Eastern Research Group, Inc.

EMFAC ON-ROAD MOBILE SOURCE EMISSION MODEL

EVAPORATIVE EMISSIONS RESEARCH WHITE PAPER

DRAFT

ARB Contract No. 16AQP004

Prepared for:

California Air Resources Board

Prepared by:

Eastern Research Group, Inc.

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Prepared for:

California Air Resources Board
P. O. Box 2815
Sacramento, CA 95812

Prepared by:

John Koupal
Timothy DeFries
Sandeep Kishan

Eastern Research Group, Inc.
3508 Far West Blvd., Suite 210
Austin, TX 78731

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1 Introduction

ARB is in the process of updating the evaporative emissions module in EMFAC, and is basing the update on the approach taken in U.S. EPA's MOVES model. The MOVES approach, summarized in Section 3 incorporates a number of updates from EPA's previous model MOBILE to better account for distinct physical processes of evaporative emissions, and the influence of malfunctioning vehicles on overall fleet emission levels. These updates where made in conjunction with new methods in the lab and field which supported new elements of the model – for example, the separation of permeation and vapor emissions in traditional lab diurnal testing; the emergence of field measurement techniques to detect high emitting vehicles (RSD, PSHED); and the availability of OBD failure information on a growing majority of the light-duty vehicle fleet. Once the initial adaptation of MOVES evap module to EMFAC is complete, ARB will need to develop a research strategy to continue to populate and update the model over time. The incorporation of the MOVES approach into EMFAC provides the short-term opportunity for ARB to further improve the model with California-specific data. Longer term, as field measurement methods continue to improve and the importance of quantifying evap malfunctions continues to grow, new approaches to quantifying real-world evaporative emissions can be considered. The purpose of this white paper is to provide recommendations to ARB for both near term needs to populate the new EMFAC evaporative module, and longer term considerations for quantifying evaporative emissions considering new technologies and approaches. An overview of current challenges for quantifying evap emissions is presented, followed by an overview of MOVES approach, data needs, and near-term options for populating EMFAC. Finally, longer-term ideas for quanitifying evaporative emissions are presented based on in-situ measurement.

2 Current Challenges in Quantifying Fleet Evaporative Emissions

There are challenges that impede efforts at quantifying and modeling fleet evaporative emissions. Some of these have dogged us for years and others are a consequence of the dramatically lowered evaporative emissions that newly produced gasoline-fueled vehicles have today. A brief discussion of each of these challenges will help point the way to cost-effective methods for collecting data to update EMFAC evaporative emissions modules.

Evaporative Emissions are Quite Low – Due to continuing advances in evaporative emissions control systems, since the uncontrolled days of the early 1970s, the evaporative emissions of today's vehicles are amazingly low. For example, the federal running loss certification standard is 50 mg/mile with a vehicle operating on a 9 psi RVP fuel at an ambient temperature of 95 F for one hour during a driving cycle that simulates stop-and-go traffic. 50 mg/mile is roughly the equivalent of the amount of hydrocarbon vapor that would fill a ping-pong ball stretched over one mile. Vehicles certified to this standard means that they must actually have measured emissions levels during certification that are below that standard. Of course, this does not mean that these vehicles always operate below 50 mg/mile. As mentioned earlier, if conditions get more severe than the certification conditions, even vehicles that meet the certification will emit at higher levels. Clearly, the certification standard is merely used as a hurdle that manufacturers must clear to be able to produce vehicles. The certification data at this one test condition cannot be used effectively to model evaporative emissions at the wide variety of operating conditions that vehicles encounter in normal everyday use. Modeling the evaporative emissions under that wide variety of conditions is the challenge of the EMFAC model.

Highly Skewed Evaporative Emissions Distributions – The evaporative emission control systems of vehicles on the road today were designed to produce low levels of evaporative emissions. However, the inherent tendency of any emission control system is to fail (because of entropy) and thereby move the vehicle back to its "natural" high emitting state. Because of OBD systems, vehicle maintenance, IM programs, fleet turnover, tight manufacturing standards, and environmental regulations, the rate at which evaporative emission control systems fail seems to be low. Because of these factors, the distribution of instantaneous evaporative emission rates is highly skewed. Most of the time, most of the vehicles on the road are operating under conditions when evaporative emissions control systems are allowing only very small evaporative emissions flow rates. However, occasionally a problem-free vehicle may encounter an operating condition that produces what might be called an elevated emission or an evaporative control system might degrade or fail to produce an elevated emission. Based on the results of this study and other studies, these events are probably relatively unusual.

We should not necessarily regard running loss emissions greater than 50 mg/mile as elevated since they will most certainly happen even on a problem-free vehicle if vehicle operating conditions get more severe than those used to certify the vehicle.

There are two consequences of the highly skewed distribution of evaporative emissions. The first is that since most vehicles and operating conditions produce evaporative emissions that are very low, it is currently difficult to measure these low levels except in the most carefully maintained, and therefore expensive, laboratory settings. The second is that selecting vehicles for individual testing using random sampling methods would require sampling large numbers of vehicles to create a representative sample since such a low percentage of the vehicles have noticeably elevated evaporative emissions. One technique to sample from skewed distributions is stratified random sampling, but this needs to be carefully planned to be effective and to avoid biases in the sample.

Varied and Complicated Evaporative Emission Control Systems – To achieve the low levels of evaporative emissions that today's new vehicles produce, manufacturers have developed control systems that are mechanically simple. Vapors from the head space of the fuel tank are routed to the emission control system canister. If the canister capacity is exceeded, the vapors break through the canister and are emitted to the atmosphere. However, the vapor line between the fuel tank and the canister has a tee that can carry hydrocarbon vapor to the engine intake manifold for combustion. The feature that makes the operation of the system complicated is the decisions made by the computer that controls the valves on the vapor line to control purging of the system via engine vacuum using information obtained from sensors on the vehicle. The evaporative emission control system and the algorithms used to operate it are different for every different make, model, and engine combination on the road. Thus, testing even a problem-free vehicle enough to completely understand the operation of the emission control system to model the controlled evaporative emissions would be prohibitively expensive and it would need to be done for every make, model, and engine combination. The fallback is to perform a few evaporative emissions tests at a few conditions and hope that that characterizes the vehicle under other conditions as well.

Non-Linear/Dynamic Running Loss Emissions Process – Diurnal emissions may be the simplest of the evaporative emissions processes. The engine is off, and the headspace of the fuel tank expands and contracts in response to the ambient temperature. This is a relatively slow process and the hydrocarbons are routed to and from the canister. No purging is occurring because the engine is off.

The hot-soak emission process is a little more complicated. Hot-soaks occur immediately after engine shutdown. This is a period when many systems on the vehicle are in a transient; however, there is no canister purging because the engine is off. As heat goes into the fuel tank, the vapor in the fuel tank headspace expands and again the hydrocarbons go to and from the canister. This process is over within approximately an hour, and during the first fifteen minutes most of the hydrocarbon adsorption by the canister occurs.

The refueling process also can produce evaporative emissions. In this case, liquid fuel is added to the fuel tank and in vehicles since about 1998, which have onboard refueling vapor recovery (ORVR) systems, as fuel is added to the tank, headspace vapor is pushed into the canister. Because refueling happens over a much shorter time as compared to diurnal and hot-soak emissions and because a large volume of headspace vapor is sent to the canister, canister capacities need to be quite large. Capacities of 50 or 100 grams are common. In fact, canister sizing on most vehicles is governed by the requirements of controlling refueling emissions rather than by any of the other types of evaporative emissions requirements.

Compared to the other evaporative emissions process, running loss emissions are the most complex. The uncontrolled evaporative emissions of a vehicle can be modeled reasonably well using inputs of gasoline volatility, fuel tank volume, fuel tank fill level, fuel tank temperature and the rate of increase of fuel tank temperature (which is a function of ambient temperature, driving history, and fuel tank level). However, as soon as an evaporative emission control system is used to control the evaporative emissions, things get complicated.

