	8-9	0	0.0102	2	0.014	0.0140	
	10-14	0	0.0102			0.0102	
	15-19	0	0.0102			0.0102	
	20+	0	0.0102			0.0102	
Model Year	Age	# of tests	MOVES2010	# of E-77 tests	E-77 avg rate	weighted avg of ALL	Tier 2 / LEV II
2004 - 2015	0-3	0	0.0102	3	0.003	0.003	0.0102
	4-5	0	0.0102	10	0.01	0.01	
	6-7	0	0.0102			0	
	8-9	0	0.0102			0	
	10-14	0	0.0102			0	
	15-19	0	0.0102			0	
	20+	0	0.0102			0	
Model Year	Age	# of tests	MOVES2010			weighted avg of ALL	40% of Tier 3
2016 - 2017	0-3	0	0.0102			0	0.007
	4-5	0	0.0102			0	
	6-7	0	0.0102			0	
	8-9	0	0.0102			0	
	10-14	0	0.0102			0	
	15-19	0	0.0102			0	
	20+	0	0.0102			0	
Model Year	Age	# of tests	MOVES2010			weighted avg of ALL	60% of Tier 3
2018 - 2019	0-3	0	0.0102			0	0.006
	4-5	0	0.0102			0	
	6-7	0	0.0102			0	
	8-9	0	0.0102			0	
	10-14	0	0.0102			0	
	15-19	0	0.0102			0	
	20+	0	0.0102			0	
Model Year	Age	# of tests	MOVES2010			weighted avg of ALL	80% of Tier 3
2020 - 2021	0-3	0	0.0102			0	0.004
	4-5	0	0.0102			0	
	6-7	0	0.0102			0	
	8-9	0	0.0102			0	
	10-14	0	0.0102			0	
	15-19	0	0.0102			0	
	20+	0	0.0102			0	
Model Year	Age	# of tests	MOVES2010	# of E-77 tests	E-77 avg rate	weighted avg of ALL	100% of Tier 3
2022 and later	0-3	0	0.0102	1	0.005	0.005	0.003
	4-5	0	0.0102	1	0.002	0.002	
	6-7	0	0.0102			0	
	8-9	0	0.0102			0	
	10-14	0	0.0102			0	
	15-19	0	0.0102			0	
	20+	0	0.0102			0	

Table 7: MOVES Base Permeation Rates at 72oF

First Model Year	Last Model Year	Age Group	Base Rate
1960	1970	20+	0.311
1971	1977	10-14	0.192
		15-19	0.229
		20+	0.311
1978	1995	0-5	0.0554
		6-9	0.0913
		10-14	0.124
		15-19	0.148
		20+	0.201
1996	1996	0-5	0.0464
		6-9	0.0751
		8-9	0.0751
		15-19	0.12
		20+	0.163
1997	1997	0-5	0.0373
		6-9	0.0589
		10-14	0.0784
		15-19	0.0929
		20+	0.125
1998	1998	0-5	0.0147
		6-9	0.0183
		10-14	0.0216
		15-19	0.024
		20+	0.0293
1999	2015	all ages	0.0102
2016	2017	all ages	0.0072
2018	2019	all ages	0.0056
2020	2021	all ages	0.0041
2022	2060	all ages	0.0026

3.2.1 *Temperature Adjustment*

The E-65 permeation study found that permeation rates, on average, double for every 18˚F increase in temperature. [16] This study tested 10 vehicle fuel systems (the vehicle body was cut away from the fuel system, which remained intact on a frame) at 85˚F and 105˚F. The vehicles ranged in model year from 1978-2001. In MOVES, the base permeation rates are calculated at 72˚F, the same temperature as the certification test. Equation 3-10 is derived from this study and used to adjust the base permeation rate to account for the tank temperature described in Section 3.1.

$$P_{adj} = P_{base} e^{0.0385(T_{Tank} - T_{base})}$$	**Equation 3-10**

Where:

P_{base} = Base Permeation Rate
T_{Tank} = Tank Temperature
T_{base} = Base Temperature for a given cycle (e.g., 72°F for a federal diurnal test)

3.2.2 ***Fuel Adjustment***

Ethanol affects evaporative emissions from gasoline vehicles due to the increased permeation of specific hydrocarbon compounds through tanks and hoses. Modeling permeation emissions separately from vapor venting emissions allows us to apply these effects only on permeation where the complex chemistry of ethanol-gasoline blends increases permeation through the tanks and hoses of the fuel system.

Permeation fuel effects were developed from the CRC E-65[16] and E-65-3[17] programs, which measured evaporative emissions from ten fuel systems that were removed from the vehicles and filled with E0, E5.7, and E10 fuels. This method assures that the emissions measured are purely from permeation (assuming the systems were not leaking). Additional data was provided from the CRC E-77-2[7] and E-77-2b[8] programs, which measured evaporative emissions from sixteen intact vehicles. For this analysis, vehicles certified to enhanced-evaporative and Tier 2 standards were analyzed separately from vehicles certified to earlier standards. Enhanced evaporative standards were phased in from 1996-1999 and imposed a 2.0 gram standard over a 24-hour diurnal test. Standards previously in effect applied a 2.0 gram standard to a 1-hour simulated diurnal.

The ethanol effect is estimated with a mixed model shown in Table 8. The evaporative certification level, ethanol content, and RVP were modeled as fixed effects and the vehicle was modeled as a random effect. The natural logarithm of the emission rates over the 65-105-65°F diurnal cycle provided a normally distributed dataset to the model. The dataset was not large enough to distinguish the three ethanol levels within each evaporative certification bin. Therefore, E5.7 and E10 test results were combined into a single bin of ethanol-containing fuel which had a significant effect compared to E0 fuel.

Table 8: Mixed Model for Ethanol Effects on Permeation

Mixed Model for ETOH Effects on Permeation					
	logHC-1 ~ Standard Group + ETOHYN * Standard Group				
Standard	Value	Std. Error	DF	t-value	p-value
	3.0279465	0.1887947	59	16.038305	0
Tier 2	-0.761386	0.3095233	15	-2.459867	0.0265
Zero Evap	-1.050358	0.6297706	15	-2.938146	0.0102

The percent difference between the ethanol rate and the E0 rate is used in MOVES as the fuel adjustment. Due to the enhanced-evaporative certification standards phase in from 1996-1999 (20/40/90/100 percent), the two fuel adjustments must also be phased in for those model years. Table 9 lists the fuel adjustments used for E5 through E85 for the model year groupings used in MOVES. These values are recorded in the MOVES hcPermeationCoeff table as multiplicative factors.

Table 9: Ethanol effect for Permeation Emissions

Model Years	Percent increase due to ethanol (5-85%)
1995 and earlier	65.9
1996	75.5
1997-2000	107.3
2001 and later	113.8

3.3 *Tank Vapor Venting*

Vapor generated in the tank can escape to the atmosphere during a process labeled "Evap Vapor Venting" or "Tank Vapor Venting" (TVV). Hydrocarbons emitted by this process originate from a variety of sources. As tank temperature rises and vapor is generated within the tank, the vapors are forced out of the tank from increased pressure. Fully sealed gas tanks are rare as they must be constructed with metal to prevent bloating. Using metal as a tank material can be expensive, heavy, and difficult to shape for tightly packed modern vehicles. Instead, most vehicles are equipped with an activated charcoal canister to adsorb the vapors as they are generated. Later, the vapors are consumed as they purge to the engine (through the intake manifold) during vehicle operation. The canister is open (or vented) to the atmosphere to prevent pressure from building within the fuel system. Consequently, if the engine is not operated for several days, fuel vapors can diffuse through the charcoal or even freely pass through a completely saturated canister. Tampering, mal-maintenance, and system failure can result in excess evaporative emissions. Inspection and maintenance (I/M) programs can also influence how leaks and other problems are controlled over the life of a vehicle. MOVES models vapor venting for vehicles using gasoline and E85 fuels.

In MOVES, vapor venting default values are recorded in several tables. The emissionratebyage table stores the vapor venting rates (process 12) for hot soak (opmode 150) and running (opmode 300). Cold soak (opmode 151) emission equations and parameters are recorded in cumTvvCoeffs as explained below.

Integral to the understanding of Tank Vapor Venting (TVV) is the calculation of Tank Vapor Generated (TVG). Tank vapor generated depends on the rise in fuel tank temperature (F), ethanol content (vol. percent), Reid vapor pressure (RVP, psi) and altitude. Calculations in MOVES use the Wade-Reddy equation for vapor generation (Equation 3-11).[31]

$$TVG = Ae^{B*RVP}(e^{CT_x} - e^{CT_1}) \qquad \textbf{Equation 3-11}$$

Where:

T_1 = Initial temperature

T_x = Temperature at time x

In Equation 3-11 coefficients A, B, C vary by altitude and fuel ethanol content. These coefficients, stored in the database table TankVaporGenCoeffs, are shown in Table 10.

Table 10: TVG Constants for Equation 3-11

E0 Gasoline			**E10 Gasoline**	
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

The vapor venting emission process occurs during all three operation modes: running, hot soak and cold soak. While running, vapors are generated as the fuel system is warming and active. During hot soak, vapor generation is caused by latent heat transfer due to fuel recirculation and other convective processes. Cold soak vapor generation is concurrent with ambient temperature increases. MOVES modeling of fuel system warming is detailed in Section 3.1.

3.3.1 ***Altitude***

Evaporative vapor generation is affected by the lower ambient pressure at high altitudes. MOVES accounts for this effect during the calculation of tank vapor generated. This process relies on the values in Table 10 for high altitude (Denver, CO) and a low altitude (Sea Level). MOVES applies linear interpolation/extrapolation based on the barometric pressure in each county.

3.3.2 ***Cold Soak***

Cold soak vapor emissions occur while a vehicle is not operating, and the engine and fuel system have cooled to ambient temperature. Emissions occurring under these conditions are also referred to as diurnal emissions.

Emission quantification started with the measurement of emissions based solely on standard regulatory test cycles. As the emissions levels over the test cycles became more controlled, concern grew about “off-cycle emissions”- real-world emissions that occur outside of the test procedure constraints on ambient temperatures, fuel RVP and soak time.

3.3.2.1 Multi-day Diurnals

As a vehicle sits through multiple diurnal cycles, the carbon canister accumulates vapor every day. It can only adsorb vapor until it reaches its capacity; then it begins to vent to the atmosphere. A canister with degraded/damaged carbon may have reduced capacity, and eventually every canister will vent to the atmosphere once it reaches saturation. During cooling hours, a canister backpurges to the fuel tank and regains some capacity. Then, during the subsequent warming period the canister is re-filled with vapor and any vapor generated beyond capacity will escape to the atmosphere.

Figure 5: Multiday Vapor Accumulation in Charcoal Canister

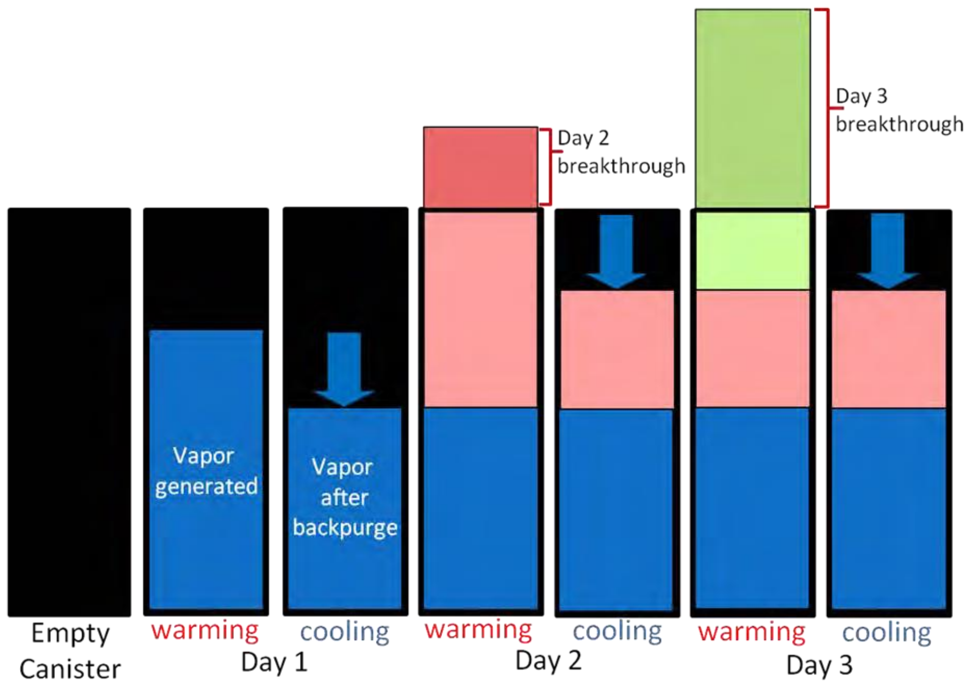
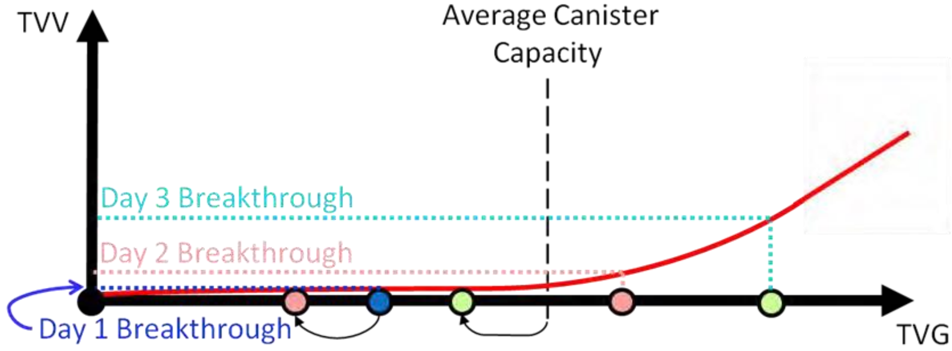


Figure 5 illustrates the dynamic behavior of vapor within a charcoal canister over three days of continuous cold soaking. During the first day, vapor accumulates within the canister but does not exceed the canister capacity. During the cooling period of day 1, we observe backpurge when some of the fuel vapors that were previously adsorbed to the charcoal flow back into the cooling tank. The fresh air is drawn in through the canister vent while the vapor condenses in the tank during the cooling portion of the cycle. During warming on day 2, we see generated fuel vapors that exceed the canister capacity (though some canisters may be constructed to hold more than 2 days of vapor). These emissions are lost to the atmosphere, and only what remains in the canister can be backpurged during the subsequent cooling cycle. In day 3, more vapor is generated and consequently lost to the atmosphere. Any additional days without engine purge during normal driving (i.e. inactivity) will exhibit the same behavior as day 3. It should be mentioned that plug-in hybrid electric vehicles that are mainly driven on short (electric only) trips, may also exhibit similar breakthrough over time. However, modeling of these vehicles is currently beyond the scope of MOVES since the penetration rates of these technologies are low, and we are not aware of any multi-day diurnal data collected on PHEVs.

3.3.2.2 Cold Soak Emissions for the Average Fleet

Modeling a fleet of vehicles involves a diverse population of canisters with differing capacities. A given amount of vapor will be fully contained by some vehicles but exceed the canister capacity in others. Figure 6 illustrates the approach for calculating the tank vapor vented (TVV) as a function of the tank vapor generated (TVG).

