A Study of R134a Leaks in Heavy Duty Vehicles

CARB Contract No. 06-342

Andrew Burnette
infoWedge

Rick Baker
Eastern Research Group

Acknowledgements

- Dr. Tao Huai, Dr. Tao Zhan, Dr. Alberto Ayala, Dorothy Shimer (CARB)
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- Dr. Stephen Andersen (US EPA)
- Multiple Sacramento area fleets (most of whom requested to stay anonymous)

Outline

- Introduction
- Methods
  - Gravimetric
  - Maintenance (mass-balance)
- Results
  - Gravimetric
  - Maintenance (mass-balance)
- Analysis/Discussion
  - Gravimetric
  - Maintenance (mass-balance)
- Summary/Recommendation

Background

- Refrigerants used in mobile air conditioning (MAC) systems can enter the atmosphere through a number of mechanisms
  - low-level, long-term leaks
  - rapid leaks caused by discrete incidents (e.g., system failure)
  - regular system servicing
  - end-of-life losses

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1,1,1,2-tetrafluoroethane (HFC-134a)

- R134a is one of the most common refrigerants used in MAC systems today
- It has a global warming potential (GWP) of 1,300 (1,2)
- ARB estimated that total R134a emissions from all MAC systems in California (including light-duty vehicle systems) approximately 4-million metric tons of CO_2-equivalent (CO_2E) in 2004 (3)

(1) Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4), 2007
(2) Updated GWP from AR4 is 1430, but legacy value of 1300 is used here for comparison to previous inventories
(3) California Air Resources Board, Initial Statement of Reasons for Proposed Regulation for Small Containers of Automotive Refrigerant, December 5, 2008, p. 4.

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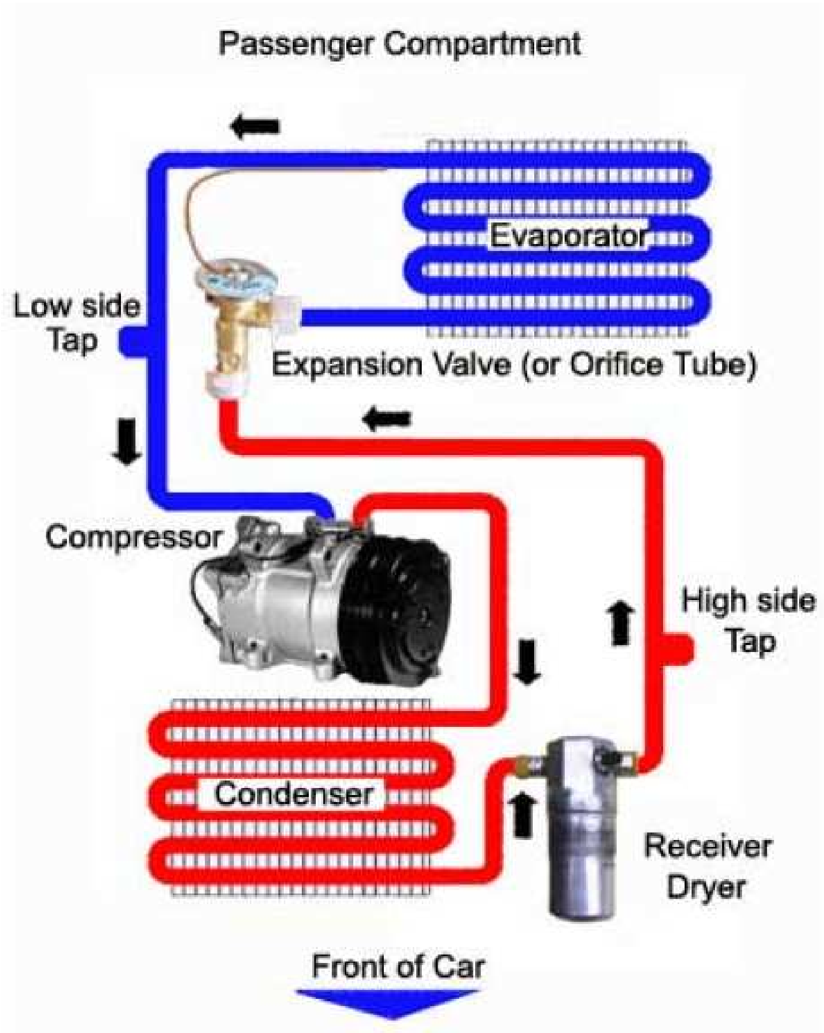
Generic MAC System (vapor compression cycle)