The running loss evaporative emissions process for a vehicle with an evaporative emissions control system is the most complicated because like diurnal, hot-soak, and refueling processes, vapors being generated at the fuel tank are sent to the canister, but in addition, the engine is operating and therefore, depending on the engine computer's commanded purge schedule, the engine may (or may not) be purging the canister at the same time. Changes in instantaneous driving affect both tank vapor generation and canister purging simultaneously. Because of these time-dependent influences and the limited capacity of the canister, it is possible for a vehicle to be operating with essentially no running loss emissions for a period when vapor generation in the fuel tank is smaller than the purge rate. But once the excess hydrocarbon generated in the tank saturates the canister, the emissions break through the canister vent to the atmosphere, producing an abrupt and large evaporative emission. Then, if the vehicle driving changes so that the purge rate becomes larger than the vapor generation rate, the canister breakthrough will stop, producing an abrupt drop in the evaporative emissions. This example demonstrates the highly non-linear, differential, and dynamic process by which the evaporative emission control system of a vehicle affects how much and under what conditions a running loss occurs. Such a process is too complicated to be modelled mechanistically. Accordingly, modelling shortcuts would need to be imposed to approximate the net running loss generation processes.

Malfunctioning Evaporative ECSs are a Problem to Model – The previous description for running loss emissions in problem-free vehicles demonstrates how complicated a properly operating system would be to model. A malfunctioning evaporative emissions control system is just as complicated, but in addition, every individual malfunctioning vehicle can be broken in a different way. Since tank vapor generation is the source of the vapor that needs to be controlled, thermal control of tank temperature is a major strategy that manufacturers use to control running loss emissions. Manufacturers use fuel tank shielding to minimize heat transfer from exhaust system heat, engine heat, and pavement heat. Thus, tank heat shields are a key part of the evaporative emissions control systems; if a heat shield becomes damaged or even comes off, the running loss emissions of the vehicle will increase. Any malfunction that reduces purging will also cause the running loss emissions to rise.

A completely malfunctioning control system is actually easiest to model because the model would just be based on the uncontrolled evaporative emissions produced by the vehicle. However, if the system is partially malfunctioning, then producing a vehicle-specific model would be difficult, and it would require model factors/approaches that approximate the effects that various types of malfunctions might have on the efficiency of the evaporative emissions control systems of vehicles in the fleet.

In addition, there is the problem of determining the fraction of the fleet that is malfunctioning. And what is the definition of malfunctioning? There are ways to estimate these factors, but they may only be necessary to use if the model is based on information from individual vehicle measurements.

Evaporative and Tailpipe Emissions Both Contain Hydrocarbon – When prototype vehicles are certified for running loss evaporative emissions, the exhaust is routed outside the SHED so that any hydrocarbon in the exhaust does not cause an artificially elevated level of hydrocarbon in the air in the SHED which would be mistaken as evaporative emissions. When a remote sensing technique is proposed for on-road measurement of running loss emissions, some sort of method needs to be used to separate the signal derived from exhaust hydrocarbon from the signal derived from evaporative emission hydrocarbons. Without such a separation method, both the evaporative HC values and the exhaust HC values will be in error. For the EMFAC model, we want to separate the contributions from those two sources and calculate them independently for the fleet.

3 Overview of the MOVES Evaporative Approach & Data Needs

3.1 MOVES Evaporative Approach

Evaporative emissions are comprised of several unique emission processes that span across all modes of vehicle activity. Evaporative emissions occur in multiple ways depending on the activity of the vehicle, and depend greatly on ambient conditions over the course of a day. Evaporative emissions are highly dependent on hour of the day and the state of vehicle activity, including how long it has been parked at what time of day. Evaporative emissions are the release of raw fuel vapor into the atmosphere, as VOC and toxic emissions. The physical processes behind this are:

- Fuel vapor generated within the vehicle's fuel tank through an increase in fuel temperature, and escaping into the atmosphere. Fuel temperature increases in one of two ways – natural variation in daily temperature, or due to vehicle operation

- Fuel vapor produced by the permeation of liquid fuel through fuel tank and hose
- Leaks of liquid fuel through tank/hose connections, or the fuel delivery system.
- Fuel vapor in the tank displaced during refueling
- Liquid fuel spilled during refueling

Approaches diverge between prior versions of EMFAC and MOVES, driven in part by an evolution in how these emissions are measured for compliance and inventory purposes. A mapping of the physical processes described above to the EMFAC and MOVES emission processes is outlined in Table 1.

Table 1: Evaporative Emission Processes in EMFAC and MOVES

Physical Process	Previous EMFAC Processes	MOVES Processes
Fuel vapor generated in the tank while the vehicle is parked & cooled off	Diurnal Resting Loss	Tank Vapor Venting (off network, cold soak)
Fuel vapor generated in the tank while the vehicle is parked & still hot, immediately after shut-off	Hot Soak	Tank Vapor Venting (off network, hot soak)
Fuel vapor generated in the tank while the vehicle is operating	Running Loss	Tank Vapor Venting (on network, operating)
Fuel vapor produced by the permeation of liquid fuel through fuel tank and hose	Diurnal Resting Loss Running Loss	Permeation (off & on network)
Fuel vapor produced for leaks of liquid fuel through tank/hose connections, or the fuel delivery system.	Diurnal Resting Loss Running Loss Hot Soak	Liquid leaks (off & on network)

As shown in Table 1, the EMFAC processes encompass multiple physical processes; for example, “diurnal” process emissions will include vapor generated in the tank, permeation, and fuel leaks while the vehicle is parked. This breakdown of process is a legacy of the process for measuring evaporative emissions in compliance testing, which measures total emissions in an enclosed test chamber over a simulated diurnal temperature profile. The MOVES processes were developed be more aligned with physical processes – primarily by separating fuel tank vapor, permeation and liquid leaks. The distinctions in spatial variation are handled in MOVES through assignment of emissions to on-network (i.e. vehicle is operating) and off-network (i.e. vehicle is parked), reported as separate rates. MOVES also calculates hourly emissions for each process. The distinctions in MOVES of process, operating mode and hourly activity are central to structure of the algorithms and code used to estimate evap.

3.2 Overview of Data Needs

The initial implementation of the updated EMFAC module relied on a combination of California-specific data and U.S. defaults from MOVES. The model can continue to be improved and update with California-specific data from existing sources, and over time with new research programs. In general, the model requires data on vehicle attributes, activity patterns, base emissions (emission levels under controlled conditions), and the prevalence of malfunctions that drive real-world emissions. These elements are required across the different evaporative emissions processes covered in the model – i.e. permeation, vapor venting and liquid fuel leaks – for parked and operating modes of operation.

For reference and context, Table 2 gives a general overview of data sources used in the first implementation of EMFAC, by way of MOVES data sources and ongoing research. Parameters shown in red are factors known to influence these emissions, but not explicitly accounted for in the current model.

Table 2: Overview of Data Types & Sources in MOVES

Data Type	**Permeation**	**Vapor Venting**	**Liquid Leaks**
Vehicle activity	Instrumented vehicle trip data Tank temperature rise Average tank fill		
Vehicle attributes	Model year Age	Model year Age Average canister size Average tank size	Age
Base emission rate	SHED tests w/ external canister	SHED test w/ external canister; induced leaks for failed emissions (cold soak, running loss) PSHED (hot soak)	Engineering estimate

Malfunction prevalence	n/a	OBD trouble codes Field (PSHED, RSD, imaging) Canister degradation	Visual inspection

Sections 4-6 then discuss in detail the data sources used to populate these elements in MOVES, and by extension the updated EMFAC module. Because research is ongoing to improve and expand field test methods, these sections also discuss new methods which could be considered by ARB to expand and improve on what has been used to date.