Figure 6: Vapor Vented Curve



Several factors accommodate this modeling approach. The following variables, explained in more detail below, are included in the MOVES default database in the 'cumTvvCoeffs' table:

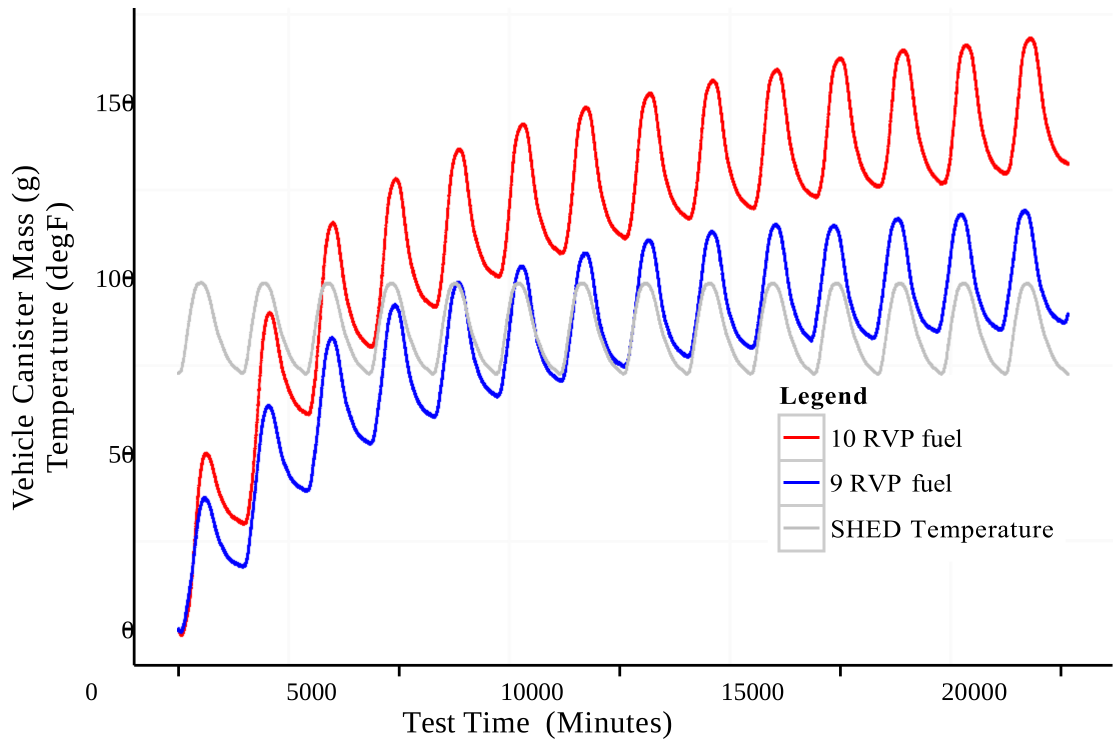
- BackPurge Factor
- Average Canister Capacity
- Tank Size
- Tank Fill Fraction
- Leak Fraction (Prevalence)
- Leak Fraction (Prevalence)IM
- TVV Equation
- Leak Equation

3.3.2.3 BackPurge Factor

The backpurge factor is the percent of hydrocarbon vapor that is desorbed from a vehicle's canister during cooling hours when pressure decreases within the tank, drawing ambient air in through the canister vent. In the real-world, this process occurs nightly as temperatures cool and restore some canister capacity. In the Multiday Diurnal Study [18] , test vehicles soaked for 14 consecutive 72˚F-96˚F diurnals (the Federal Test Procedure temperature cycle). During this time, the vehicle canister mass was measured continuously. During the cooling period, the measured mass of the vehicle canisters decreased. This cyclical effect can be observed in Figure 7.

An average value of 23.8 percent backpurge was developed from these results and is used in the MOVES model. For example, a vehicle canister with 100 grams of hydrocarbons will backpurge 23.8 grams and begin the next day with 76.2 grams. A more complex model for backpurge was considered (similar to tank vapor generation), but it would require significant computational resources and potentially slow model performance considerably. As diurnal temperatures are relatively symmetrical, detailed modeling of tank vapor generation has already provided a high level of precision, justifying a simpler model here.

Figure 7: Vehicle Canister Mass, 14-day Diurnal Test



3.3.2.4 Average Canister Capacity

The canister capacity reflects how much vapor generated in the tank can be contained by the canister before breaking through. Note that while average canister capacity is stored in the MOVES database, it is not actually used in the MOVES model. Instead, it was used in the DELTA pre-processor [32].

To calculate a sales-weighted average canister size, we used sales data[33] and EPA evaporation certification data.[22] Certification data includes the evaporative family code which contains the Butane Working Capacity (BWC) of the canister; it is found in digits 7, 8 and 9 for enhanced evap vehicles, and in digits 5, 6 and 7 for pre-enhanced vehicles. The BWC represents the ability of a canister to capture butane vapor, rather than gasoline vapor, so it must be adjusted by a factor of 0.92[34].

Evaporative control was introduced in 1971, so canisters are not modelled for pre-1971 vehicles. For model years beyond 2010, the 2010 average canister capacity was used. The calculated average canister capacities for cars and trucks combined are listed in Table 11. A peak in average canister size at model year 2005 corresponds to greater sales of cars with larger fuel tanks. Motorcycles are modeled without canisters, because they were not being used at the time of the analysis. We hope to review and revise in future versions of the model. Heavy-duty gasoline vehicles are modeled with the same canister capacity as light-duty vehicles.

Table 11: Average Canister Capacity by Model Year

Model Year Group	Average Canister Capacity (grams)
1960-1970	0
1971-1977	64.7
1978-1995	72.8
1996	78.7
1997	83
1998	115.4
1999-2003	122.9
2004	145
2005	150.7
2006	145.3
2007	142.9
2008	138.6
2009	136.2
2010+	137.5

3.3.2.5 Tank Size

The average tank size for a given model year is an important facet of the vapor generation calculation because a larger tank will have more space in which vapor can accumulate. Both sales data [33] and tank size information [35] were required to calculate a sales-weighted average tank size for model years 1990-2010. For this analysis, car and truck sales, and tank sizes were combined. For vehicles with multiple styles (i.e. different cab sizes on pick-up trucks) with different tank sizes, the average available tank size was used as sales information was unavailable by style. Data sources only span from 1990-2010, so past and future values were projected. Vehicles in the 1990-2010 range have tanks with an average capacity of 1.25 times greater than a calculated 300-mile range, so this ratio was applied using fuel economy data going back to model year 1975. [36]. Pre-1975 vehicles use the 1975 fuel tank size. For future vehicles, tank size is assumed to stay constant from 2010 on. It is also possible that manufacturers will maintain range with a shrinking fuel tank. In future versions of MOVES, we will reexamine this assumption. The calculated sales-weighted tank sizes are in Table 12.

Table 12: Sales-Weighted Average Fuel Tank Size

Model Year Group	Tank Size (gal)
1960-1970	28
1971-1977	27.3
1978-1995	18.6
1996-1997	19.1
1998	19.5
1999-2003	19.9
2004	20.5
2005	20.3
2006	20
2007	19.7
2008	19
2009-2030	19.1
HD Vehicles	38
Motorcycles	3

3.3.2.6 Tank Fill Fraction

The tank fill fraction is an important input used in calculating tank vapor generation. The more vapor space above the liquid fuel, the more capacity there is for vapors to accumulate. The average tank fill fraction used in the model is 40 percent fill. This is a typical fill level for certification procedures and many of the test programs from which our data originates. It is also a figure supported by existing research on tank filling behavior by consumers [37].

3.3.2.7 Vapor Leak Prevalence

In order to accurately quantify emissions from leaking vehicles, one must not only estimate emission rates from leaks of various sizes, but also prevalence of leaks in the fleet. This corresponds to an emissions rate and its corresponding activity. Our estimates of leak prevalence are informed by the analysis of a field study which took place at the Ken Caryl IM Station in Denver, CO during the summer of 2009 [11]. In this study, a remote sensing device (RSD) was used to recruit high emitting vehicles which were then tested in a Portable Sealed Housing for Evaporative Detection (PSHED). The vehicle's hydrocarbon emissions were measured over 15 minutes during hot-soak conditions, and vehicles were inspected to identify the cause/source of the leaks when possible. The set of hot-soak measurement from individual vehicles, with inverse-probability sampling weights and solicitation response weights applied to all vehicles, allows the prevalence of leaks in the fleet to be estimated.

We have defined a vapor leaker as any vehicle that would fail the enhanced evaporative standard of 2 grams. The standard sums the emissions from the worst day of a 3-day diurnal test and the hot soak. To develop a surrogate standard for a 15-minute hot soak test, we used knowledge of certification testing to attribute 0.4 grams (g) of the 2 g standard to the hot soak portion, and 76 percent of 0.4 g to the first 15 minutes of the hour-long hot soak test. This approach suggests that 0.3 g can be taken as a surrogate standard for a 15-minute hot soak.

Figure 8: Prevalence of Vapor Leaks Above a Given Threshold in the 2009 Ken Caryl Fleet

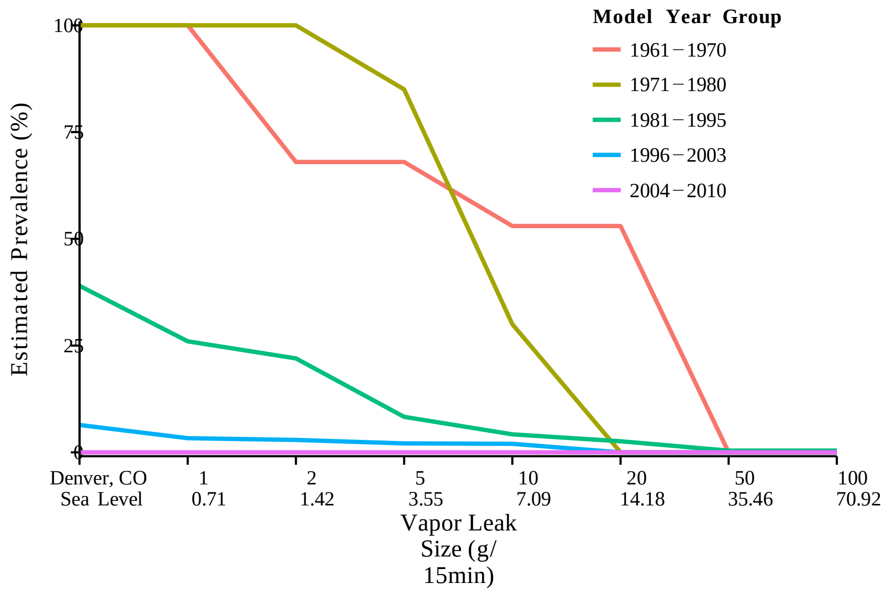


Table 13 (plotted in Figure 8) displays leak prevalence at various emission thresholds for what constitutes a “leak”. Observing the difference between any two points determines how many vehicles fall into a particular range. Looking at Table 13, in model year group 1981-1995, 2.6 percent of vehicles are leaking at more than 20 grams and 4.2 percent of vehicles are leaking at more than 10 grams. Subtracting these two values yields that 1.6 percent of vehicles in the model year group have a leak between 10 and 20 grams.

The data only contain prevalence rates for PSHED measurements as low as 1.0g/15min. Failure rates are extrapolated to 0.3g/15min. Using aggregate data from the Ken Caryl station, it is found that 0.3g/15min PSHED measurements are 50 percent more prevalent than 1.0g/15min PSHED measurements.

Table 13: Prevalence of Leaks Above a Given Threshold (g/15min)

Leak Threshold (g/15 min)								
Denver	100	50	20	10	5	2	1	0.3
Sea Level (MOVES)	70.9	35.5	14.1	7	3.6	1.4	.7	.2
Prevalence by MY Group								
1961 - 1970	0	0	0.53	0.53	0.68	0.68	1	1
1971 - 1980	0	0	0	0.3	0.85	1	1	1
1981 - 1995	0.004	0.004	0.026	0.042	0.083	0.22	0.26	0.39
1996 - 2003	0	0	0	0.02	0.021	0.029	0.033	0.064
2004 - 2010	0	0	0	0	0	0	0	0

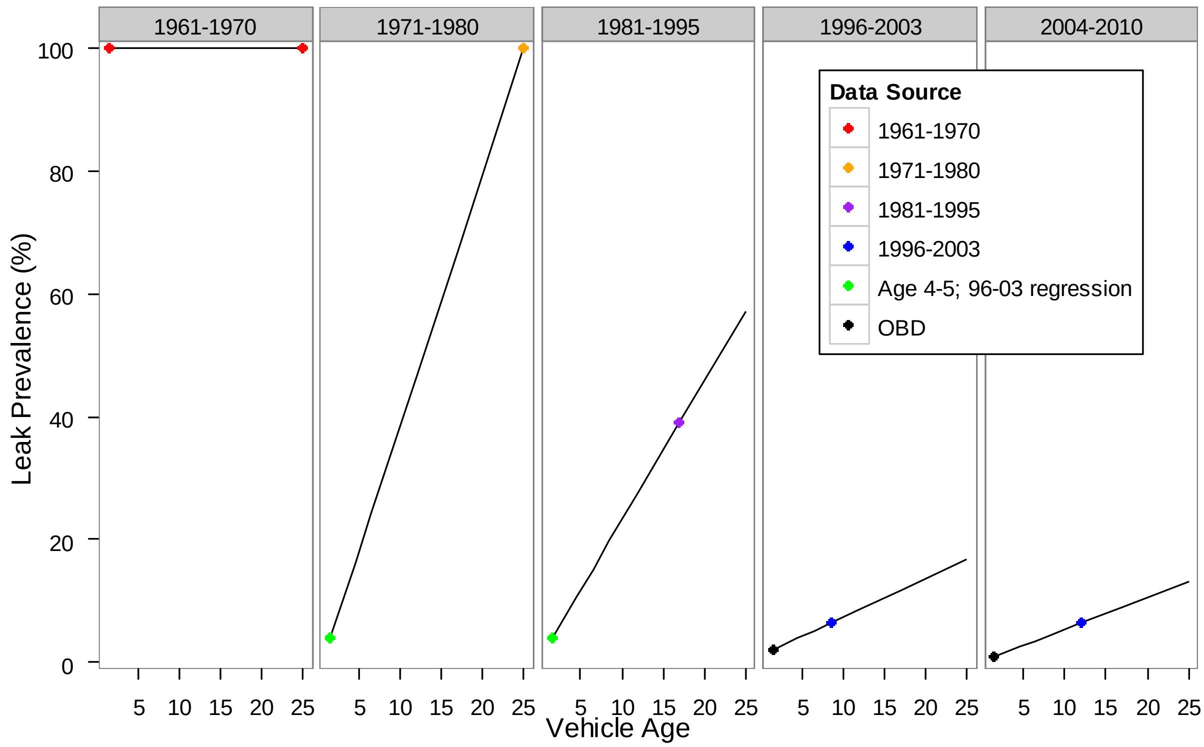
Because the data used to estimate leak prevalence was collected in Denver, Colorado at an altitude of 5,280 feet above sea level, measurements must be adjusted to sea level. At sea level, the amount of vapor generated will be less due to higher atmospheric pressure. To determine the appropriate correction factor, we performed the Wade-Reddy calculation and found that under identical conditions, the higher altitude will generate 41 percent more vapor. Colorado is a strategic location to perform a leak quantification program because a given vapor leak will produce higher levels of emissions at a higher altitude, therefore making it easier to detect. Each of the leak magnitude bins have been corrected for altitude by this factor. For example, the prevalence of leaks at 1g-2g levels in Denver will be the same prevalence of leaks at .71g-1.42g levels at sea level.