4 Vehicle activity data

Like EMFAC, MOVES2014a uses aggregate measures of vehicle start, trip and park activity as the basis for calculating vehicle start and evaporative emissions. For MOVES, these metrics include starts per vehicle, temporal distribution of starts, and soak distribution. Unique to evaporative emissions in MOVES, aggregate fuel tank temperatures are also used. Because in reality different elements of vehicle activity are interdependent (e.g. more starts results in shorter soak times), and with the emergence of datasets with large numbers of instrumented vehicles, MOVES includes an activity generator component that distills individual vehicle trips into aggregate start, trip and park metrics that are internally consistent; and then estimates real-time fuel tank temperature to assist in the estimation of evaporative emissions over running and parked operation, and to define hot soak vs. cold soak (operating mode distribution), in conjunction with tank temperature rise parameters provided by the user or (almost exclusively) from default data. For EMFAC these MOVES functions are being set up as a pre-process, for simplicity – details of this are discussed in the Software Design Specification document (SDS). Further details on the internal logic which distills individual trip data into aggregate trip metrics, fuel tank temperature and the distribution of time spent in hot soak, cold soak or operation are contained in MOVES technical documentation. An overview of inputs, outputs and algorithms is shown below

4.1 Start & Park Activity Generation

Activity data includes individual vehicle trip key-on and key-off times culled from instrumented vehicle surveys, accounting for the proportion of vehicles that do not take a trip on a given day. MOVES performs a series of calculations to convert these raw trip data to aggregated activity metrics similar to what EMFAC currently uses. Specifically, soak times are calculated for each trip (difference between previous key-off time and key-on for the next trip). In each hour, the following are then calculated:

- Fraction of vehicles starting and ending trips
- Temporal distribution of soak times
- Temporal distribution of starts

To illustrate MOVES' activity logic, Table 3 shows a excerpt of an intermediate table MOVES generated (but not retained in final output) in order to calculate the three bullets above. Using individual vehicle trip data culled from instrumented vehicle studies, MOVES tallies all of the trip startsand trip ends in a given hour, as well as trip duration and soak times. This table can be cross-tabulated to calculated the temporal distribution of soak times and starts, and the amount of vehicle operating time, for each hour of the day.

Table 3. Excerpt from intermediate MOVES table generated to map individual vehicle trips to aggregate activity metrics

vehID	tripID	hourID	priorTripID	keyOnTime	keyOffTime	endOfHour	startOfTrip	endOfTrip
2	4	9	0	514	540	540	1	0
2	4	10	0	541	556	600	0	1
2	5	10	4	565	572	600	1	1
2	6	11	5	616	620	660	1	1
2	7	11	6	620	660	660	1	0
2	7	12	6	661	667	720	0	1
2	8	12	7	668	683	720	1	1
2	9	12	8	684	692	720	1	1
2	10	12	9	709	711	720	1	1
2	11	15	10	883	900	900	1	0

4.2 Tank Temperature Generation

Tank temperature is calculated in MOVES based on inputs of hourly ambient temperature, trip data described above, and fuel tank temperature rise coefficients. For each individual vehicle, tank temperature is tracked throughout the day. Tank temperature rises while the vehicle is operating (operating, aka running loss). These are linear functions of times based on tank temperature rise recorded on regulatory running loss tests, scaled by time and ambient temperature. Test-derived tank temperature rise is stored as a user-definable parameter in the MOVES input database, though default values are used in actuality. Tank temperature decrease directly after engine shut-off (hot soak) based on a linear function of the difference between tank and ambient temperature, detailed in MOVES MOVES evaporative technical documentation.[1] When the tank temperature falls to ambient, the vehicle is considered in cold soak mode. Tank temperature after longer periods of in-operation (cold soak) track ambient temperatures. MOVES currently does not account for the difference in tank temperatures for vehicles or equipment stored in garages, as EMFAC does. Adjustments updated for ARB by ERG in 2013 could be used by ARB to supplement the MOVES tank temperature calculation when adapted to EMFAC.[2]

4.3 Sources of Trip Data

Data on individual trips representing overall California driving are available via the California Household Travel Survey (CHTS).[3] Administered by Caltrans, the CHTS is conducted every 10 years to gather travel behavior data for tens of thousands of households statewide. The most recent CHTS was conducted over 2010-2012 and included instrumented data collection over roughly 1 week for over 2,000 vehicles and 60,000 individual trips. Small portable data loggers installed on vehicle on-board diagnostic (OBD) ports capture data on key-on/key-off times and 1 Hz data on vehicle speed. For this purpose only the key-on/key-off times are necessary to populate the MOVES trip tables. Flat files of individual trip records are available from the CHTS website, and can be processed directly into MOVES inputs as described in Section 4.3. For this case study the 2010-12 California Household Travel Survey (CHTS), used to develop EMFAC2017 activity inputs, can be populated into the *SampleVehicleTrip* table in place of MOVES defaults.

4.4 Recommended Sources of Fuel Tank Temperature Rise Data

Fuel tank temperature rise is a critical variable for estimating running loss emissions. Current estimates from MOVES are based on early 1990s data[4] and account for differences in vehicle type (car vs. truck) and emission standard (pre- and post-enhanced evaporative standards, implemented in the mid 1990s). However, given the evolution of the design and materials used in fuel and evaporative systems, and vehicle aerodynamic profiles, an updated California-specific study of in-use tank temperatures is advised. Initially, data submitted by manufacturers for running loss emissions certification for California could be analyzed, and used to update the current default tank temperature rise parameters in the model (based on the same running loss certification test cycle). When ARB's running loss test capabilities are online with the

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[1] U.S. EPA, *Evaporative Emissions from On-Road Vehicles in MOVES2014*, Technical Report September 2014

[2] ERG, *Analysis of Offroad Correction Factors*, Report for ARB May 2013

[3] California Household Travel Survey webshite http://www.dot.ca.gov/hq/tpp/offices/omsp/statewide_travel_analysis/chts.html

[4] Cam et al. *Running Loss Temperature Profiles*. SAE Paper 930078, 1993.

new lab, these data could also be collected on vehicles in the lab. Ultimately, it would be beneficial to collect real-world tank temperature data with an in-use driving survey with vehicles instrumented to measure fuel temperature, key-off and key-on. Tank fill data is also an input for MOVES, but defaults to the standard 40 percent fill level used in compliance tests. An in-use survey could better estimate whether this is representative of in-use levels or not.

5 Vehicle attribute data

Evaporative-related vehicle attributes used as direct input for the EMFAC evaporative module include average tank size and average canister size. For MOVES, these data were distilled from Federal emissions certification data. Though most vehicles receive 50-state certification, similar data are available for California certifications. Differences in the California mix of vehicles and evaporative emission standards (prior to harmonization with Federal standards) will affect these attributes, and can be directly updated in the model.

6 Base emission rate data

Base emissions rates form the basis of emission rates within MOVES and EMFAC. These are not necessarily the same value, because for many processes, the MOVES emission rate is a product of base emissions for functioning and malfunctioning vehicles, weighted by a malfunction prevalence (Section 7). Base emission rates for MOVES have been generated from SHED and an enclosed 3 x 6 x 2.5 meter vinyl tent coupled with a portable emissions measurement system, known collectively as Portable Sealed Housing for Evaporative Determination (PSHED).

6.1 Diurnal SHED Tests

The basis of MOVES emission rates for vapor venting and permeation over cold soak diurnal modes are regulatory grade 3--day diurnal tests conducted in SHEDs from a combination of in-use surveillance (e.g. IUVP), and specialized research programs (e.g CRC E-65 and E-77). The CRC research studies introduced the approach of separating permeation and vapor emissions (via a canister removed from the vehicle, placed outside of the SHED and monitored for breakthrough), which form the basis of both permeation and tank vapor venting emission rates in MOVES.

As evaporative emission diurnal standards have evolved to essentially mandate zero vapor loss (and with LEV III zero permeation as well), the usefulness of these test on functioning vehicles is reduced. Recognizing this, the CRC E-77 program also conducted SHED tests on vehicles with induced leaks with diameter of 0.02 and 0.04 inches, the threshold for detection by vehicle evaporative OBD systems. The 0.02 inch leak tests therefore provide the "high emitter" rate., for compatibility to OBD MIL-on data, which can be used to update high emitter rates going forward on a state-specific basis The leak prevalence discussed in 6.1.2 is used to develop the weighted emission rates housed in the MOVES emission rate database tables, as detailed in Section 3 of the MOVES evaporative technical report

6.2 Running Loss Tests

Current running loss emission rates (recouched as the "operating" mode for vapor venting, permeation and liquid leaks) are all taken from SHED tests. For vehicles with low running loss emission rates, in-lab measurements will have the advantage over on-road measurements primarily because current on-road measurement method probably do not have the low detection limits that would be needed to quantify the running loss emission rates. Vehicles with low running loss emission rates include those with problem-free evaporative emission control systems for the newer technologies under mild and moderate operating conditions, and problem-free older control technologies under mild conditions.

We expect that for vehicles with problem-free evaporative emission control systems and for operation before canister breakthrough, the dependence of the running loss emissions on operating conditions will be weak. That is, the fluctuations in the tank vapor generation will be muted or attenuated by the storage capacity of the canister and the purging schedule. Consequently, the design of the in-lab test conditions can be relatively simple thereby reducing the number of runs applied to each test vehicle.

The SHED and portable SHED (PSHED) are two methods that are available for in-lab running loss testing. The approaches are contrasted in Section 6.3, with an emphasis on running losses as prototype PSHED testing has been conducted to quantify these emissions.

6.3 SHED vs. PSHED

The SHED method is the accepted method for measuring vehicle evaporative emissions for diurnal, hot soak and running loss emissions. It is used to certify prototype vehicles before production begins, and conduct in-use verification testing (e.g. IUVP). Running loss emissions tests conducted in a certified SHED are accurate even down to low emission levels. Because of the required capabilities of a SHED, SHED tests are time-consuming and expensive and can test a vehicle for only one operating condition at a time. However, because established test methods can provide an emissions baseline for the breadth of diurnal, hot soak and running loss emissions in a way field measurements cannot, these tests are an important element to quantifying the rate of evaporative emissions on the current vehicle fleet. Table 4 provides a summary of the advantages, disadvantages, and trade-offs for using a SHED as part of a study to determine the running loss emissions of a fleet.

Because certified SHEDs are in permanent locations, measurement of evaporative emissions in the field may not be near them. Therefore, ERG developed the portable SHED (PSHED) concept in 2008 as part of work for the Colorado Department of Public Health and Environment.

To provide portability and a lower expense, the PSHED concept allows a minimum level of leakage, increased inaccuracy, slightly higher detection limit, and no enclosure temperature control. Further study focused on establishing a correlation between RSD levels and direct evaporative emission measurements made in an enclosed 3 x 6 x 2.5 meter vinyl tent coupled with a portable emissions measurement system, known collectively as Portable Sealed Housing for Evaporative Determination (PSHED). A pilot study conducted in Summer 2008 at Air Care Denver's Lipan Street inspection station in Denver selected 85 vehicles based on RSD measurement to put through a test procedure that included a pre-conditioning route, two back-to-back RSD measurements, and a 15 minute "hot soak" in the PSHED (U.S. EPA 2014c). This study was followed up with testing of an additional 175 vehicles at the Air Care Denver's Ken Caryll station near Denver in Summer 2009 (U.S. EPA 2014a).

Originally the PSHED was used for hot-soak emissions measurements, but in ARB's recent study[5] in Sacramento, the PSHED was further adapted to estimate running loss emissions. In the Sacramento study, to allow some measure of running loss emissions, the PSHED testing also eliminated transient operation of the test vehicle on a dynamometer, accurate simulation of on-road fuel tank heating, and allowed combustion of the enclosure air by the engine and some possible contamination of the enclosure air by exhaust gas leakage. As described in Table 4, some of the PSHED measurement disadvantages of the SHED are still present, such as testing one vehicle at a time, testing one condition at a time, and testing vehicles not in their normal operating environment, which is on the road.

The Sacramento study's PSHED method for measuring running losses used vehicle idling during the test to promote fuel tank heating. However, since it is likely that many vehicles will not purge the evaporative emissions control system during idling, the running loss emissions measured in the Sacramento study are probably overestimating the running losses that the test vehicles would emit while driving on the road. Thus, a

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[5] DeFries et al.,*Running Loss Characteristics of Light-Duty Gasoline Vehicles Inspected at California I/M Stations, Version 4,* prepared for California Air Resources Board by ERG, August 2017.

potential improvement to the PSHED method for measuring running losses would be to install the PSHED over a chassis dynamometer so that a test vehicle could be operated at a test condition where engine purging might be taking place. Using a dynamometer under transient conditions introduces the additional complication of extracting exhaust gas from the vehicle under changing exhaust gas flow rates. Doing this would probably require custom adapters to fit the lab exhaust extraction system to the tailpipes of many different vehicles and would consequently substantially lengthen the time required to test an individual vehicle.

Table 4. Attributes of Lab-Based Running Loss Measurement Methods

	SHED	**PSHED**
Advantages	An accepted method for running loss measurement, high accuracy and low detection limit for each test, separate measures of running loss HC and exhaust HC. More accurate for testing low emitting /non malfunctioning vehicles.	Portable installation, relatively inexpensive, relaxed vehicle preparation for each test, less expensive than SHED, less difficult than SHED to recruit vehicles for testing, less extensive vehicle preparation for testing, ability to test more vehicles at lower cost in a given time than SHED.
Disadvantages	Permanent installation, test one vehicle at a time, one test condition at a time, not in-situ, expensive, difficult to recruit vehicles for testing, only small numbers of vehicles can be tested, extensive vehicle preparation for testing, conversion of measurements to inventory requires a difficult modeling exercise.	Test one vehicle at a time, one test condition at a time, not in-situ, only small numbers of vehicles can be tested, conversion of measurements to inventory requires a difficult modeling exercise. PSHED air temperature is not controlled.
Trade-offs	SHED provides accurate and low detection limit running loss measurements by requiring a certified SHED system with tight requirements for enclosure leakage, enclosure temperature control, accurate simulation of on-road fuel tank heating, no combustion of enclosure air by the engine, no contamination of the enclosure air by exhaust gas.	PSHED method provides portability, and lower expense by relaxing requirements for low enclosure leak rate, accuracy, detection limit, enclosure temperature control, accurate simulation of on-road fuel tank heating, no combustion of enclosure air by the engine, no contamination of the enclosure air by exhaust gas.

	SHED	**PSHED**
Potential improvements	None.	Use dyno to induce some purging, custom adaptor fit to tailpipe would then be required, detailed stratified random sampling plan required to get representative vehicle sample.
Modeling method	Same as for PSHED: Difficult modeling required (or relax inventory accuracy requirements) to extrapolate results to fleet, detailed stratified random sampling plan required to get representative vehicle sample, requires measurement of problem-free vehicles, malfunctioning vehicles, old and new technology vehicles.	Same as for SHED: Difficult modeling required (or relax inventory accuracy requirements) to extrapolate results to fleet, detailed stratified random sampling plan required to get representative vehicle sample, requires measurement of problem-free vehicles, malfunctioning vehicles, old and new technology vehicles.

The comparison in Table 4 reveals the large differences and trade-offs for these two different methods. Specifically, the strict SHED method is slow but accurate, and the PSHED method is fast and approximate. The major drawback of the PSHED method seems to be poor purge schedule simulation (since running losses are measured at engine idle) and lack of PSHED temperature control. It seems that a compromise between the strict SHED and approximate PSHED methods might be possible. Such a procedure might be to use the SHED facility but to abbreviate the procedure to test only running losses and eliminate hot-soak and diurnal testing. This might make it possible to test several vehicles on each test day.

6.4 Design approach for a thorough lab-based Running Loss study

To characterize factors important to emissions, a variety of test vehicles would need to be recruited. These vehicles would need to include a mix of evaporative emission control system technologies and a variety of malfunctioning statuses of those systems. The selection and recruiting of vehicles to test in the lab will be challenging since the distribution of running loss emissions in the fleet is highly skewed and measurement of vehicles with malfunctioning evaporative emissions control systems, which could dominate the running loss inventory, might be expected to have different running loss emissions characteristics.