Because this was a cross-sectional study, we must populate the model for many model year and age group combinations that were not measured. A set of linear regressions was used to model vapor leak prevalence for ages and model years where data is not available. We divided model year groups in years when new technologies or standards were introduced. Modeling was based on the assumption that newer cars will have lower leak prevalence than older cars due to the advancing technology and use of more durable materials. Therefore, data from the 1996-2003 model year group was used as a surrogate for new vehicles in the 1971-1980 and 1981-1995 model year groups. However, because vapor leaks also occur due to tampering and mal-maintenance, deterioration is not the only factor involved in occurrence of vapor leaks. The regressions from the older model year show more rapid vehicle deterioration rates than newer model years.

Figure 9 shows the vapor leak prevalence as the percent of the vehicle fleet with a leak larger than 0.3g/15min. For model years 1996 and later, the estimate for leak prevalence at ages 0-3 was developed with I/M data from five states. The analysis revealed that 1-2 percent of vehicles consistently arrived at I/M stations with an evap Diagnostic Trouble Code (DTC) set. The vast majority of the DTCs set specifically indicated a vapor leak detected. The green diamonds in the 1971-1980 and 1981-1995 model year groups are an assumption made based on the 1996-2003 data to describe these vehicles' leak rates when they were new. The slope of the

2004-2010 prevalence rates was developed by applying the 5-10 year-old 1996-2003 data point to the 10-15 year old 2004-2010 point.

Figure 9: Non-IM Vapor Leak Prevalence, Extrapolated from data



Tier 3 and LEV III Leak Prevalence

To model the leak prevalence rates of LEV III and Tier 3 vehicles, the effectiveness of improved OBD systems and the efficacy of vehicle leak testing were quantified. In the above mentioned field study performed in Colorado, it was found that 70 percent of evaporative leaks were due to deterioration of the evaporative system (e.g. corroded fuel lines, filler neck, cracked hoses etc.) that could be improved with new design and material considerations. The remaining 30 percent of evaporative leaks were beyond manufacturer control. (e.g. Improper maintenance, tampering, missing gas caps, etc). See Table 14.

OBD effectiveness and OBD readiness are also important factors in the detection and repair of leaks after they occur. OBD effectiveness refers to the ability of diagnostic systems to identify leaks within the fuel system and alert the driver by illuminating a warning light. OBD readiness refers to the time during which vehicle diagnostics are actively assessing the integrity of the vehicle fuel system.

Our reference case assumed 40 percent OBD effectiveness and 95 percent OBD readiness. These numbers were based on an assessment of vehicles with OBD-detectable leaks and whether or not the leak was identified by the vehicle and the driver alerted via a check engine light. [38]

We estimated the implementation of LEV III would immediately reduce the 70 percent of deterioration-caused leaks by 33 percent simply due to the lower emissions standard. Longitudinally, we see reductions in leak prevalence associated with lower emissions standards. We also estimated that due to improved vehicle diagnostic systems, 80 percent of detectable leaks will be discovered and reported by the vehicle. In addition, we assumed that with the increased rigor of requirements the readiness will increase to 99 percent.

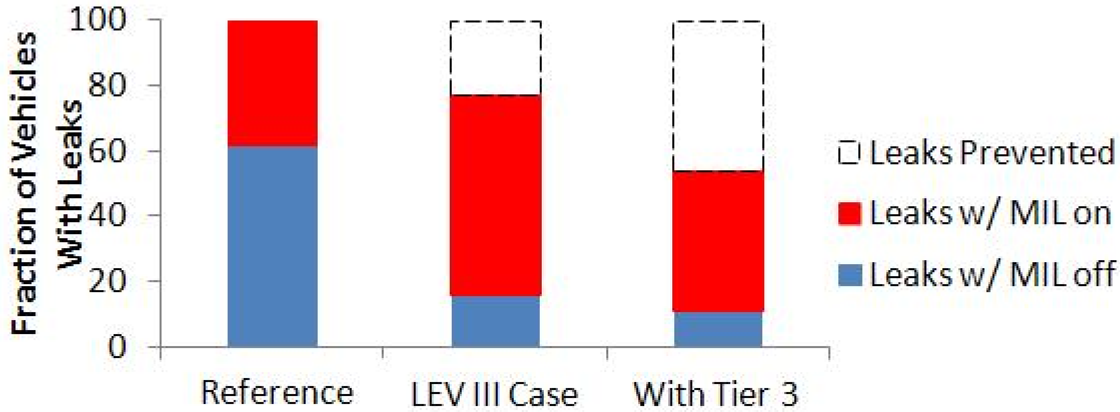
We estimated that the implementation of Tier 3 would immediately reduce the 70 percent of deterioration-caused leaks by 66 percent due to the additional benefit of the Tier 3 leak standard. As in LEV III estimates, we also estimated that 80 percent of detectable leaks will be discovered and reported by Tier 3 vehicles, as well as an increase of 99 percent readiness.

These estimates result in an overall reduction of leak frequency of 26 percent for the LEV III program and 49 percent for the Tier 3 program

Table 14: Summary of Tier 3 and LEV Assumptions

Base Inputs	
# of Leaks >0.020”	100
% Mal-Repair	30%
% Durability	70%
<u>Tier 2 Case</u>	
OBD Ready %	95%
OBD Effectiveness	40%
<u>LEV III Control Case</u>	
% of “durability” leaks prevented	33%
OBD Ready %	99%
OBD Effectiveness	80%
<u>Tier 3 Control Case</u>	
% of ”durability” leaks prevented	66%
OBD Ready %	99%
OBD Effectiveness	80%

Figure 10: LEV III, Tier 3 Leak Prevalence Estimates

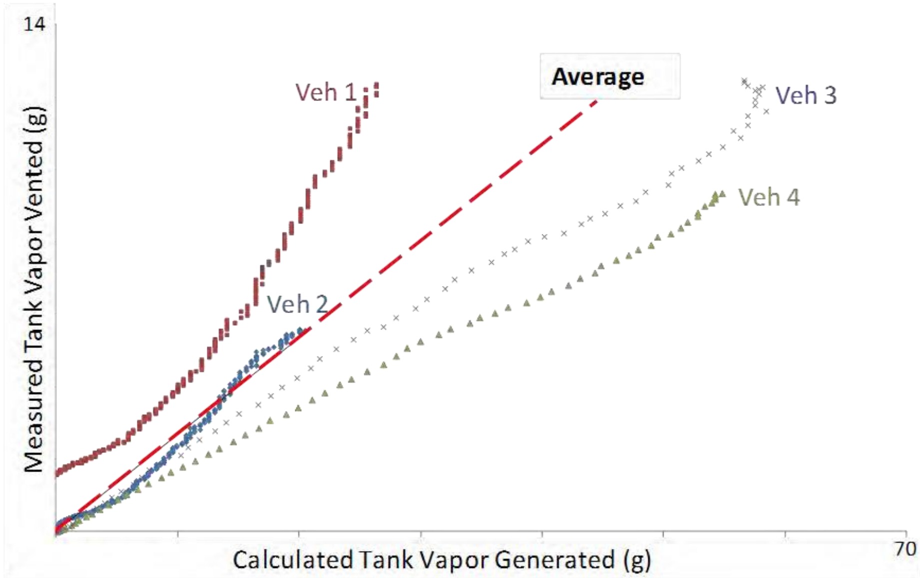


3.3.2.8 Vapor Leak Emissions

In MOVES2014 and later versions of MOVES, vapor leak emissions are calculated separately from the vapor emissions vented from the canister during normal operation. In some ways, vapor leaks and normal venting might be considered different processes or operating modes, but they are not formally distinguished in MOVES; the vapor leaks and normal venting emissions are combined before output and do not have unique identifiers.

It is important to characterize leaking emissions separately because they can potentially be orders of magnitude higher than normal venting described above. Unlike non-leak emissions, leak emissions can be modeled as a linear function with vapor generation. In Figure 11, measured vapor emissions are plotted on the y-axis against the calculated tank vapor generated. The average for four vehicles is overlaid and is used as the representative leak emission rate in MOVES.

Figure 11: SHED Leak Emissions for one Severity Bin



Vapor generated in the tank (TVG) is calculated using the Wade-Reddy equation (Equation 3-11), thus requiring fuel RVP, fuel ethanol content, and temperature data. Two datasets containing this information were used in developing leak emission rates. The E-77 suite of programs [6, 7, 8, 9] measured high-emitting vehicles, with known fuel properties and artificially implanted leaks, on the California (65◦F-105◦F) diurnal cycle. In another effort, the Colorado Department of Public Health and Environment (CDPHE) carried out a repair effectiveness program during the summer of 2010 in collaboration with the Regional Air Quality Council (RAQC). This program [39] measured 16 vehicles with identified leaks. A 6-hour test was performed with a temperature increase of 72◦F- 96◦F. This effort was less resource-intensive than the full diurnal procedure and still provides the necessary information to calculate TVG. The SHED measurements of Tank Vapor Vented (TVV) and calculated TVG form the basis for a linear regression of TVV vs. TVG for each vehicle. The resulting slope represents the mass of vapor vented per mass of vapor generated. The average of the regressions becomes the leak rate for that severity bin. This approach can be observed in Figure 11. This test procedure could not distinguish permeation and leak vapor emissions. However, permeation for these vehicles is assumed to be negligible during the 6-hour test given the severity of the leak emissions. In the E-77 program, TVV emissions were collected in a canister external to the SHED. The external canister was connected to the vent on the vehicle canister. No permeation was included in the measurement.

Because the emissions measured were highly variable, spanning several orders of magnitude, the emissions data for leaking vehicles was binned by magnitude. Accordingly, both emission rates and prevalence were calculated within these bins. As the leak prevalence estimates were measured at high altitude in Denver, it is essential to develop adjustments to apply the binning process at lower altitudes, such as sea level. Application of the Wade-Reddy equation (Equation 3-11) suggests that an E10 fuel in Denver generates 1.41 times as much vapor as at sea level. For example, a vapor leak at 0.3g/15min in Denver would have an equivalent rate of 0.21g/15min at sea level. The bins used to categorize leak severity as well as the average leak emission rate for that bin are listed in Table 15.

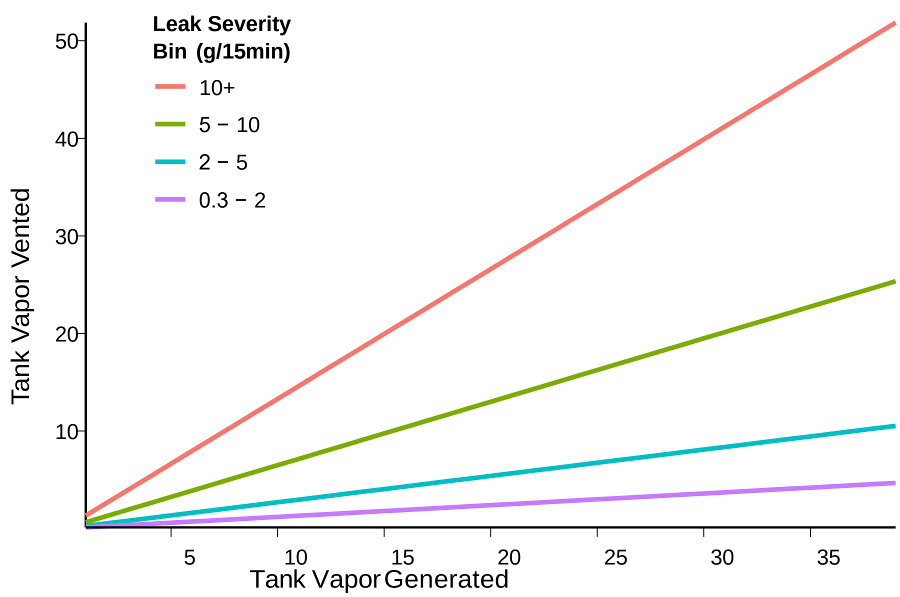
Table 15: Leak Emission Rates by Bin

Denver bins (g/15min)	Sea Level bins (g/15min)	Average Ratio of Grams vented / Grams generated
0.3 - 2	0.2 - 1.4	0.12
2 - 5	1.4 - 3.6	0.27
5 - 10	3.6 - 7.1	0.65
>10	>7.1	1.33

Each data point was binned by its hot soak measurement from the E-77 programs or PSHED. (Portable SHED) measurement from the Denver program. The PSHED tests are 15-minute hot soak measurements.

Figure 12 illustrates the leak emission rates for each leak severity bin. The average emission rate for vehicles with 15-min hot soak measurements greater than 10g exceeds 1. It is possible to measure more fuel vapor in the SHED than is calculated with Equation 3-11 It is known that the equation is less reliable at higher temperatures. Also, complicated factors such as fuel sloshing and tank geometry can influence vapor generation beyond the estimation capabilities of the Wade-Reddy equation.

Figure 12: Leak Emission Rates by Leak Severity Bin



An average emission coefficient for an “average severity” leak (Table 16) was computed based on the prevalence information in Section 3.3.2.7. These values are recorded in the leakEquation field in the cumTVVCoeffs table of the MOVES default database.

Table 16 Leak Emission Coefficients

Regulatory Class	Model Years	Age Group	Leak Coefficient
All Except Motorcycles	1960-1970	20+	0.952
	1971-1977	10-14	0.782
		15-19	0.79
		20+	0.796
	1978-1995	0-3	0.524
		4-5	0.408
		6-7	0.388
		8-9	0.376
		10-14	0.365
		15-19	0.357
		20+	0.351
	1996 and Later	All	0.524
Motorcycles	All	All	0.814

Then the estimated vapor venting from leaking for each of soaking day is a multiplicative function of the first day vapor generation (TVGDaily) as shown in Equation 3-13.

LeakEmissions = LeakCoefficient * TVGDaily	**Equation 3-12**

TVGDaily is the same for each soakDayID, and is also the same as X_n[soakDayID=1] (see below), such that TVGDaily = tvgSumIH.

3.3.2.9 Tank Vapor Venting Equation

For normally operating non-leaking vehicles, tank vapor vented (TVV) from the canister was calculated. First MOVES estimates the quantity of vapor generated using Equation 3-11 in g/gal-headspace, based on the maximum temperature for the day, interpolated for the appropriate altitude and gasoline ethanol level, and allocated to hour of the day.

The model then estimates the vapor vented for consecutive days of parked (soak) activity. The algorithm accounts for average canister capacity (ACC) and backpurge factor. Daily backpurge removes fuel vapors from the canister, increasing capacity to store vapor generated during successive days. Vapor generated above the ACC is lost to the atmosphere, therefore backpurge only applies to what remains in the canister. For each hour of continuous parking time, the model calculates the vapor generated on soak day "n", represented as X_n in Equation 3-13 below.

X_n[soakDayID=1] = tvgSumIH X_n[soakDayID=2] = ((1-backPurgeFactor)*least(tvgSumI24,averageCanisterCapacity)) +tvgSum1H Xn[soakDayID>2] = ((1-backPurgeFactor)*least(Xn[soakDayID-1] + tvgSumH24,averageCanisterCapacity))+tvgSum1H	**Equation 3-13**

X_n is calculated for soak days 1 through 5. Beyond five days, the algorithm assumes that breakthrough has occurred and that behavior over additional days has stabilized. The vapor emissions are fleet averages by model year group. Vapor venting emissions rises on successive days as more vehicles exceed their canister capacities and begin venting fuel vapors.

The vapor generated values are then summed for each hour. The vapor leak and the cold soak emissions are totaled using the following equations for vehicle groups with and without relevant Inspection and Maintenance (I/M) programs.

tankVaporVented = (1-leakFraction)*(TVV equation) + leakFraction*(Leak equation). tankVaporVentedIM = (1-leakFractionIM)*(TVV equation) + leakFractionIM*(Leak equation).	**Equation 3-14**

Where:

leakFraction is the appropriate leak prevalence as described in Section 3.3.2.7

TVV equation is a function of Xn as listed in the leakEquation field in the *cumTVVCoeffs* table of the MOVES default database.
Leak equation is the result of Equation 3-13, above.
leadFractionIM is the leak prevalence described in Section 3.4.2.

For more detail on the vapor venting calculations, see the MOVES code at *database\MultidayTankVaporVentingCalculator.sql* and documentation of the DELTA pre-processor.[32]

3.3.2.10 Activity

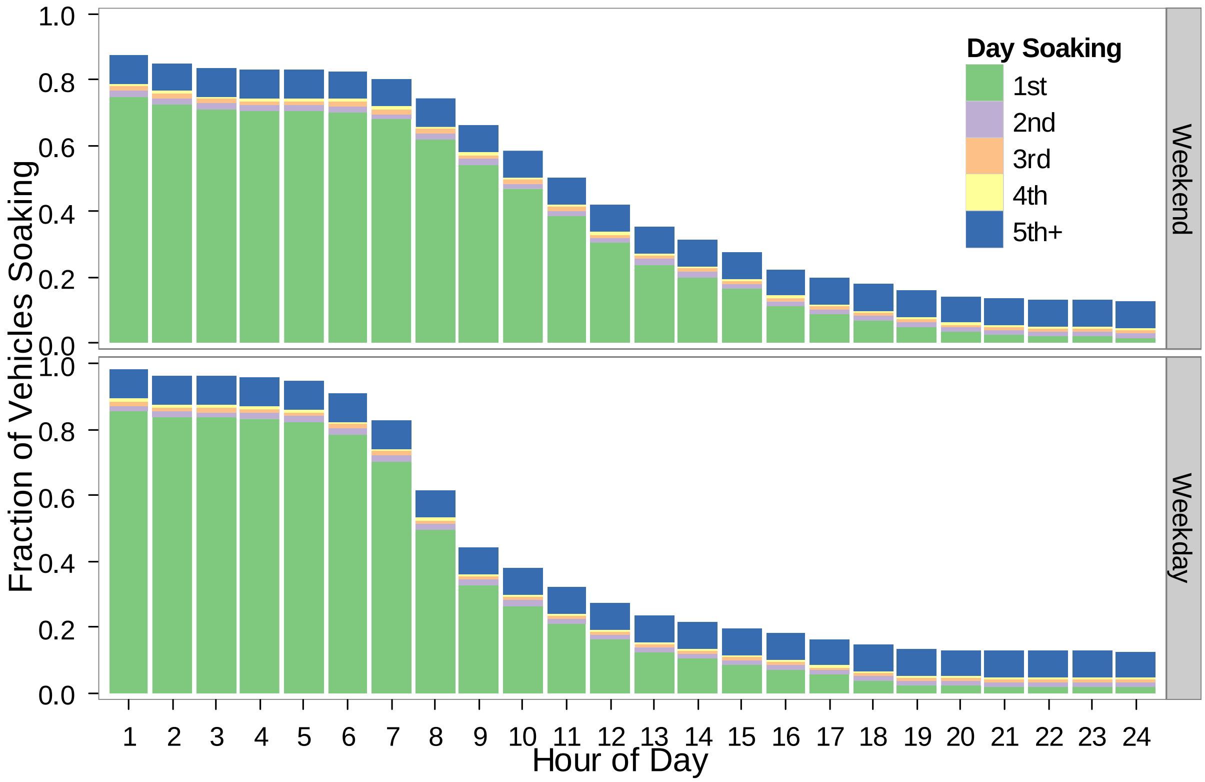
In order to properly account for off-cycle emissions, MOVES must account for the different emissions rates of short (several hours) and long (multiple day) soaks. For any modeled day, there is a sub-population of vehicles exhibiting 1st, 2nd, 3rd, nth day diurnal emissions. The fractional allocations for 1^{st}, 2^{nd}, 3^{rd}, and nth day diurnals are calculated from the sampleVehicleTrip and sampleVehicleDays tables in MOVES. SampleVehicleTrip assigns numbers of first starts during each hour of the day. For the fraction of vehicles having soaked since at least midnight, the first engine start ends the cold soak episode. SampleVehicleDay contains the population of vehicles for each sourceTypeID.[40] Combining information for both tables, it is simple to calculate the fraction of vehicles having soaked since midnight at any given hour. For example, at 1:00AM, some fraction of vehicles less than 100 percent have not yet started. The fraction continuously decreases throughout the day as more and more vehicles start. At 12:00AM, the fraction only represents vehicles that were not driven.

Once the fraction of vehicles soaking at a given hour has been calculated, it must be estimated how many prior days each has been soaking. We classify vehicles as 1^{st} day, 2^{nd} day, 3^{rd} day, 4^{th} day, or 5+ days. We assume that after the 5^{th} day, vehicles will exhibit repeat emissions since the evaporative canister will either have broken through or be in conditions that will never cause breakthrough. An activity study performed by Georgia Technological University [41] suggest that 16 percent of vehicles drive less than 3,000 miles per year. The MOVES inputs are based on the conservative estimate that 50 percent of these low-mileage vehicles, or 8 percent of all vehicles, have been soaking for more than 5 days on any given day.

The sampleVehicleSoakingDayBasis table establishes the fraction of vehicles soaking for 5+ days. It contains five values, one for each soak day. The value for SoakDayID 1 is the percentage of vehicles soaking at the final hour of day 1. The product of SoakDayID=1 and SoakDayID=2 is the percent of vehicles soaking at the final hour of day 2. The product of all five values is the percent of vehicles soaking for five days or longer.

Figure 13 presents the fraction of soaking vehicles throughout the day. The majority of vehicles were driven the previous day and are on their first day soaking. The fractions of vehicles on 2nd through 4th day soaking are developed from the remainder of 1st day soaking vehicles at hour 24. The fraction of vehicles soaking for 5 days or longer is 8 percent at hour 24. This method models bimodal vehicle usage, with most vehicles being driven almost daily and the remaining vehicles being driven more intermittently.

Figure 13. Passenger Car Soak Distribution on a Weekday



3.3.3 ***Hot Soak***

Hot-soak vapor emissions begin immediately after a car ceases operation and continue until the fuel tank reaches ambient temperature. In MOVES, the process of calculating hot-soak vapor emissions is simpler than that for cold soak. Base rates exist for each model year and age group and are expressed in units of grams per hour. They represent emissions at sea level with RVP assumed at 9.0 psi. In developing the rates, leak and non-leak rates are weighted together to form the base rate, similar to cold soak.

3.3.3.1 Hot Soak Data

Hot soak data comes from several programs with diverse testing procedures, vehicle model years and technology, fuel parameters, and altitude. These programs include three summer programs in Colorado and the E-77-2 programs in Arizona. See Table 17.

Table 17: Hot Soak Evaporative Test Programs

Program	Location	Hot Soak Length	Fuel RVP	Altitude (ft)	No. Obs.
High Evap	Lipan IM station, CO	15 min	Fuel Supply	5130	100
High Evap	Ken Caryl IM station, CO	15min	Fuel Supply	5130	175
High Evap	Denver IM station, CO	15min, 1 hour	Fuel Supply	5130	100
E-77-2	Mesa, AZ	1 hour	7, 9, 10	1243	100

As explained below, the data collected in these programs was adjusted to the MOVES baseline of a one-hour rate on 9.0 RVP fuel at sea level.

In addition, some tests were removed from our analysis. The vehicles in Colorado that participated in the studies were recruited in-situ and therefore were subject to a wide range of leak mechanisms. It was observed that some vehicles emitting more than 50 grams in 15 minutes in the PSHED had liquid leaks present. All vehicles with a calculated 15-minute measurement greater than 50g/15min were removed from vapor leak analysis.

Furthermore, vehicles in the E-77 program were tested multiple times with different fuels, whereas each vehicle in the Colorado population was tested once. In order to not over-represent the E-77 vehicles in our sample, one measurement from each vehicle was selected with preference given to the measurements on 9 RVP, E10 fuels (where available).

3.3.3.2 Test Duration Conversion

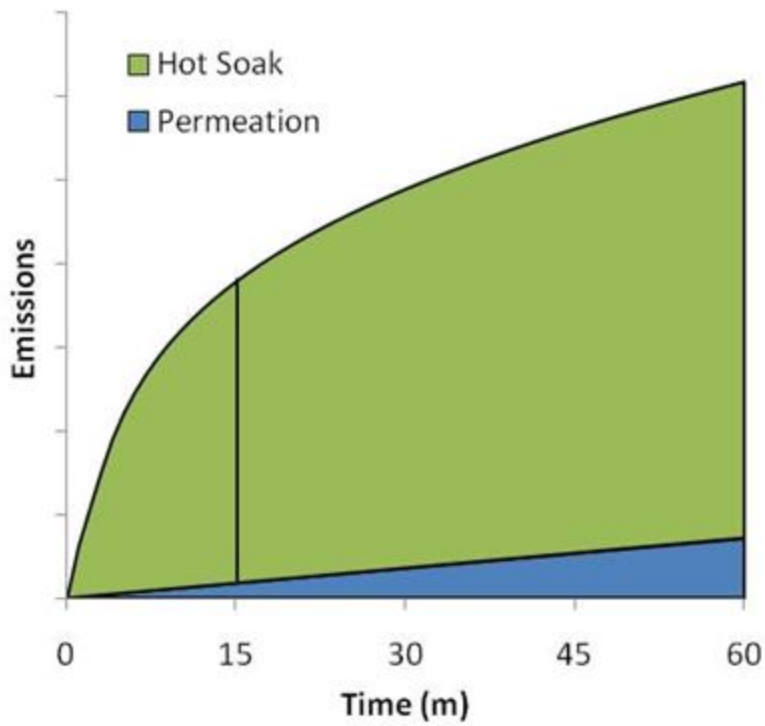
Every datum required a 15-minute mass and a one-hour mass because base rates in the MOVES input table must be expressed in grams per hour; however, our method for distinguishing leaks from non-leaks uses the 15-minute rate. Furthermore, if a measurement is designated as from a leaking vehicle, the 15-minute measurement is used to project its rate of occurrence in the fleet.

Because engines and fuel systems do not cool at a uniform rate, existing data was used to develop this test-length conversion factor. In the E-77 suite, the cumulative time series data for hot-soak tests on a minute-by-minute scale was readily available, enabling estimation of vapor emissions over 15 minutes. Each set of vehicle data also contained a permeation rate. The permeation rate was subtracted from the 15-minute hot soak measurement. The result is the assumed vapor emissions during 15-minutes of hot soak. Similarly, hourly permeation was subtracted from the 1-hour hot soak measurement. After compiling the 15-minute and 1-hour values, the fraction of emissions occurring in the first 15 minutes can be calculated.

All of the Denver testing programs provided similar vehicle measurements to augment the E-77 dataset. A subset of the vehicles were transported to a lab to receive a Hot Soak test. Readings were taken at both 15 and 60 minutes.

Figure 14 illustrates the evaporative emissions occurring during a Hot Soak test. Vapor emitted by permeation is assumed to accumulate at a linear rate while vapor emissions attributed to the hot soak accumulate rapidly following engine shutoff but more slowly as the engine cools.

Figure 14: Cumulative Hot Soak and Permeation Emissions



Using the combined data from E-77 and Denver testing, we estimated the average fraction of emissions in the first fifteen minutes following engine shutoff. At first, it was thought that this fraction would vary among groups of vehicles certified to different evaporative standards. However, analysis of test results by certification groups did not seem to yield notably different results. Instead a single fraction developed from all available data was applied fleet-wide. It was estimated that 54 percent of emissions from a one-hour hot soak occur in the first 15 minutes. Conversely, emissions from a 15-minute hot soak must be multiplied by 1.85 to estimate a full hour's emissions.

3.3.3.3 Correction for RVP and Altitude

MOVES base emission rates are intended to represent emissions on 9.0 RVP gasoline at sea level so, the hot soak test data must also be corrected to account for the RVP and altitude of each test.

Emissions in the available datasets were measured at varying levels of RVP. Some programs recorded RVP, while other data has no explicit RVP information. Our first step is to estimate the RVP for all measurements that do not contain this information.

The majority of the data with unknown RVP was gathered in the summer months in locations with available fuel survey data. The mean RVP for June through August 2010 in Denver was

8.40 RVP (standard deviation 0.20 RVP), and this value was assumed for all vehicles tested from May through September. For non-summer months, RVP information was collected with a small subset of the vehicle measurements. In the case of a non-summer measurement without RVP information, the mean of all non-summer months is assumed. The mean RVP for non-summer vehicles is 10.67 (standard deviation 1.75 RVP). The testing at the Lipan station was all performed in the summer, so the RVP of the Lipan dataset is assumed to be 8.4.

Associating an RVP value with every measurement enables calculation of corrections for altitude. All vehicles were tested either in Colorado (Elev. = 5,130 ft) or Mesa, AZ (Elev. = 1,243 ft). Both locations are far enough above sea-level that it would be erroneous to assume their emissions are representative of sea-level emissions. Our approach is to use the E10 values in Table 10 to solve the Wade-Reddy equation (Equation 3-11) for RVP and thus calculate the equivalent RVP at sea level that would generate the same amount of emissions as measured at higher altitude, as shown in Equation 3-15

$$RVP_{SeaLevel} = \left(\frac{1}{B_{SeaLevel}}\right) * ln\left(\frac{TVG_{high}}{A_{SeaLevel} * (e^{C_{SeaLevel}*T_1} - e^{C_{SeaLevel}*T_0})}\right)$$	**Equation 3-15**

This approach requires the assumption that vapor emissions will increase/decrease proportionally to vapor generation. As a rule, to generate the same amount of vapor at high altitude as generated at sea level, a fuel will have a lower RVP. Also, after a Monte-Carlo analysis of varying starting and ending temperatures, the effect of either was found to be negligible within the conditions these vehicles are likely to experience during testing. Therefore, temperatures T0 = 60˚F and T1 = 65˚F were chosen for this analysis.