Recruited vehicles would need to be tested using fuels of different RVPs, though this could be simplified to test a summer-only California RVP (e.g. 7.0 RVP), initial boiling points, and different fuel levels. A few different ambient temperature conditions would need to be selected. For in-lab testing to produce realistic temperature increase rates and canister purge rates, a dynamometer driving cycle would need to be selected, and the tank temperature rise of each test vehicle would need to be measured on the road. A conditioning procedure to establish consistent canister saturation at the start of the test, consistent purging history, and consistent saturation state during the test would need to be produced by selecting a standard conditioning procedure. Finally, to evaluate the running loss effects of fuel leaks and vapor leaks, a separate study of the prevalence and severity of those defects in the fleet would need to be conducted.

A test program as outlined above would be difficult and expensive to carry out. A fallback strategy would be to not vary the factors that are believed to have a minor influence on running loss emissions, model those factors that are important but are modellable based on known physical chemical relationships, and test only the factors that are not modellable but are believed to be very influential on running loss emissions. For example, the effects of canister saturation at the start of the trip, canister purging history, and current canister saturation state probably have a minor effect, and therefore could be taken care of by selecting a single conditioning procedure that is applied to all test vehicles. The effects of fuel volatility, initial boiling point, fuel level, ambient temperature, and tank temperature increase rate on tank vapor generation are very important, but they can be estimated well using physical chemistry models. Tank temperature increase rate itself could be assumed to be the same time profile for different model year groups in the fleet. The canister capacities and fuel tank properties of the test vehicles could be determined as part of the in-lab testing. For the running loss dynamometer test itself, a test cycle would need to be selected that covered a wide range of operating conditions so that the canister purge schedule of each test vehicle would have a chance to operate under several conditions.

The idea of using in-lab testing to gather data for modeling running loss emissions is based on the notion that if in-lab testing is good for certification then it's good for model building. Certainly, new vehicles are certified for evaporative emissions performance using in-lab testing. For that purpose, all the factors that affect running losses can be specified, since running loss performance at only one test condition is needed to determine if a prototype vehicle passes or fails the specification. However, for the purposes of modeling running loss emissions, using the in-lab testing approach for a relatively small set of test vehicles would be either very expensive and time-consuming or potentially would provide poor estimates of the running loss emissions of the fleet.

7 Malfunction prevalence data

Malfunction prevalence is a key variable to quantify given the outsize importance of high emitters on evaporative emissions. Field studies over the past decade have focused on quantifying these vehicles better than traditional surveillance programs.

7.1 OBD

The prevalence of evaporative vapor leaks is critical to quantify for accurate emission inventory, and over time this will likely be the single most important factor for evap modeling. Different approaches to detecting leaks focus on a single mode of vehicle operation (generally hot soak or running operation), but in general leak prevalence results from these studies are extrapolated to all modes of vehicle operation.

On-Board Diagnostics (OBD) systems check for evaporative system leaks with induced pressure bleed-downs. Diagnostic Trouble Codes (DTCs) are required to trigger when a leak equivalent to 0.2" diameter is detected. California's Smog Check program checks DTC status during inspection, which provides an ongoing stream of vapor leak prevalence data by model year and age. ERG has evaluated the prevalence of evaporative DTCs in several states, and EPA used these data in part for leak prevalence rates used in MOVES. Figure 1 shows the percentage of vehicles with evaporative DTCs in California, Colorado, Georgia and New Jersey by vehicle age.[6] Interestingly, Colorado has the highest failure rate and is also the only of these state for which OBD results are not enforced as part of the I/M program.

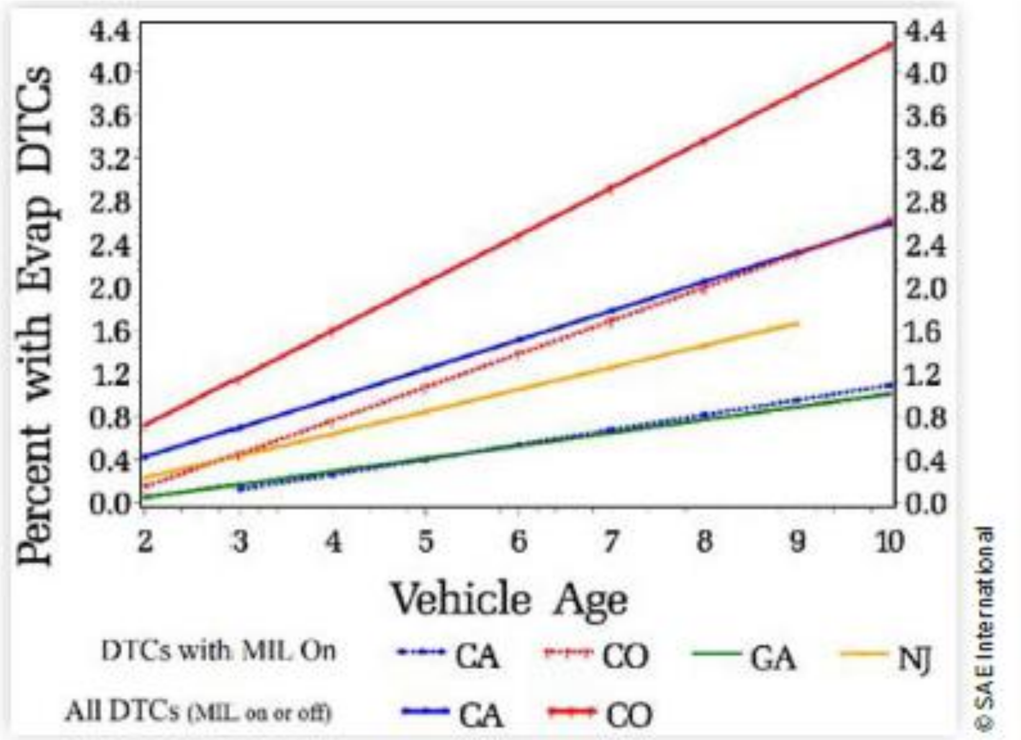

Figure 1 - OBD failure fraction by vehicle age & state [SAE 07-11-01-0001]

Though Smog Check provides a large, ongoing sample of vapor leak prevalence, DTC rate from roadside pullover suggest the on-road DTCs rates are higher than those in Smog Check. Sabisch et al. reported that the DTC rate for roadside pullover data was 5.3 percent vs. 1.4 percent from Smog Check. This suggests that while Smog Check is a ready source of leak prevalence data for updating EMFAC, data from roadside pullover or other more randomized programs is an important supplement – for example, such data may be useful to adjust Smog Check rates.

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[6] Sabisch et al, *Analysis of Evaporative and Exhaust-Related On-Board Diagnostic (OBD) Readiness Monitors and DTCs Using I/M and Roadside Data*. SAE Int J Passeng Cars Electron Electr Syst. 2018;11(1):5-15. doi: 10.4271/07-11-01-0001.

7.2 RSD & PSHED

RSD has been used to measure vehicle exhaust on a large scale since the late 1980s.[7] RSD measures the attenuation of a beam of UV and/or IR light (depending on pollutant) through a vehicle's exhaust plume, and from this calculates an instantaneous pollutant concentration for a passing vehicle. In the past three decades, numerous RSD studies have been conducted worldwide for both on- and off-road vehicles; a typical RSD campaign will gather data on tens of thousands of vehicles per week, providing an efficient approach to gauging emissions levels and trends for local vehicle fleets (University of Denver). Though RSD has traditionally focused just on tailpipe exhaust emissions, over the past decade studies conducted with newer generation RSD technology and calculation methods have confirmed the presence of evaporative emissions in roadside HC measurements. The presence of evaporative emissions in RSD measurements was first investigated in studies that found a divergence in RSD and exhaust-only inspection/maintenance (I/M) results, including high RSD HC readings for vehicles that had passed exhaust-only I/M tests.[8] Follow-on studies confirmed the ability of RSD to detect known high evaporative emissions, based on measurements on a passing vehicle with induced evaporative control malfunctions.[9]

Further study focused on establishing a correlation between RSD levels and direct evaporative emission measurements made in a PSHED. A pilot study conducted in Summer 2008 at Air Care Denver's Lipan Street inspection station in Denver selected 85 vehicles based on RSD measurement to put through a test procedure that included a pre-conditioning route, two back-to-back RSD measurements, and a 15 minute "hot soak" in the PSHED.[10] This study was followed up with testing of an additional 175 vehicles at the Air Care Denver's Ken Caryll station near Denver in Summer 2009.[11] For MOVES, PSHED levels were used directly to estimate leak prevalence for pre-OBD vehicles. As detailed in the MOVES evaporative technical report, based on correlation between paired PSHED and SHED tests, EPA established a failure threshold of 0.3 grams/quarter hour for a vehicle certified to enhanced evap standards, and based leak prevalence on PSHED levels above or below this threshold. This also provides a basis of

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[7] University of Denver Fuel Efficiency Automobile Test (FEAT) Data Center www.feat.biochem.du.edu/.