The Wade-Reddy equation provides no coefficients for Mesa, AZ elevation so the adjustment is a simple linear interpolation between Sea Level and Denver elevations. For example, to solve for the TVG_{high} used in Equation 3-15 corresponding to Mesa, Equation 3-16 was used.

$$TVG_{Mesa} = TVG_L + \left((TVG_H - TVG_L) * \frac{Elevation_{Mesa}}{Elevation_{Denver}}\right)$$	**Equation 3-16**

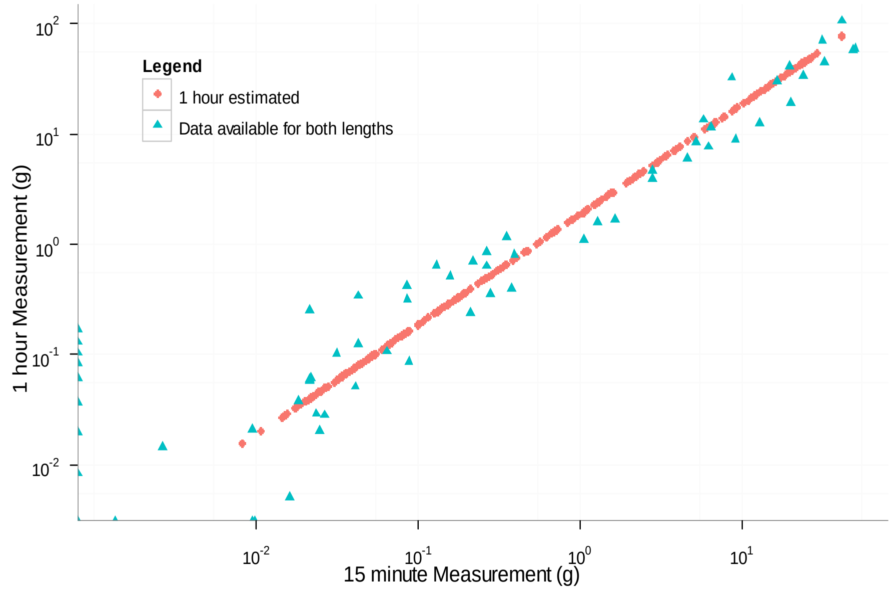
Thus, every measurement was paired with an RVP value that would generate the same emissions at sea level. The next step was to estimate the emission result on fuel with an RVP of 9.0 psi.

In order to calculate an adjustment for each measurement, the same assumptions were employed as above. Using the same temperature values, vapor generated at the sea level RVP and at 9.0 RVP was calculated. Using Equation 3-17, the ratio between these two values was applied to the original emission measurements to calculate the base MOVES emission rate.

$TVG_{measRVP} = A_{SeaLevel}e^{B_{SeaLevel}*RVP_{meas}}(e^{C_{SeaLevel}*T_1} - e^{C_{SeaLevel}*T_0})$ $TVG_{MOVES} = A_{high}e^{B_{high}*9.0}(e^{C_{high}*T_1} - e^{C_{high}*T_0})$ $HotSoak_{MOVES} = HotSoak_{Measured} * \left(\frac{TVG_{measRVP}}{TVG_{MOVES}}\right)$	**Equation 3-17**

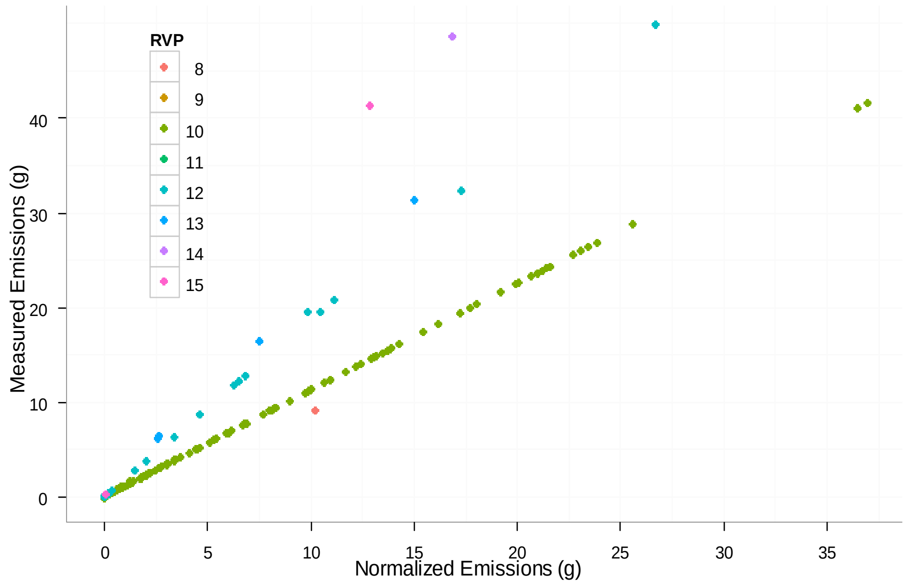
Thus, for each measurement we have an estimated emission rate for both 15 minutes and 60 minutes, at sea level, with 9 RVP fuel. As a quality check, the results of our 15-minute emissions to 60-minute conversion and the results for data at both durations are plotted in Figure 17. As expected, the estimated hourly emissions (red circles) from the 15-minute measurements closely match the measurements (blue triangles) where data at both test lengths were available.

Figure 17: Hot Soak Measurement Test Length



Quality assurance checks were also performed on the emissions values before and after calculating their equivalences at Sea Level and 9.0 psi fuel. As expected, the tests measured with higher RVP fuels at high altitude were reduced by wider margins under the influence of the two corrections.

Figure 18: Hot Soak Measurement Normalization to 9.0 RVP



3.3.3.4 Extrapolation to Missing Model Years and Ages

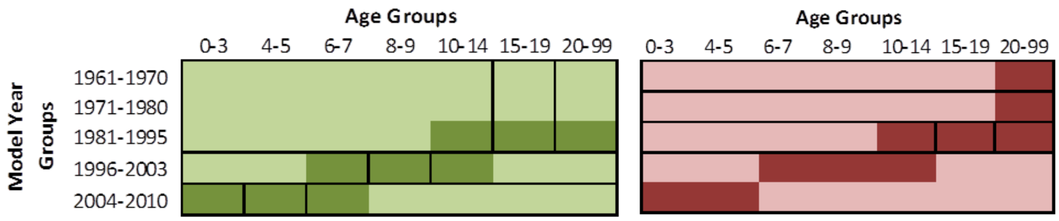
After normalizing the complete dataset, the results were incorporated into the MOVES database. In the MOVES emission rates tables, emission rates must exist for all model year and age group combinations. As with most cross-sectional datasets, this required additional modeling. For example, there is no data for 20-year-old, model year 2010 vehicles, or brand new 1980 vehicles. To address this problem, we extrapolated the emission rate values. Table 18 describes the data.

Table 18: Hot Soak Measurements by Model Year and Age

		Age Group														
		0-3		4-5		6-7		8-9		10-14		15-19		20+		
	Leak?	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	**Total**
Model Year Group	1961-1970														5	5
	1971-1980														8	8
	1981-1995									6	15	46	55	8	39	169
	1996-2003			1		26	6	36	6	53	30					158
	2004-2010	12	3	26	2	5										48
	Total	12	3	27	2	31	6	36	6	59	45	46	55	8	52	388

In ranges where no data was collected, leak and non-leak measurements are extrapolated from similar MY/age groups. In MY/age groups where very small amounts of data were collected, the measurements are combined with similar MY/age groups. Figure 18 illustrates how we populated model year and age group emission rates where there was no data.

Figure 19: Measurement Averaging

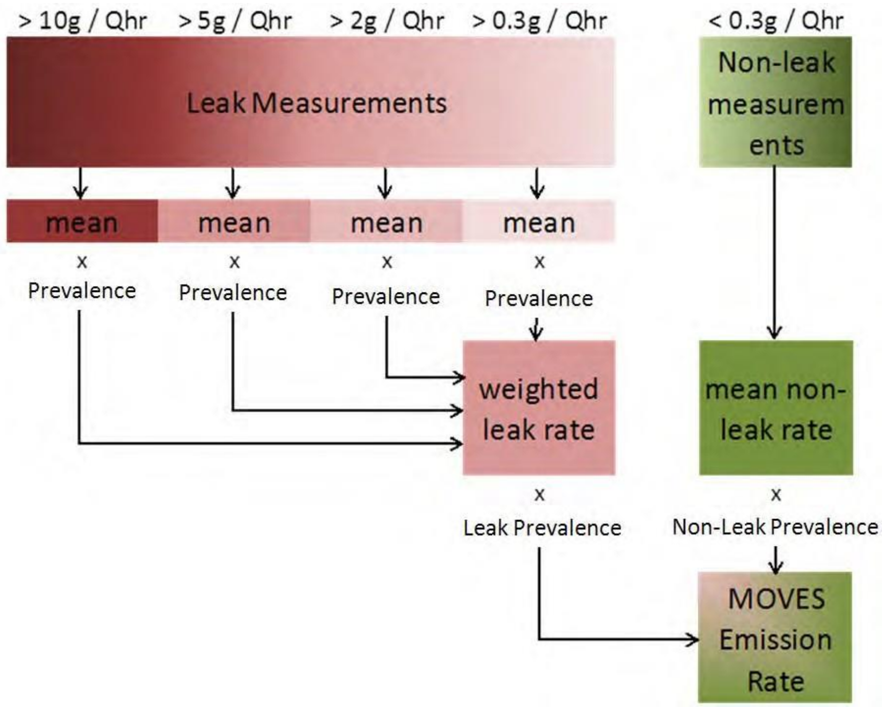


(a) Non-Leak (b) Leak

- A darker shaded cell represents a bin where data is present.
- An enclosed area represents one rate. The rate is calculated by averaging all enclosed data.

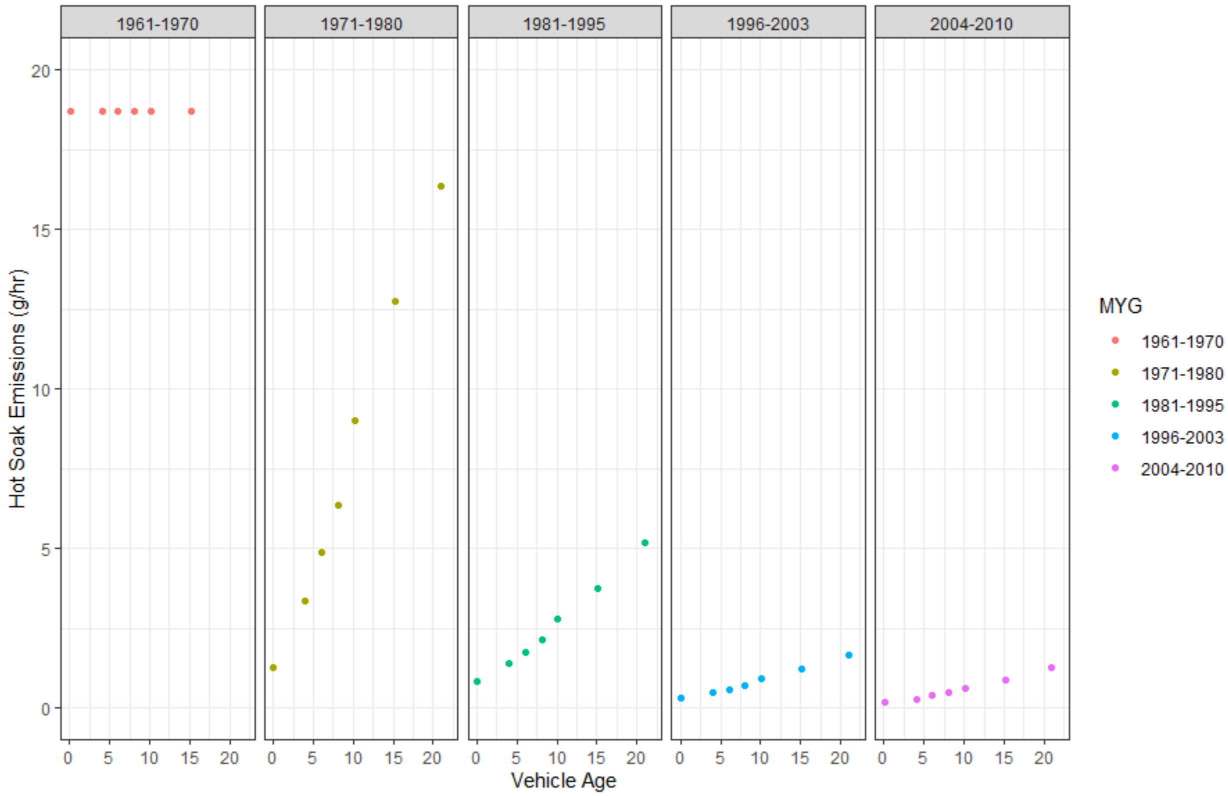
For example, one non-leak rate exists for model years 1996-2003, ages 0-7. The rate is calculated by averaging available data, which only exists at age 6-7. For every model year and age group, there is a leaking rate and non-leaking rate. The two rates, weighted by leak prevalence, form the average hourly hot soak emission rate for a given bin. Figure 20 demonstrates how leak rates and non-leak rates are combined to form a final weighted rate for a given model year and age combination.

Figure 20: Calculate Weighted Evaporative Emissions



For every model year and age group combination, the calculation outlined in Figure 20 is performed. Figure 21 shows the Hot Soak rates. The inclusion of leaking vehicle resulted in higher emissions, particularly for older model years where leaks are more prevalent.

Figure 21: Hot Soak Emission Base Rates (9.0 RVP at Sea Level)



3.3.4 ***Running Loss***

3.3.4.1 Pre-Tier 2 Emission Rates

Running Loss emissions consist of vapor venting during vehicle operation. Data used to develop running loss emission rates for Pre-Tier 2 vehicles is from CRC E-35[13] and CRC E-41.[14, 15] These two programs tested 200 vehicles with model years ranging from 1971-1997.

For each vehicle, fuel tank temperature was calculated at the end of the running loss test using the fuel tank temperature algorithm (See Section 3.1). The running loss test performed in E-35 consisted of a UDDS, a two minute idle, a New York City Cycle (NYCC), a two minute idle, a second NYCC, a two minute idle, a UDDS, and a final two minute idle.

The data was filtered/reduced such that each test meets the following requirements:

1. Non-liquid-leakers (emissions <137.2 g/hour[d])
- As received vehicles (no retests)
- Fuel system pressure test result must be pass, fail, or blank

The average tank temperature was calculated by assuming a linear increase in temperature.

[d] Converted from 7.0 g/mile used in MOBILE6 [36]

Thus, the average is calculated by averaging the start temperature of the test and the final temperature. The average temperature is used to estimate the permeation rate using default permeation rates and the permeation temperature adjustment.

Gram/hour rates were calculated by dividing total emissions by the duration of the running loss test (4300 seconds). Permeation was subtracted for each hour to segregate tank vapor venting (TVV) emissions. After analysis of the TVV data, running loss TVV rates were distinguished by model year only. Table 19 shows the results of the analysis.

An I/M effect was not observable from this data, so the MOVES running loss TVV rates for I/M and non-I/M are the same.

Table 19: Pre-Tier 2 Running Loss Emission Rates by Model Year and Age

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

3.3.4.2 Tier 2 & Later Emission Rates

Running loss emission rates for Tier 2 and later vehicles were developed from a 2014 study of five Tier 2 vehicles.[30] In this study, vehicles were tested at two fuel RVP levels (7.51 psi and 10.33 psi) with and without implanted vapor leaks. Vapor leaks were installed at either the canister or top of fuel tank, and with either 0.020" or 0.040" diameters, for a total of 4 possible leak configurations. The canister and fuel tank locations were chosen due to their high rate of occurrence in the fleet.[39]

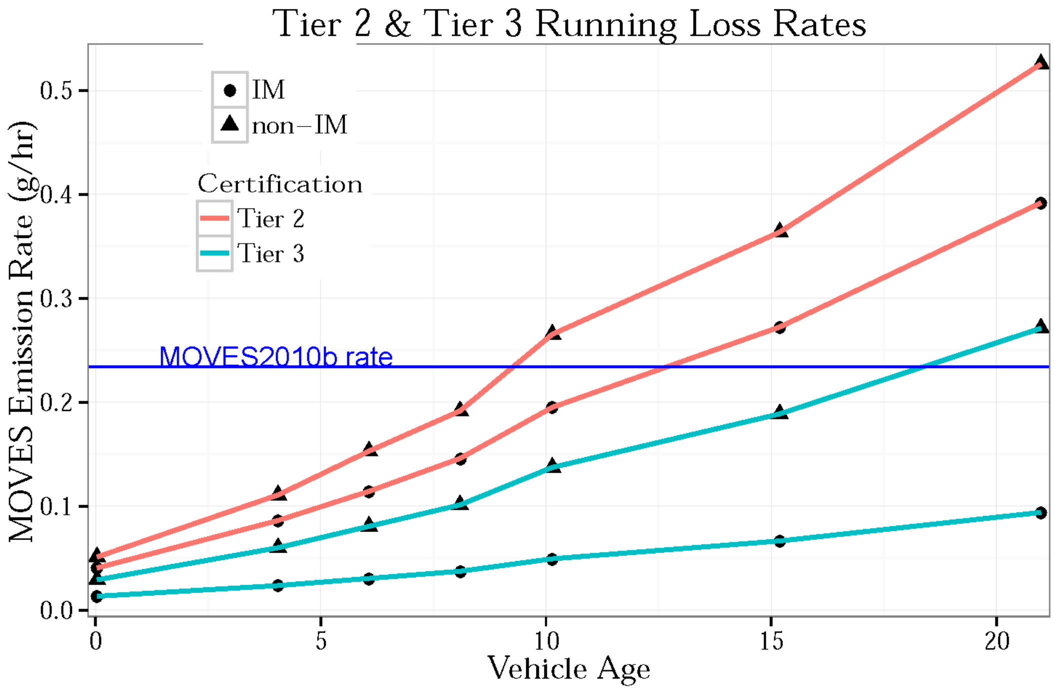
MOVES running loss emission rates are expressed in grams per hour and with a fuel vapor pressure of 9 psi. Results from this testing are expressed in grams per test (4300 seconds) and at two fuel vapor pressures (7.51 and 10.33). Therefore, the reported results must be normalized to MOVES dimensions.

As in the development of Pre-Tier 2 emission rates, gram/hour rates were calculated by dividing total emissions by the duration of the running loss test (4300 seconds). The measurements were then adjusted to a 9-RVP equivalent emissions measurement using the equations and coefficients described in Section 3.3.4.3.

Because our determination of a given vapor leak's rate of occurrence among all vapor leaks is based on its hot soak emissions, each running loss test was immediately followed by a standard one-hour hot soak procedure. Using the same process as in Section 3.3.3.2, the one-hour hot soak results were multiplied by .54 to estimate the emissions at the 15 minute point. With this result, each measurement was binned and the weighted average leak emissions rate determined.

Using the average non-leak value, the weighted average leak value, and the leak prevalences from Section 3.3.2.7, an average emissions rate is calculated. Tier 2 and later running loss emission rates are the first running loss rates in MOVES to account for vapor leak emissions. Tier 3 rates were estimated using ratios to Tier 2 standards. The resulting running rates are shown in Figure 22.

Figure 22: Tier 2 & Tier 3 Running Loss Rates



3.3.4.3 Running Loss Fuel & Temperature Effects

Running Losses are affected by both temperature and fuel Reid Vapor Pressure (RVP). The adjustments used in MOVES3 are taken from MOBILE6 and are applied to all model years and source types. MOBILE6 was run for a series of temperatures and RVP levels for passenger cars. A linear model was fit to the MOBILE6 results. The mean base emission rates for running losses in MOVES are recorded in the *'EmissionRateByAge'* table. Running loss rates were assumed to be measured at 9 RVP and 95˚F. The results from MOBILE6 were normalized to the MOVES emission rates as multiplicative adjustments to the mean base rates. For example, a multiplicative adjustment of 1 would be applied to a 9 RVP fuel at 95˚F.

The running loss adjustments:

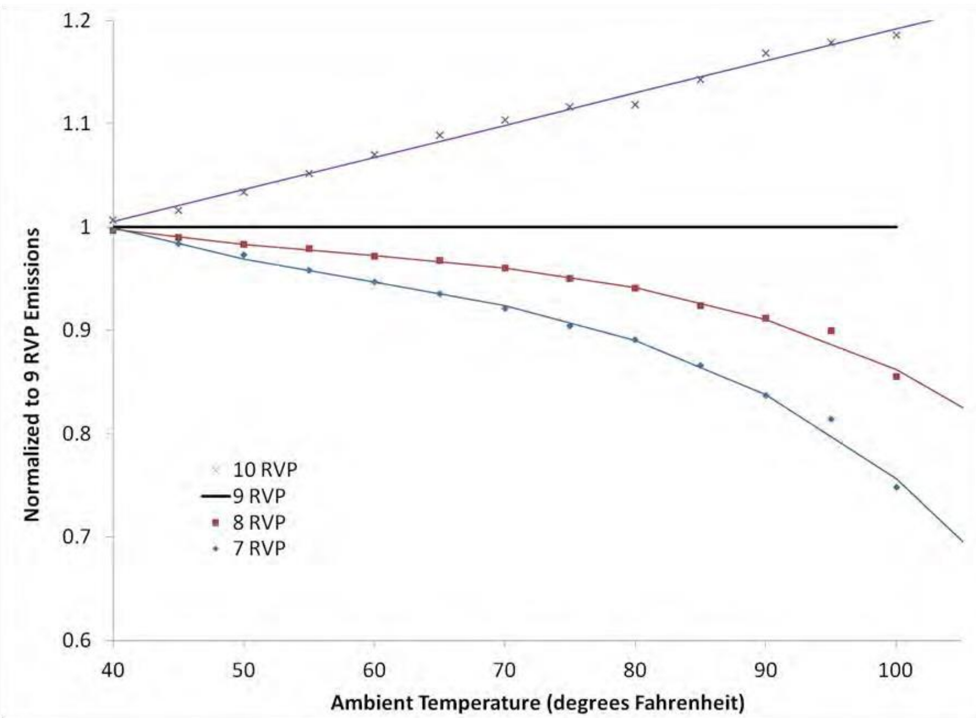
- Are multiplicative adjustments.
- Apply to all gasoline source types and model years.
- Are the same at temperatures at or below 40˚F.

- Are applied as a function of both RVP and ambient temperature.
- Use the 7 RVP coefficients for RVP values below 7 psi.
- Use the 10 RVP coefficients for RVP values above 10 psi.
- Are not adjusted for RVP at temperatures of 40˚F or below.

$$AdjustedRunningLoss = RunningLoss * Adjustment(Temperature, RVP) \quad (12)$$

The adjustment coefficients are recorded in the evapRvpTemperatureAdjustment table in the default MOVES database. The RVP adjustment range is dynamic; if new sets of coefficients for RVP values greater than 10 or less than 7 are added to the table, MOVES will use those values and set new minimum and maximum RVP values. Figure 23 shows the calculated adjustment values.

Figure 23: Running Loss Temperature and RVP Effect



3.4 *Inspection/Maintenance (I/M) Program Effects*

Inspection and Maintenance program efforts vary in their procedures for testing evaporative emissions. Some locations use a fill pipe pressure check and gas cap check, others use just a scan of the onboard diagnostics (OBD), and others will use all three approaches. These types of tests are not expected to reduce permeation or liquid leaks and do not guarantee the detection of a vapor leak within a vehicle. MOVES assumes tank vapor venting is the only evaporative process where I/M benefits are realized.

The I/M effects for evaporative emissions are calculated as a function of three types of information:

- I/M program coverage, which describes program coverage by location and year (see the MOVES Emissions Adjustments report[42]),
- I/M factor which describes the relative effectiveness of different I/M program designs for different vehicles (see Section 3.4.1)
- Vapor venting emission rates with a reference I/M program, in comparison to rates with no program. For the cold soak operating mode (opModeID =151) These are calculated based on differences in leak prevalence as explained in Section 3.4.2. For hot soak (opModeID=150) and running loss (opModeID=300), they are calculated based on rates in the EmissionRateByAge table.

3.4.1 *I/M Factor (Relative Program Effectiveness)*

In MOVES, the I/M factor describes the relative effectiveness of an I/M program; a higher I/M factor indicates a more effective I/M program. This data is stored in the MOVES IMFactor table for gasoline and E85 passenger cars, passenger trucks and light commercial vehicles. The I/M factors vary with inspection frequency, type of test (testStandardsID), model year group and vehicle age.

Data from four I/M programs were used in the development of MOVES I/M factors for evaporative emissions. The Phoenix, AZ program contained the most extensive data, so we have used it to represent a reference condition relative to which other programs can be assessed. Data from programs in Tucson, AZ, Colorado, and North Carolina were used to determine the effectiveness of other I/M program designs. See Table 20.

Table 20: Description of I/M Programs [43]

Location	Gas Cap Test	OBD	Pressure test	Frequency	Network	Years
Colorado	Y	Advisory	N	Biennial	Hybrid Annual	2003-2006
N. Carolina	N	Y	N	Annual	Annual	2002-2006
Phoenix	Y	Y	Y	Biennial	Centralized	2002-2006
Tucson	Y	Y	N	Annual	Centralized	2002-2006

In order to develop I/M factors, failure data was used from I/M programs. These failure frequencies were only used to estimate the relative effectiveness of differing evaporative I/M programs. They were not used to model the actual prevalence of evaporative leaks. For information on the modeling of vapor leak prevalence please see Section 3.3.2.7. For information on liquid leaks, see Section 3.5.

The Phoenix evaporative I/M program performed 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 assign evaporative failures are listed in Table 21for all vehicle makes and additionally P1456 and P1457 for Honda and Acura vehicles. Vehicles with 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, the total number of failures is the sum of gas cap and pressure/OBD failures.

Table 21: OBD Evaporative Emission Trouble Codes

OBD Code	Description
P0440	Evaporative Emission Control System Malfunction
P0442	Evaporative Emission Control System Leak Detected (small leak)
P0445	Evaporative Emission Control System Purge Control Valve Circuit Shorted
P0446	Evaporative Emission Control System Vent Control Circuit Malfunction
P0447	Evaporative Emission Control System Vent Control Circuit Open
P1456	EVAP Emission Control System Leak Detected (Fuel Tank System)
P1457	EVAP Emission Control System Leak Detected (Control Canister System)

To determine the reference program effectiveness, we estimated failure frequencies with I/M and without I/M ("non-I/M"). The I/M failure frequencies were developed from the Phoenix data using initial and final results for a vehicle in a given I/M cycle. For passing vehicles, the initial and final tests are the same. The initial and final failure frequencies were averaged to develop an I/M failure frequency for each model year and age group. Using the initial failure frequencies alone would neglect the required repairs occurring on most failing vehicles, while using only final failure frequencies would neglect the prior existence of failing vehicles.

To develop non-I/M failure frequencies, the sample was restricted to vehicles that were inspected, but were registered in states that do not have any I/M programs.

The Tucson data was used to determine the effect of I/M program frequency (annual vs. biennial). For OBD-equipped vehicles, Tucson performs gas-cap and OBD tests annually, while Phoenix performs them biennially. Therefore, we were able to develop an the effectiveness ratio for Annual/Biennial programs by analyzing the Tucson data.

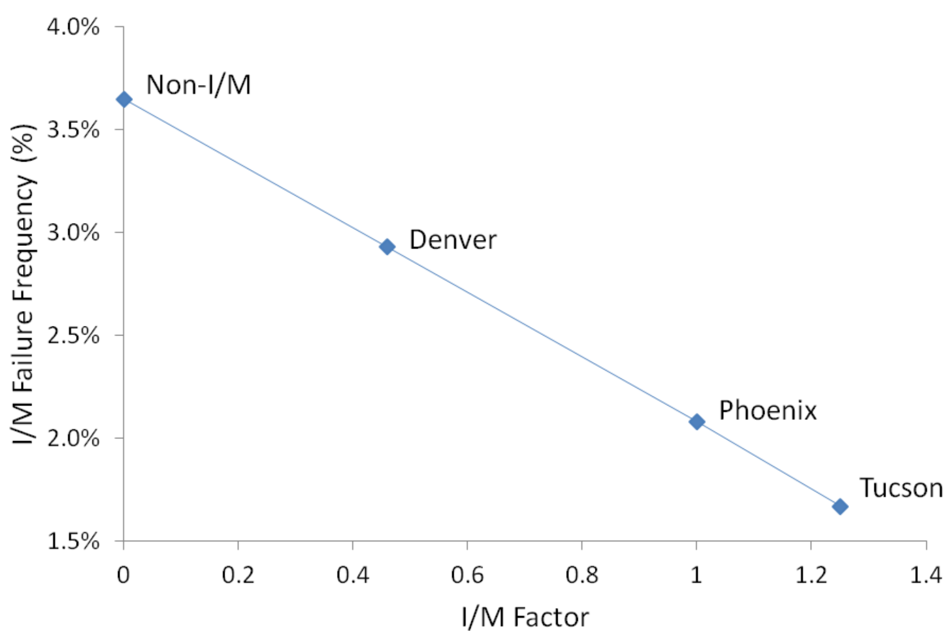
The North Carolina data was used to estimate the effectiveness of using the OBD scan as the sole test in a program. In North Carolina, expansion of I/M program boundaries led to many vehicles being tested for the first time. These vehicles were effectively non-I/M until their first test. Vehicles were flagged as non-I/M tests if they were tested before the official start of the I/M program or were registered in a new I/M county. Failure frequencies of the non-I/M vehicles were compared to vehicles tested in I/M areas. The I/M effectiveness of an OBD only I/M program is estimated to be a 63 percent reduction in failures or a non-I/M to I/M failure ratio of 1.6. This ratio was then applied to Phoenix OBD and pressure test failure frequencies to determine non-I/M failure frequencies.

The Colorado data was used to determine the effectiveness of gas cap tests. In Colorado, the

I/M data is primarily from the Denver and Boulder metropolitan areas. However, some residents are new to this area, having moved from non-I/M counties and states. These vehicles were effectively non-I/M until their first test. Vehicles were flagged as non-I/M if they were registered in a state without an I/M program, or in a non-I/M county within Colorado. Colorado OBD data was not used, because OBD in Colorado is only advisory and does not pass or fail a vehicle. The failure rates of the non-I/M vehicles were compared to those in the I/M fleet. The effectiveness of a gas-cap-only I/M program is estimated to be a 45 percent reduction in failures or a non-I/M to I/M failure ratio of 1.2. This ratio was then applied to gas cap failure frequencies to determine non-I/M failure frequencies.

The I/M factor in MOVES adjusts emission rates depending on the characteristics of a given county's I/M program. Our reference program, Phoenix, has an IM factor of 1. Non-I/M areas have an IM factor of 0. The failure frequencies from the other counties are used to calculate I/M factors for the diverse types of evaporative I/M procedures. The I/M factor is assumed to have a linear relationship with failure frequency. Figure 24 illustrates how the I/M factor varies with different I/M programs. Different programs fall on the line as determined by the analysis above, based on specific evaporative tests performed. For the vehicles in Figure 24, Tucson's OBD and gas cap tests are annual, compared to Phoenix's biennial requirement, which gives Tucson a lower failure frequency, thus a higher I/M factor. Colorado's frequency is biennial, but their OBD test is non-enforcing. As a result, their data shows a higher failure frequency, resulting in a lower I/M factor.