[8] Burnette, A., et al., 2008. *Evaluation of Remote Sensing for Improving California's Smog Check Program Final Report*, ARB-080303, Prepared for California Air. Resources Board and California Bureau of Automotive Repair by Eastern Research Group, Inc. March 2008

[9] DeFries, et al. *Estimated Summer Hot-soak Evaporative Emissions Distributions for the Denver Fleet*, Report Prepared for Colorado Department of Public Health and Environment by ERG, Inc. November 2012

[10] U.S. EPA *Investigation of Techniques for High Evaporative Emissions Vehicle Detection: Denver Summer 2008 Pilot Study at Lipan Street Station* EPA-420-R-14- 027 Prepared for U.S. EPA by ERG October 2014

[11] U.S. EPA *Estimated Summer Hot-soak Distributions for Denver's Ken Caryl I/M Station* Fleet EPA-420-R-14-027 Prepared for U.S. EPA by ERG October 2014

comparison for OBD failures, where MIL-on vehicles were classified as leakers for OBD-equipped vehicles.

ERG worked with the ESP technical staff in projects for CDPHE and EPA to investigate the possibility of using the Opus Accuscan instrument for measuring on-road running loss emissions. During those efforts[12] in the 2009-2012 timeframe, ERG developed an evaporative emissions index using internal data in the instrument. The purpose of the index was to identify vehicles that had elevated running loss emissions but not to quantify those emissions. The technique worked marginally for uncontrolled vehicles with no evaporative emission controls but could not consistently identify vehicles with problem-free emission systems of newer vehicles.

Mid-level emitters – those between problem-free vehicles and uncontrolled vehicles – may be critically important to quantify. While these vehicles may not represent a large portion of the fleet, as problem-free vehicles do, or may not have large running loss emissions, as uncontrolled vehicles do, they may make a large portion of the total running loss inventory hydrocarbon mass. Thus, it will be important for an RSD running loss technology to be able to measure these mid-level emitters. Our earlier experience with the Accuscan instrument indicates that it may not be able to quantify these mid-level emitters.

Since that time Opus has developed their own qualitative running loss emission sensing techniques, which may be an improvement on the early index developed by ERG. However, we expect that given the moderate detection limits and moderate accuracy for exhaust emissions measurements by the Accuscan instrument, the instrument probably has no better than a weak ability to detect moderate running loss emitters. It is possible that the CRC RW-105 study may also evaluate the Opus Accuscan instrument for its running loss measurement capability.

To date, RSD has not been used directly to quantify the prevalence of high evaporative emissions in MOVES. However, a recent analysis attempts to link RSD vs. PSHED results directly to high evap vehicles solely based on RSD. This was applied for data in Mexico City, for which only RSD data were available.[13] Drawing from principles of internal combustion engines and prior RSD studies, a comparison of aggregate HC and CO concentrations was used as a surrogate for identifying non-exhaust HC emissions in the RSD measurements. Applying this principle, the slope of HC vs. CO correlation was assessed as a marker of potential evaporative HC emissions. The Mexico RSD correlation for both passenger cars and taxis has a steeper slope than tailpipe emissions

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[12] DeFries et al. *Estimated Summer Hot-Soak Emissions Distributions for the Denver Fleet, Version 3*, prepared for the Colorado Department of Public Health and Environment, prepared by ERG November 2012.

[13] Koupal, Palacios *Impact of new fuel specifications on vehicle emissions in Mexico*, Atmospheric Environment 201 (2019) 41–49

from Mexico City I/M for vehicles aged five years and up. To draw a link between Mexico City RSD and direct evaporative measurements, regression analysis of the Lipan PSHED study found a significant difference at the 0.05 level in RSD levels for vehicles above and below this PSHED measurement threshold. HC:CO levels from the Mexico City RSD was more consistent with the PSHED "fail" threshold, defined as vehicles emitting at a "pre-enhanced" evaporative emission standard level.

7.3 Emerging On-Road Techniques

The above RSD studies were based on UV & IR-based roadside systems designed to capture tailpipe exhaust. However, new techniques under evaluation may be better tailored to detecting high evaporative emissions. In the discussion below, we present evaluation of HEAT EDAR RSD, Opus Accuscan RSD, Rebellion Photonics Gas Cloud Imaging camera, PEAQS, ambient air monitoring approaches for on-road measurements of such moderate and high running loss emitting vehicles.

On-Road: HEAT EDAR Infrared Laser Remote Sensing – HEAT is a new entry into the remote-sensing exhaust measurement market with the EDAR instrument, which uses a scanning laser beam to sense emissions in the vortex and in a large part of the plume behind a vehicle. Because of the laser's high-resolution infrared spectral capability, the instrument can measure exhaust CO, NO, and CO2 with lower detection limits and better accuracies than the Opus Accuscan instrument (to be discussed next). For exhaust hydrocarbon, which is a mixture of many hydrocarbon compounds, the accuracy of the HEAT and Opus instruments may be comparable for the measurement of exhaust emissions.

For both the HEAT EDAR and Opus Accuscan remote sensing instruments, separating the hydrocarbon signal into the evaporative HC component and the exhaust HC component and rejecting noise are important and substantial challenges for quantifying running loss emissions with good accuracy and low detection limit. In this situation, the EDAR has an advantage because it collects abundant raw data (about 10,000 individual measurements) from above and behind the vehicle and across the full width of the lane. Thus, the location of the exhaust and evaporative emissions plumes are routinely quantified in two dimensions.

In SEP 2016, ERG, EPA, CDPHE, TTI and HEAT conducted staged tests[14] of test vehicles releasing known rates of simulated running loss emissions while vehicle speed, release location, exhaust HC concentration, and vehicle body shape were varied. Initial examinations of EDAR's infrared plume images indicate that evaporative emissions absorbances are at least roughly proportional to the running loss emission rate (g/mile).

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[14] DeFries, *HEAT EDAR IR Laser Remote Sensing Device for Running Loss Evaporative Emissions of Light-Duty Gasoline Vehicles: Field Data Collection of September 2016,* prepared by ERG December 2017

We believe the application of an appropriate mathematical algorithm to the instrument-internal data could separate the evaporative HC signal from the exhaust HC signal and improve the running loss detection limit. Ideally, this separation would lead to an ability to post-process EDAR internal remote sensing data to quantify on-road running loss emissions.

We have now received an EPA work assignment that funds an analysis of the SEP 2016 staged data to evaluate EDAR's potential for measuring on-road running loss emissions by the EDAR instrument. Of the five on-road measurement methods discussed in this section, we think that the EDAR RSD method had the most promise. In addition, the CRC RW-105 is expected to evaluate the running loss measurement potential of the HEAT EDAR instrument of an on-road fleet evaluation study in around October 2019.

PEAQS – ARB's PEAQS system can also be considered for on-road testing of running loss emissions. The PEAQS system aspirates air that surrounds a vehicle as it drives past the aspirator inlet tubing. A PEAQS advantage is that it uses conventional analytical instruments to measure the ambient concentrations introduced by the passing vehicle. Tailpipe exhaust concentrations can be calculated for gasoline vehicles using the measured ambient concentration time series in a manner similar to the calculation method for the ESP Accuscan RSD instrument.