Figure 24: I/M Factor, MY 1999-2003, Age 4-5

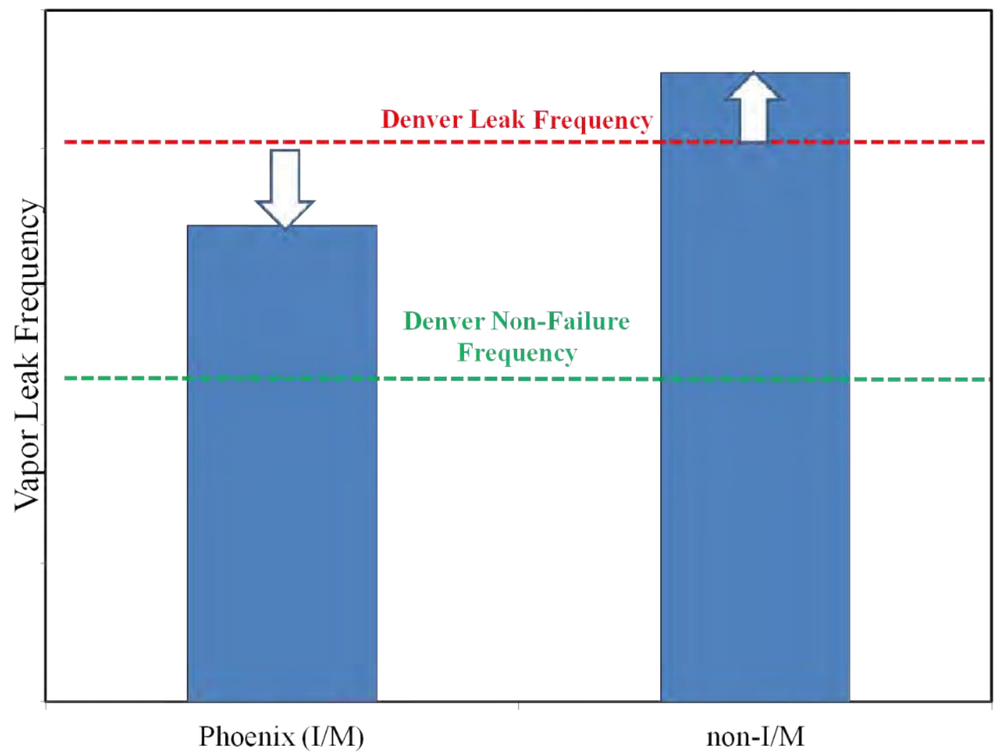


3.4.2 *Leak Prevalence*

To estimate the impact of an I/M program, the appropriate I/M factor is applied to the estimated vapor leak prevalence rates. However, because the leak prevalence rates were developed from a test program in the Denver, CO area, and because, as explained above, the Denver program is not the MOVES reference program, the Denver vapor leak prevalence rates, developed in Section 3.3.2.7 must be adjusted for use in MOVES.

As illustrated in Figure 24, the with-I/M failure frequency in Denver is about 30 percent less than non-IM (I/M factor = 0) and 30 percent higher than Phoenix (I/M factor = 1) so the leak prevalence rates developed from Denver data were adjusted accordingly before being added to the MOVES database. This adjustment reflects the analysis described in the previous section and can be observed in Figure 25. During a MOVES run for the Denver area, the Denver I/M factor will be applied to the adjusted leak prevalence rates and emissions will be modeled with the same prevalence rates originally estimated for Denver.

Figure 25: Adjusting Denver Leak Prevalence Data



3.5 *Liquid Leaks*

Liquid leaks include any non-vapor fuel escaping the fuel system. The average liquid leaking rate is determined using the leaking vehicles excluded from the analysis above. Because the testing methods used did not distinguish the different evaporative emission processes, permeation and tank vapor venting are estimated using the calculation methods described in Section 3.2 and Section 3.3 and subtracted from the total measurement. The remaining emissions after permeation and vapor venting are subtracted are assumed to be caused by liquid leaks. Due to limitations in the data quality and quantity, the measurements are averaged across all vehicles by the three different modes and shown in Table 22.

Table 22: Liquid Leak Emission Rates (g/hr)

Operating Mode	Liquid leak rate
Cold Soak	9.85
Hot Soak	19.0
Operating	178

The liquid leak emission rates must be multiplied by the percentage of leakers in the fleet to get an average liquid leaking emission rate. The studies by BAR [20] and API [21] provided this data. The estimates of liquid leak prevalence are shown in Table 23 It is assumed that most leaks do not occur until vehicles are 15 years or older.

Table 23: Percentage of Liquid Leaks by Age

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

Table 24 contains the fleet-weighted liquid leak rate. There is insufficient data to conclude that these rates change with model year or are affected by I/M programs.

Table 24: Weighted Liquid Leak Emissions(g/hr)

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	1.360
20+	0.235	0.452	4.230

As with vapor leaks, we expect a reduction in liquid leak prevalence due to improved system design and integrity under the Tier 3 regulations. However, liquid leaks in advanced evaporative systems are primarily caused by tampering and mal-maintenance. Therefore, we estimate Tier 3 will prevent half as many liquid leaks as vapor leaks, shown in Table 25.

Table 25: Weighted Tier 3 Liquid Leak Emissions (g/hr**)**

Age group	Cold soak	Hot soak	Operating
0-9	0.007	0.013	0.123
10-14	0.019	0.037	0.342
15-19	0.058	0.113	1.054
20+	0.180	0.348	3.258

3.6 *Refueling*

Refueling emissions are the fuel vapors when liquid fuel is added to the tank. In MOVES these are reported as Refueling Displacement Vapor Loss (processid = 18) and Refueling Spillage Loss (processid = 19). Refueling emissions are estimated from the total volume of fuel dispensed (gallons). This volume is estimated from the average daily distance travelled (VMT) and the estimated fuel consumption. Both the spillage and the vapor displacement associated with refueling events are in terms of grams per gallon of fuel dispensed. Diesel vehicles are assumed to have negligible vapor displacement, but fuel spillage is calculated for diesel vehicles.

The refueling calculations are fairly simple and do not account for altitude, saturation of vapor storage systems, or differences in vehicle fueling system design.

Two emission control strategies exist to limit fuel lost during refueling for gasoline and E85 vehicles. First, there are programs designed to capture refueling vapors at the pump. These are often referred to as Stage II vapor control programs and vary by location. Second, vehicles manufactured since 1998 have onboard refueling vapor recovery (ORVR) systems that store refueling vapors in the vehicle's evaporative emission canister. Stage II programs are assumed to reduce emissions from vehicles not equipped with ORVR and additionally, any refueling emissions that are not captured by the ORVR systems. MOVES does not model any interaction between ORVR systems and gasoline dispensing stations equipped with Stage II equipment; that is, we do not model any interference or complementary effects.

The implementations of Stage II systems vary from area to area and affect the fuel vapor displacement and the amount of spillage. MOVES uses two factors to adjust the refueling losses and account for this variation.

1. The *refueling vapor program adjustment* is a value between zero and one indicating the percent reduction of total potential vapor losses by state or local programs (such as Stage II recovery programs).
2. The *refueling spill program adjustment* is a value between zero and one indicating the percent reduction of refueling spillage losses by state or local programs (such as Stage II recovery programs).

These program adjustments in MOVES are applied by county. Each county has a unique value for vapor and spillage program adjustments. The MOVES default database contains information about all of the existing Stage II programs by county based on the parameters used for the 2005 National Emission Inventory (NEI) with minor subsequent updates. The estimated effects of Stage II programs can be altered by manually editing the MOVES Stage II tables. The program adjustment values for each county and calendar year are stored in the default MOVES 'CountyYear' table. We are aware that this table does not capture some Stage II program terminations, and plan to update this table in a future MOVES version.

MOVES uses separate factors to address the on-board refueling vapor recovery (ORVR) systems on gasoline and E85 vehicles. The effects of ORVR technology is phased in beginning in model year 1998, as shown in Table 26. There is no ORVR for motorcycles or heavy-duty vehicles with GVWR> 14,000. In MOVES, ORVR reduces emissions from both vapor and spillage.

Table 26: Phase-In of Onboard Refueling Vapor Recovery

Model Year	Passenger Cars	Light Trucks <6,000 lbs GVWR	Light Trucks 6,000-8,500 lbs GVWR	Heavy Duty Trucks 8,500-10,000 lbs GVWR	Heavy Duty Trucks 10,000-14,000 lbs GVWR
1998	40%	0%	0%	0%	0%
1999	80%	0%	0%	0%	0%
2000	100%	0%	0%	0%	0%
2001	100%	40%	0%	0%	0%
2002	100%	80%	0%	0%	0%
2003	100%	100%	0%	0%	0%
2004	100%	100%	40%	40%	0%
2005	100%	100%	80%	80%	0%
2006 -2017	100%	100%	100%	100%	0%
2018 and newer	100%	100%	100%	100%	100%

3.6.1 *Vapor Loss*

As noted above, the Refueling Displacement Vapor Loss process (processID 18) estimates the displaced grams of fuel vapor per gallon of liquid fuel consumed. For an uncontrolled system, the vapor displaced by refueling with gasoline or E85 is a function of the fuel's Reid Vapor Pressure (RVP), the dispensed gasoline temperature, and the temperature difference between the vehicle's fuel tank and the dispensed gasoline, as shown in Equation 3-18:[44]

$$DVR = \exp(-1.2798 - 0.0049 d_T + 0.0203 T_{DF} + 0.1315 RVP) \quad \textbf{Equation 3-18}$$

Where:

DVR = base displaced vapor rate (g/gal)
d_T = difference in temperature between the vehicle's fuel tank and the dispensed fuel (°F) (see Equation 3-20)
T_{DF} = temperature of the dispensed fuel (°F) (see Equation 3-19)
RVP = Reid Vapor Pressure of the dispensed fuel (psi)

In MOVES, the coefficients of Equation 3-18 are stored in the RefuelingFactors table of the default database as vaporTermA, vaporTermB, vaporTermC, and vaporTermD, respectively.

The temperature of the dispensed fuel (T_{DF}) depends on the temperature of the fueling station's storage tank temperature, which is modeled as a function of the ambient temperature, as shown in Equation 3-19:[45]

$$T_{DF} = 20.3 + 0.81 \times T_{amb} \quad \textbf{Equation 3-19}$$

Where:

T_{DF} = temperature of the dispensed fuel (°F)
T_{amb} = ambient temperature (°F), bounded between 45°F and 90°F[e]

In MOVES, the lower bound of 45°F and upper bound of 90°F are stored in the RefuelingFactors table of the default database as vaporLowTLimit and vaporHighTLimit, respectively. The coefficients of Equation 3-19 are not stored in the default database; instead, they are hard coded directly in the MOVES algorithm. The ambient temperature (T_{amb}) is stored in the ZoneMonthHour table of the default database, which varies by county, month, and hour of day.

The difference in temperature between the vehicle's fuel tank and the dispensed fuel (T_{DF}) is calculated as shown in Equation 3-20:[46]

$$d_T = 0.418 \times T_{DF} - 16.6 \quad \textbf{Equation 3-20}$$

Where:

d_T = difference in temperature between the vehicle's fuel tank and the dispensed fuel (°F), up to a maximum difference of 20°F
T_{DF} = temperature of the dispensed fuel (°F)

In MOVES, the coefficients of Equation 3-20 are stored in the RefuelingFactors table of the default database as vaporTermE and vaporTermF, respectively. The upper bound of d_T is stored as tankTDiffLimit. This upper bound is implemented because in the Amoco study[46] that this equation relies on, the difference in temperature was never greater than 20 degrees.

Base displaced vapor values calculated for a warm summer day with an ambient temperature

[e] The lack of data on dispensed fuel temperatures for ambient temperatures above 90 degrees Fahrenheit is a limitation in our modeling that may be important in areas with sustained high temperatures.

of 90°F and 7.8 psi RVP fuel are about 4.7 grams per gallon. With unseasonable weather, extreme values could range between about 2 grams per gallon with low temperatures (45°F) and low summer RVP values (6.5 psi), and 9.2 grams per gallon with high temperatures (90°F) and high winter RVP (13 psi).

We limit the base displaced vapor rate to a minimum value of 1.8 grams per gallon, which is stored in the RefuelingFactors table of the default database as minimumRefuelingVaporLoss. This is equivalent to the value calculated with a low ambient temperature (less than 45°F) and an RVP of 5.7.

After calculating the base displaced vapor rate for uncontrolled systems, we calculate an adjusted displaced vapor rate, which accounts for controls on displaced vapors from refueling. This step is presented as two separate calculations for clarity, as shown in Equation 3-21 and Equation 3-22.

Equation 3-21 calculates the adjusted displaced vapor rate for uncontrolled vehicles, which accounts for Stage II controls and the fraction of vehicles without functioning ORVR controls:

$$ADVR_U = DVR \times (1 - S2C) \times (1 - RTA) \qquad \textbf{Equation 3-21}$$

Where:

$ADVR_U$ = adjusted displaced vapor rate for uncontrolled vehicles (g/gal)
DVR = base displaced vapor rate (g/gal)
$S2C$ = Stage II controls described as *refueling vapor program adjustment* above, dimensionless
RTA = refueling technology adjustment, dimensionless

For the above equation, DVR is calculated as shown in Equation 3-18. $S2C$ represents the presence and effectiveness of Stage II controls. A hypothetical value of 1 represents full penetration and effectiveness of Stage II controls, which would result in an $ADVR_U$ of 0 g/gal. Conversely, a value of 0 for $S2C$ represents a lack of Stage II controls, which would result in no adjustment to the base displaced vapor rate due to Stage II.

RTA is stored in the RefuelingControlTechnology table of the default database, and is determined by regulatory class,[f] fuel type, vehicle age, and model year. This value incorporates both the ORVR technology adoption rates from Table 26 and information on real-world ORVR function derived from the "High Evaporated Emission Investigation Field Study."[47] This EPA study investigated the percentage of vehicles which had observable refueling emissions plumes. A year-dependent regression was developed to determine the percent increase in observed plumes (and thus the decrease in ORVR effectiveness) as a proxy of age. The decrease was calculated as -0.68 percent per year[g] which was applied for ages 0

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[f] In a future version of MOVES we intend to add a distinction by source type, allowing MOVES to more accurately implement the last column of the ORVR phase-in shown in Table 26.

[g] The MOVES value is slightly different than that listed in the report (-0.56%/ year) because the MOVES value included an extra year and some vehicles determined to be light-duty after additional VIN decoding work.

through 19[h] and used for all model years and regulatory classes with ORVR implemented. The RTA value is the same in all locations.

Since RTA essentially represents the penetration of functioning ORVR technology, $1 - RTA$ represents the fraction of vehicles that do not have functioning ORVR and is thus used to adjust the base displaced vapor rate to calculate $ADVR_U$.

Equation 3-22 calculates the adjusted displaced vapor rate for the fraction of ORVR-controlled vehicles:

$$ADVR_C = CRR \times (1 - S2C) \times RTA \quad \textbf{Equation 3-22}$$

Where:

- $ADVR_C$ = adjusted displaced vapor rate for ORVR-controlled vehicles (g/gal)
- CRR = controlled refueling rate (g/gal)
- $S2C$ = Stage II controls described as *refueling vapor program adjustment* above, dimensionless
- RTA = refueling technology adjustment, dimensionless

In the above equation, CRR represents the refueling vapor losses in a controlled ORVR system. This value is based on measurements from the In-Use Verification Program (IUVP). The mean HC emissions of the functional ORVR systems (defined as those with emission below the certification level of 0.2 g/gal) as measured in the 2009-2020 light-duty IUVP data was 0.0361 g/gal.[48] This value was used for all vehicles with controlled ORVR systems. It is stored in the RefuelingControlTechnology table of the default database, but does not vary by age, model year, or regulatory class.

Equation 3-22 has the same Stage II control adjustment for CRR as Equation 3-21 has for DVR, as Stage II programs are assumed to reduce any refueling emissions not captured by ORVR systems.