We suspect that PEAQS may have similar drawbacks as the ESP Accuscan RSD instrument: an insufficiently low HC detection limit; a low number of individual, independent measurements for each vehicle pass; and a single HC channel that responds to both exhaust HC and evaporative HC. Since PEAQS uses conventional analyzers, analyzer choices may be able to address two of these concerns. First, a very sensitive HC analyzer may be available to get to very low ambient concentrations; however, the detection limit of such an analyzer may not be the limiting factor. If background ambient HC levels are variable, then the effective detection limit may be higher than the instrumental detection limit. Second, a single HC channel and a low number of individual, independent measurements mean that separation of the HC signal into an exhaust HC signal and an evaporative HC signal will be difficult. To eliminate the separation requirement, one solution might be to use an analyzer that is specific to a compound that is found primarily in evaporative emissions, for example, butane or ethanol. The instrument would still need to have a low detection limit and be able to produce a time series of individual, independent measurements for each vehicle pass.

Ambient Air Monitoring Approaches – Rather than obtaining detailed running loss emission measurements on individual vehicles at individual operating conditions, an alternative source of emission data is the measurement of ambient concentrations of pollutants in the "canopy" that surrounds the flow of traffic. As vehicles drive down a roadway, their emissions are laid down and add to the mix of pollutants from the vehicles that passed the location in front of them. Over time the ambient concentrations near and above the roadway reflect the accumulating pollutants from the traffic. An analysis of the time series of ambient pollutant concentrations near the roadway could lead to the development of an emissions model for the fleet of vehicles passing down the roadway without measuring the specific emissions of each individual vehicle.

A variety of analytical techniques can be considered for measuring these ambient concentrations. For example, an infrared technique that uses a scanning laser beam could provide a curtain of laser light transverse to the direction of traffic flow through which all vehicles in one direction drive. Rather than triggering data collection on each individual vehicle, the instrument could collect data continuously to provide a measure of the total mass of emissions in the two-dimensional scan. An instrument that uses a laser beam can have output channels for individual compounds.

If the instrument is located at a place where the air above the roadway is surrounded by a physical structure, for example, a tunnel, or an overpass, then a retro-reflective tape can be used to reflect the outgoing laser beam back to the instrument for the analysis over the entire cross-section of the air above the roadway. Another possible method to return the instrument's outgoing light beam is to use a corner prism on the far side of the roadway. Unlike a first surface mirror, a corner prism will return the light beam to the instrument even if the prism and/or the instrument is vibrating.

Separation of signals from running loss evaporative hydrocarbons and from exhaust hydrocarbons would need to be performed. One possible approach is to use Fourier Transform Infrared spectroscopy (FTIR). That method would produce a high-resolution absorption spectrum of the air above the roadway. The spectral features could be used to quantify evaporative emissions, which is made up primarily of a few compounds (butanes, pentanes, and ethanol) as opposed to exhaust hydrocarbon compounds.

Another possible spectroscopic method is gas filter correlation spectroscopy (GFC). This method uses a cell in the instrument that contains a sample of the analyte gas to act as a high-resolution filter for detecting the same gas in the open path across the roadway. For measuring escaped gasoline headspace vapor, the instrument cell would be filled with gasoline headspace vapor. And for measuring gasoline vapor from gross liquid leaks, another instrument cell would be filled with volatilized gasoline. This offers the opportunity for measuring headspace vapor and gross liquid leaks simultaneously. The GFC method has benefits of low detection limit and improved rejection of interfering compounds, such as, in our problem, other hydrocarbons in the ambient air.

7.4 Liquid leaks

Liquid leak prevalence rates in MOVES are a product of visual inspection programs, primarily Smog Check, one of few state I/M programs to include a visual inspection for liquid fuel leaks. Because data specific to liquid leaks is scarce, MOVES relied primarily on Smog Check data in the development of liquid leak prevalence. This provides a steady stream of data for updating EMFAC, though there is some concern with underestimation as owners have incentive to fix vehicles prior to inspection. MOVES also relied on visual data from a 1990s API research program for in-use rates, which were higher than Smog Check levels. Overall, the data available were not sufficient to develop separate rates by model year of vehicle type; the rates in MOVES are in broad age bins only. In general, liquid leaks requires visual inspection to isolate. They are not detected either by OBD, and remote detection cannot distinguish between vapor and liquid leaks. Liquid leaks are often a product of "user error" – Colorado field data turn up liquid leaks as a result of accidents, amateur bodywork, and even child seat installation fails. Visual inspection is the most reliable way to detect these very unique malfunctions.

7.5 Canister Degradation

The prevalence of canister degradation is not explicitly accounted for in MOVES or EMFAC. Canister degradation will lead to high evaporative emissions over all modes of operation, but will affect cold soak diurnal and refueling emissions the most because when the vehicle is not operating there is no purge system to draw vapors and help mitigate the loss of vapor storage (the same is true of hot soak, but having just come off of a period of vehicle operation the canister will not have built significant vapor). Canister degradation cannot be monitored by OBD, and field methods which focus on running less of hot soak emissions will not pick up canister issues. Degraded canisters were found in the course of field inspections [cite Colorado & EPA], leading to concerns of their unquantified impact on real-world diurnal emissions. A recent focus of field research has been to attempt to identify these canister failures using non-intrusive means. This section summarizes the status of imaging methods to determine canister degradation.

On-Road: Rebellion Photonics Gas Cloud Imaging IR Camera – Rebellion Photonics has developed an infrared camera for detecting vapor leaks at industrial plants, such as refineries and chemical plants. The camera divides each pixel in its view into several infrared bands every one-fifteenth second to produce a video in the infrared. By combining the absorbances of the infrared bands that match the absorbances of individual compounds or groups of compounds, the camera can produce a video that images specific gaseous compounds or mixtures, for example, gasoline vapor. The camera uses background infrared radiation that is present in a scene as the light source for the absorbance measurements.

ERG evaluated the Rebellion camera for detecting refueling evaporative emissions at a gas station in a 2015 EPA project.[15] Refueling emissions were best detected by looking for movement in the infrared video in a location near the point of refueling, that is, around the fuel fill door or the rear of the vehicle. This method was used to detect refueling emissions from pre-ORVR vehicles and from canister breakthrough of newer technology vehicles when vehicles were being refueled with high volatility gasoline on an abnormally warm day. The results were qualitative. The low-level refueling emissions of well controlled vehicles were not detectable by the viewing the camera's image. The technique as used in that project – viewing refueling events from a 100-foot distance – was not able to determine if a vehicle had a vapor leak, a fuel leak, or a defective canister even though vehicles were stationary. It is possible that shorter viewing distances might allow these different types of sources to be distinguished.

As a follow-on to that 2015 study, we are now performing a larger-scale 2017-2018 EPA study in Denver gas stations with the goal of semi-quantifying the refueling HC emissions with the Rebellion Photonics camera using advanced data post-processing techniques. The goal will be to determine the prevalence and rate of refueling emissions (gHC/gallonFuelDispensed) as ORVR vehicles age.

Detecting evaporative emissions from a moving vehicle is much more difficult than from a stationary vehicle because the evaporative emissions plume is diluted and dispersed as the vehicle moves. ERG's back-of-the-envelope calculations indicate the only way that the current camera would be able to detect even high level running loss emissions would be for the camera to look at the rear of vehicles as they drive away from the camera so that the pathlength of the optical absorption is very long. Looking at the evaporative emissions plume from above the roadway or from the side was not expected to produce a long enough pathlength for evaporative emissions detection.

Given the relatively low sensitivity of the camera in the environment of a moving vehicle and the expected need for the video to be continuously observed for the presence of a moving hydrocarbon plume, suggests that the Rebellion camera in its current state of development would not be a good candidate even just detecting running loss emissions – even though its ability to screen vehicles for elevated refueling emissions was demonstrated in the EPA study.

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[15] DeFries, *Evaluation of Rebellion Photonics Gas Cloud Imaging Camera for Screening Refueling Evaporative Emissions from Light-Duty Vehicles*, prepared for U.S. EPA by ERG April 2016.

8 Longer Term: In-Situ Measurement & Validation

8.1 Design Approach for On-Road Testing

An alternative to in-lab testing on a small set of in-use vehicles, which was described above, is to measure the running loss emissions of large numbers of vehicles or traffic on the road, that is, in the natural running loss emitting environment. The goal is to find the relationship that can predict the running loss emissions of the fleet and its major subsets as the vehicle mix changes and as the fleet operating environment changes. As discussed below, this approach to estimating fleet running loss emissions completely changes the measurement and modeling requirements.