As described above, RTA represents the penetration of functioning ORVR technology and is therefore applied directly to adjust the controlled refueling rate to calculate $ADVR_C$.

The total adjusted displaced vapor rate is then calculated by combining Equation 3-21 and Equation 3-22, as shown in Equation 3-23:

$$ADVR = ADVR_U + ADVR_C \quad \textbf{Equation 3-23}$$

Where:

- $ADVR$ = total adjusted displaced vapor rate (g/gal)
- $ADVR_U$ = adjusted displaced vapor rate for uncontrolled vehicles (g/gal)
- $ADVR_C$ = adjusted displaced vapor rate for ORVR-controlled vehicles (g/gal)

The result of Equation 3-23 is an adjusted vapor rate of grams of HC emissions per gallon of

[h] For ages 19 and older we set a minimum value of 87 percent since this was the oldest age with fully phased-in ORVR in the field study.

fuel consumed. While MOVES does not directly calculate fuel consumption, it does calculate total energy consumption. To calculate refueling displacement vapor loss, MOVES implements Equation 3-24:

$$RDVL = ADVR \times \frac{TEC}{EnergyContent \times FuelDensity}$$ **Equation 3-24**

Where:

$RDVL$ = refueling displacement vapor loss (g)
$ADVR$ = total adjusted displaced vapor rate (g/gal)
TEC = total energy consumption (kJ)
EC = energy content of the fuel (kJ/g)
FD = fuel density (g/gal)

The total energy consumption (TEC) is calculated as described in the MOVES GHG and Energy Consumption technical report.[49] The fuel energy content (EC) and density (FD) are stored in the FuelSubType and FuelType tables (respectively) of the default database and are also documented in the same technical report.

3.6.2 *Spillage*

AP-42 Volume I Section 5.2.2.3[50] lists the spillage as 0.7 lb/1000 gallons, which is 0.31g/gallon of dispensed fuel. MOVES uses this value for uncontrolled spillage from gasoline, E85, and diesel fueled-vehicles.

MOVES adjusts spillage to account for the spill reduction effects[i] of Stage II programs with *refuelingSpillProgram Adjust*, a value between zero and one as listed in the countyYear table.

MOVES also adjusts spillage to account for ORVR. The *refueling tech adjustment* for refueling spillage losses reflect the fuel type and regulatory class population fractions[j] from MOVES3.0, coupled with an assumption that gasoline vehicle spillage emissions are reduced using a 50% technology adjustment factor when ORVR technology is fully implemented. This accounts for spillage reduction due to required anti-spitback valves. The technology adjustment is the same in all locations. Unlike the *refueling tech adjustment* for vapor loss, the spillage adjustments were not changed in MOVES3.R1. They are listed in the MOVES *'SourceTypeTechAdjustment* table. The technology adjustment values take into account the technology adoption rates from Table 26 and the population fraction of the vehicles by fuel type and regulatory class (GVWR for heavy-duty vehicles) within each source type as documented in the MOVES3 Population and Activity Report.[5] Note that the factors for heavy-duty trucks 8,500 lbs and higher are reflected in the values for single-unit short-haul and long-haul vehicles (source types 52 and 53). For example,

[i] For example, Stage II systems reduce the chance of over-filling and capture some fuel drips.
[j] The population weightings in sourceTypeTechAdjustment were not updated for MOVES3.R1. We hope to update the spillage calculations in a future version of MOVES.

LHD2b3 vehicles (GVWR < 14,000 lbs) compose 49% of the population of gasoline source type 52 and 53 vehicles in model year 2014 and later in MOVES3.[k]

Refueling Spillage Loss = UncontrolledSpillage (1- refuelingSpillProgramAdjust) * (1-refuelingTechAdjustment)*	**Equation 3-25**

Appendix A Notes on Selected Evaporative Emission Data

Parameters: Vehicle Numbers, Test No., 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)
- Model years 1992 to 1997
- Average RVP: 6.5 psi
- Diurnal Temperature: 72 to 96°F
- 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: 95°F

E-9 CRC Real Time Diurnal Study (1996)

• 151 vehicles (51 vehicles MY 1971-1977, 50 vehicles MY 1980-1985, 50 vehicles MY 1986-1991)

- 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 96°F
- Fuel System: Port Fuel Injection, Carburetor, Throttle Body Injection

CRC E-35 Running Loss Study (1997)

• 150 vehicles (50 vehicles MY 1971-1977, 50 vehicles MY 1980-1985, 50 vehicles MY 1986-1991)

- Ambient Temperature in running loss enclosure: 95°F
- 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: 81.67°F

- Fuel System: Port Fuel Injection

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)

BL1A 1 hour Breathing Loss Evap. Test Gas Cap left On **BL1B** 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

Appendix B Tank Fuel Generator

In MOVES, we account for changes to the RVP of gasoline fuels due to weathering and comingling as a preliminary step before calculating vapor venting emissions. These calculations are handled in the Tank Fuel Generator (TFG).

TFG-1a: Calculate Average Pump Gasoline and Ethanol Blend Type

Inputs:

marketShare from FuelSupply (county, fuelYear, monthGroup, fuelFormulationID)
ETOHvolume from FuelFormulation (fuelFormulationID)
RVP from FuelFormulation (fuelFormulationID)
fuelSubTypeID from FuelFormulation (fuelFormulationID)
fuelTypeID from FuelSubType (fuelsubtypeID)

Outputs:

averageRVP (county, fuelYear, monthGroup)
tankAverageETOHVolume (county, fuelYear, monthGroup)

Calculations:

averageRVP = For all FuelFormulations in county, fuel year & monthGroup where
fuelType = "gasoline" (ie fuelTypeID = 1))
(Sum (RVP*marketshare)) / (Sum (marketshare))

tankAverageETOHVolume = For all Fuel Formulations in county, fuel year & monthgroup
where fuelType = "gasoline" (ie fuelTypeID = 1))
(Sum (ETOH Volume*marketshare)) / (Sum (marketshare))

TFG-1b: Calculate Ethanol Market Share and Ethanol BlendType

Inputs:

marketShare from FuelSupply (county, fuelYear, monthGroup, fuelFormulation)
fuelSubTypeID from FuelFormulation
fuelTypeID from FuelSubType

Outputs:

gasoholMarketShare (countyID, fuelYearID, monthGroupID)
ethanolBlendType (county, fuelYear, monthGroup)

Calculation:

gasoholMarketShare: For all FuelFormulations in county, fuelyear & monthgroup where
ETOHVolume >= 4
gasoholMarketShare =Sum (marketShare)

lowETOHRVP: For all FuelFormulations in county, fuel year & monthgroup WHERE fuelType = "gasoline" (ie fuelTypeID = 1) and ETOHVolume <4

IF (sum (marketshare) = 0,
lowETOHRVP=AverageRVP

ELSE
lowETOHRVP=(Sum (RVP*marketshare)) / (Sum (marketshare))

highETOHRVP: For all FuelFormulations in county, fuel year & monthgroup WHERE fuelType = "gasoline" (ie fuelTypeID = 1)) and ETOHVolume >= 4

IF gasoholMarketShare = 0,
highETOHRVP = AverageGasolineBlendRVP

ELSE
highETOHRVP =(Sum (RVP*marketshare)) / gasoholMarketShare

ethanolBlendType:
IF absolute value (highETOHRVP –lowETOHRVP) <= 0.2,
ethanolBlendType ="Match"
ELSE ethanolBlendType = "Splash"

TFG-1c: Calculate Commingled Tank Fuel RVP

Inputs:

gasoholMarketShare (countyID, fuelYearID, monthGroupID) from TFG-1b
averageRVP (countyID, fuelYearID, monthGroupID) from TFG-1a

Commingling Lookup (stored in MOVES)

LookupMarketShare	Commingling RVP Factor
0.0	1.000
0.1	1.016
0.2	1.028
0.3	1.035
0.4	1.039
0.5	1.040
0.6	1.038
0.7	1.034
0.8	1.027
0.9	1.018
1.0	1.000

Outputs:

commingledRVP (countyID, fuelYearID, monthGroupID)

Calculation:

commninglingFactor (countyID, fuelyearID, monthgroupID) = lookup from table using smallest value of "LookupMarketShare" that is greater than or equal to the gasoholMarketShare.

commingledRVP = averageRVP * commninglingFactor

TFG-2: Weathered RVP

TFG-2a: Calculate "EvapTemp" by ZoneID, MonthGroupID

Inputs:

temperature (zoneID, hourID monthgroupID)
zoneID from masterloopcontext

Outputs:

zoneEvapTemp (zoneID, monthgroupID)

Calculation :

zoneMin(zoneID, monthgroupID) = MIN (temperature(zoneID, monthgroupID, hourID))

zoneMax (zoneID, monthgroupID) = MAX(temperature(zoneID, monthgroupID, hourID)

zoneEvapTemp =
IF zoneMax <40 or zoneMax-zoneMin <=0, (zoneMin+zoneMax)/2
ELSE zoneEvapTemp(zoneID, monthGroupID) =
-1.7474+1.029*zoneMin+ 0.99202* (zoneMax-zoneMin)-0.0025173*zoneMin* (zoneMax-zoneMin)

TFG-2b: Calculate ratio of weathering loss for gasoline by Zone, Year & Month at actual ambient temperatures relative to a diurnal swing of 72-96 F

Inputs:

zoneEvapTemp (zoneID, monthgroupID) from previous step
commingledRVP (countyID, fuelYearID, monthgroupID) from TFG-1c
zone(countyID, zoneID)

Outputs:

ratioGasolineRVPLoss(zoneID, fuelYearID, monthgroupID)

Calculation :

ratioGasolineRVPLoss =MAX (0, [-2.4908 + 0.026196 * zoneEvapTemp + 0.00076898 * zoneEvapTemp * commingledRVP]/[-0.0860 + 0.070592 * commingledRVP])

TFG-2c: Calculate weathering loss for average fuel for standard temperatures

Inputs:

ethanolBlendType (county, fuelYear, monthGroup) from TFG-1a
gasoholMarketShare (countyID, fuelYearID, monthGroupID) from TFG-1b

Outputs:

avgWeatheringConstant (countyID, fuelYearID, monthGroupID)

Calculations:

IF ethanolBlendType = “Match”, avgWeatheringConstant = 0.049 – 0.0034 * gasoholMarketShare
ELSE avgWeatheringConstant = 0.049 – 0.0116 * gasoholMarketShare

TFG-2d: Calculate weathered RVP for county-average fuel adjusted for zone temperatures

Inputs:

ratioGasolineRVPLoss (zoneID, fuelYearID, monthgroupID) from TFG-2b
avgWeatheringConstant (countyID, fuelYearID, monthGroupID) from previous step
commingledRVP (countyID, fuelYearID, monthGroupID) from TFG-1c
zone(countyID, zoneID)

Outputs:

tankAverageGasolineRVP(zoneID, fuelYearID, monthgroupID)

Calculation :

tankAverageGasolineRVP (zoneID) = commingledRVP(countyID) * (1 – ratioGasolineRVPLoss (zoneID) * avgWeatheringConstant (countyID))

Appendix C List of Acronyms

API	American Petroleum Institute
BWC	Butane Working Capacity
CNG	Compressed Natural Gas
CRC	Coordinating Research Council
DTC	Diagnostic Trouble Code
E0	Gasoline containing 0 percent ethanol by volume
E10	Gasoline containing 10 percent ethanol by volume
E-65	CRC fuel permeation from automotive systems study
E-77-2	evaporative emission/permeation test program
EPA	U.S. Environmental Protection Agency
ETOH	Ethanol
FTP	Federal Test Procedure
HC	Hydrocarbons
HD	Heavy-Duty
I/M	Inspection and Maintenance program
LDGV	Light-Duty Gasoline Vehicle
LEV	Low emission vehicle
LEV III	California Tier 3 light-duty emission standards of 2012
MOBILE	Original Highway Vehicle Emission Factor Model pre-2004
MOBILE6	Versioned Highway Vehicle Emission Factor Model
MOVES	Motor Vehicle Emission Simulator Model
MSAT	Mobile Source Air Toxics
MTBE	Methyl tertiary-butyl ether
NMHC	Non-Methane Hydrocarbons
NMOG	Non-methane organic gases
OBD	Onboard Diagnostics
ORVR	Onboard Refueling Vapor Recovery
OTAQ	Office of Transportation and Air Quality
PI	Petroleum Institute
RVP	Reid Vapor Pressure
PSHED	Portable Sealed Housing for Evaporative Determination
SHED	Sealed Housing for Evaporative Determination
THC	Total Hydrocarbon
Tier 2	Vehicle emissions certification standards phased in from 2002 – 2007
Tier 3	Vehicle emissions certification standards phased in from 2017 - 2025
TOG	Total Organic Gases
TVG	Tank Vapor Generated
TVV	Tank Vapor Venting
VOC	Volatile Organic Compound
VSP	Vehicle specific power

Appendix D Glossary

backpurge - as the temperature decreases a vacuum is created in the fuel system which pulls the hydrocarbons from the charcoal canister into the fuel tank, creating more space in the canister for hydrocarbons to adhere during the next heating period

breakthrough - when the vapor generated by the fuel system overwhelms the charcoal canister and uncontrolled hydrocarbons are released into the atmosphere

canister - the device in an evaporative emission control system that captures and stores evaporative emissions generated within the vehicle for later combustion by the engine; a canister typically contains activated carbon as a storage medium

CRC - Coordinating Research Council, a consortium of auto and oil industry members which sponsors common research programs

diurnal cold soak - Vapor lost while vehicles are parked at ambient temperature.

HC - hydrocarbon, an organic compound consisting entirely of hydrogen and carbon; a com- bustible fuel source which can be either gaseous or liquid

hot soak - Vapor lost in the time period immediately after turning off a vehicle.

I/M - Inspection and Maintenance program run by States to find and correct emissions problems for vehicles registered in the State

light-duty vehicle/LDGV - passenger cars

MOVES - MOtor Vehicle Emissions Simulator; official US EPA model for estimating emis- sions from national fleet of onroad vehicles

MSAT - Mobile Source Air Toxic rule which regulates toxic mobile source emissions such as benzene and ethanol

permeation - the migration of hydrocarbons through materials in the fuel system

OBD - Onboard Diagnostics, an electronic automotive system with the ability to continually track the functionality of emissions control and other components, and alerts the driver and/or vehicle inspector when a problem is found

ORVR - Onboard refueling vapor recovery system which is designed to capture fuel vapors at time of refueling

PSHED - portable SHED for evaporative emissions field measurements

purge - evaporative emissions control system that creates a vacuum in the fuel system to pull the hydrocarbons from the charcoal canister while the engine is running for combustion

refueling loss - Vapor lost and spillage occurring during refueling

running loss - Vapor lost during vehicle operation.

RVP - Reid Vapor Pressure, a measure of volatility in the gasoline at 100 degrees Farenheit, as determined by the test method ASTM-D-323

SHED - Sealed Housing for Evaporative emissions Determination; structure for evaporative testing in a laboratory

Stage II - vapor control programs at refueling stations to recover fuel vapor losses from fuel displacement at the refueling pump

tank vapor generated (TVG) - vapor generated in the fuel system as temperature rises
tank vapor vented (TVV) - vapor generated in fuel system lost to the atmosphere, when not contained by evaporative emissions control systems

Tier 2 - vehicle emissions certification standards phased in from 2004 through 2007

Tier 3 - vehicle emissions certification standards will phase in from 2017 through 2025

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