Suppose analytical methods were available that could either measure the running loss emissions of vehicles on the road (for example, a remote sensing method) or a method that could measure the running loss emissions of traffic as it was driving on the road, or in a tunnel environment (ambient measurements). Instruments with such a technology could then be placed at different on-road locations to gather emissions measurements in situ.

Here is the idea of this approach. Identify a limited number of measurement sites and times that, when taken as a whole, cover a wide range of vehicle types, model years and ambient conditions. The dependence of the measured running losses at these sites and times on the factors is the running loss model. Measurement sites and times would be selected based on transportation data and license plate reader data. Output from travel demand models would be used to estimate traffic flow and vehicle speed in different locations and at different times so that a wide range of roadway operating conditions would be covered. License plate readers would be used to measure vehicle mix at different candidate sites and times.

For in-situ measurement, three factors (evap emission control system technology, ambient temperature, and vehicle speed) can be measured. Evap emission control technology of individual vehicles would be estimated by matching data from license plate readers with registration and/or IM databases. Ambient temperature would be measured at the measurement site. Vehicle speed would be measured using standard techniques used by remote sensing vendors.

Two factors (fuel volatility and initial boiling point) cannot be measured remotely, but their effects on running losses could be quantified by ensuring that measurements are taken in different seasons when fuel volatilities are different.

Five factors (canister capacity, fuel tank properties, evaporative emission control system malfunction status, vehicles with fuel leaks, and vehicles with vapor leaks) cannot be determined by independent measurements. However, these factors are associated with vehicle mix. For example, vehicle mixes that are older can be expected to have more vehicles with lower canister capacities, more malfunctioning evaporative emission control systems, more fuel leaks, and more vapor leaks. Thus, measurement sites and times that cover, as a whole, a wide range of vehicle mixes, as measured by license plate readers, will tend to have a wide range of these five factors.

The four factors (tank temperature increase rate, canister saturation at the start of trip, canister purging history, canister saturation state) that are related to operating history cannot be remotely measured. However, since they can be expected to be different for vehicles driving in different locations, a selection of a variety of measurement sites will tend to cover the range of each of those factors.

The remaining factor (fuel level) also cannot be measured remotely, but its distribution in the fleet is likely to be the same across most measurement locations.

Overall, the running loss model will be explicitly dependent on the five key factors that are associated with season or are measured: fuel volatility, initial boiling point, ambient temperature, evaporative emission control system technology, and vehicle speed. The effects of the remaining factors on running losses will not be quantified but their net effects will be included in the running loss values predicted by the model. For example, with this approach the individual vehicles that are causing major contributions to the fleet running loss emissions are not necessarily identified, but when they drive past the instrument, their contribution to the overall running loss emissions is measured.

Comparison of In-Lab and On-Road Measurement Approaches – In summary, the in-lab testing approach needs to recruit in-use test vehicles where the running loss emissions distribution is highly skewed. To do this properly, a careful stratified random sampling plan should be used. Then, the measurements in the lab would likely need to be conducted under conditions where the non-modellable and major running loss influencing factors are varied. A comparison of the observed running loss emissions with the theoretical tank vapor generation would be used to develop evaporative emissions control curves for problem-free and malfunctioning vehicles. De-stratification of the results to the fleet would require the availability of data describing the prevalence of high emitting vehicles in the fleet.

For the on-road testing approach, on-road analytical techniques would need to be developed to be able to measure running loss emissions on individual vehicles or of the traffic at any given location. These instruments would then be sited according to a stratified sampling plan based on the output of travel demand models and license plate reader data. Simultaneously with the collection of running loss data from the analytical instruments, license plate readers would be used to determine the mix of vehicle model year, odometer reading, and evaporative emission control system technology. A regression of the running loss measurements of individual vehicles at the different sites against the fuel volatility, evaporative emission control technology, vehicle age, odometer reading, ambient temperature would be used to determine the influences on running loss. That regression model would then go directly into EMFAC to predict the running loss emissions of the fleet under a variety of operating conditions.

8.2 A Hybrid Approach: On-Road Measurements plus In-Lab Measurements

Conducting a running loss measurement program using a hybrid approach is worth considering. A big challenge of the on-road testing approach is that the running loss emissions of problem-free vehicles may be below the detection limit of remote-sensing or ambient instruments. But one of the big advantages of on-road testing is that the running loss emissions are measured under the actual conditions in which they are emitted – on the road. On the other hand, a big challenge of the in-lab testing approach is finding and recruiting a representative sample of the apparently rare high-emitters in the fleet. But one of the big advantages of in-lab testing is accurate and low-detection-limit emissions measurements for vehicles that have low emissions levels and whose emissions probably do not depend greatly on the test conditions or vehicle conditioning.

Suppose on-road testing were used to measure the running loss emissions of vehicles with moderate and high emissions as a function of key factors (fuel volatility, initial boiling point, ambient temperature, evaporative emission control system technology, and vehicle speed) as described above. Then, the emissions of the vehicles that were "non-detects" in the on-road testing could be estimated using the results from the in-lab measurements. "Pasting together" the results from both types of test programs might be able to adequately estimate fleet running loss emissions. The hybrid approach might thus be able to avoid the difficult and uncertain sampling of high emitters from the skewed running loss distribution for the in-lab testing and avoid the development of an on-road analytical method[16] with a running loss detection limit that is substantially below current running loss certification standards.

As a basis for an EMFAC evaporative running loss emissions module, some sort of emissions measurements needs to be made to serve as the basis for the module. The next two subsections have descriptions of potential running loss measurement methods that could be used to gather data for a hybrid model made up of on-road measurements and in-lab measurements. The discussion below presents methods for measuring the running loss emissions of individual vehicles on the road: HEAT EDAR RSD, Opus Accuscan RSD, Rebellion Photonics Gas Cloud Imaging camera, PEAQS, ambient air monitoring approaches, and in the lab: SHED and PSHED. We described ERG's project experience where ERG has evaluated some of the approaches. For each of these types of measurements, we will discuss advantages, disadvantages, and areas for improvement for the specific technique that is discussed.

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[16] Note that the on-road method would still need to have a good technique for separating the evaporative hydrocarbon emissions signal from the exhaust hydrocarbon emissions signal.

9 Conclusion

The adaptation of MOVES evaporative module to EMFAC provides a template for evaporative research to further customize the model to California, and to develop improved methods over time. While still relying on traditional SHED evaporative tests, the MOVES approach introduced many new sources of data evaporative emissions modeling, including:

- Isolation of permeation and vapor venting loss;
- Explicit accounting for liquid leaks;
- Tracking of fuel tank temperature for estimating temperature effects;
- Use of OBD trouble code data to quantify vapor leak prevalence on newer vehicles.
- Use of field data (PSHED) to develop hot soak emission rates and quantify vapor leak prevalence.

ARB's evaporative emissions research can proceed with short, medium and long-term goals in mind. Immediately, parameters already in the new EMFAC evaporative module can be updated with California-specific data. This is already the case with trip data from CHTS, which can be updated once new survey data is made available. Vehicle attributes such as vehicle fuel tank size and canister size can be pulled from emissions certification applications. California Smog Check data can be used to update OBD DTC rates, and liquid leak rates for use in customizing emission rates.

Other parameters can be updated with California-specific data, but would require new SHED and field testing. SHED testing in the manner of CRC E-77 would generate California-specific base rates, but at this stage may be less important than quantifying real-world emissions and leak prevalence. For example, a PSHED program modeled after work in Colorado could be used to update hot soak emission rates and supplement OBD leak prevalence data, and further roadside pullover could establish if Smog Check OBD DTC rates continue to be low compared to "in the wild" vehicles.

Medium term, experimental methods for quantifying a broader range of real-world evaporative emissions and malfunction modes can be further developed. In particular, canister degradation is largely unquantified, and could be an important source of emissions while vehicles are parked. Longer term, a broader on-road program using something like ARB's PEAQS unit could shift evaporative emissions modeling to an empirical-based approach, either as means of validation for bottom-up inventory modeling, or an eventual replacement.