Source: Yingzhong Yu, "Generic Approach of Refrigerant HFC-134a Emission Modes From Mobile Air Conditioning (MAC) Systems." PhD Thesis, Ecole des Mines, Paris, France, October 23, 2008

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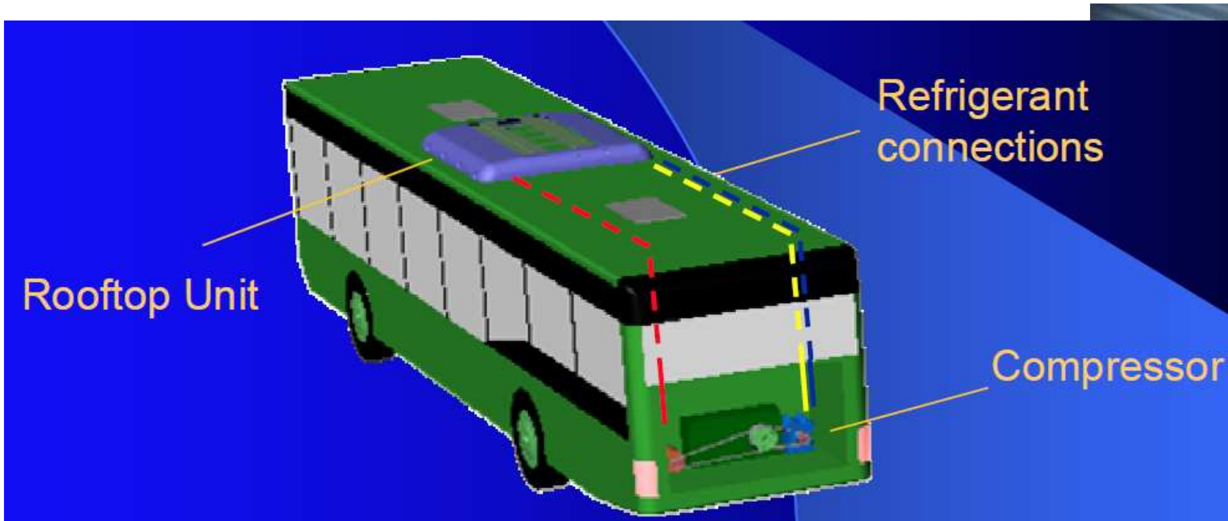
MACs In Vehicles



Project Objectives

- Characterize in-use R134a emissions from heavy-duty onroad and offroad vehicles in California
  - Estimate low-level, long-term leakage from MAC systems that use R134a
  - Combine with equipment population estimates into an annual emission inventory for the state for those types of leaks

Target Sample for the Study

- Heavy-duty, onroad and offroad
- Variety of MAC configurations
  - Joint seal type
  - Amount of permeable materials
  - Compressor type
- Budget for about 70 vehicles

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MAC Configuration Considerations

- Used SAE J2727 and industry experts to determine MAC parameters important to leak rates
- Limited sample size and probable variability of field measurements dictated 1 or 2 MAC parameters to be investigated for impacts on estimated emissions

Sample Selection

- Vehicles in professional use
- Protected, on-site garage space with power required
- Turn-key sample process takes hours to complete

Target Number of Samples

Bin ID	Vehicle Type	# Units
1	Full Sized Transit Bus	11
2	Shuttle Bus	5
3	MD Utility Truck/Van	18
4	HD Truck Tractor	18
5	Other HD Trucks (dump, waste, etc)	9
6	Construction Equipment	5
7	Agricultural Equipment	4
	Total	**70**

Gravimetric Measurement Method

- Several alternatives investigated
- Selected method blased upon one developed by Dr. Denis Clodic, Ecole des Mines, Paris, France
  - Originally for light-duty cars in a climate controlled area
  - Modified for application to heavy-duty equipment in the field
  - Similar to SAE J2762 (which is also based upon Clodic's method)

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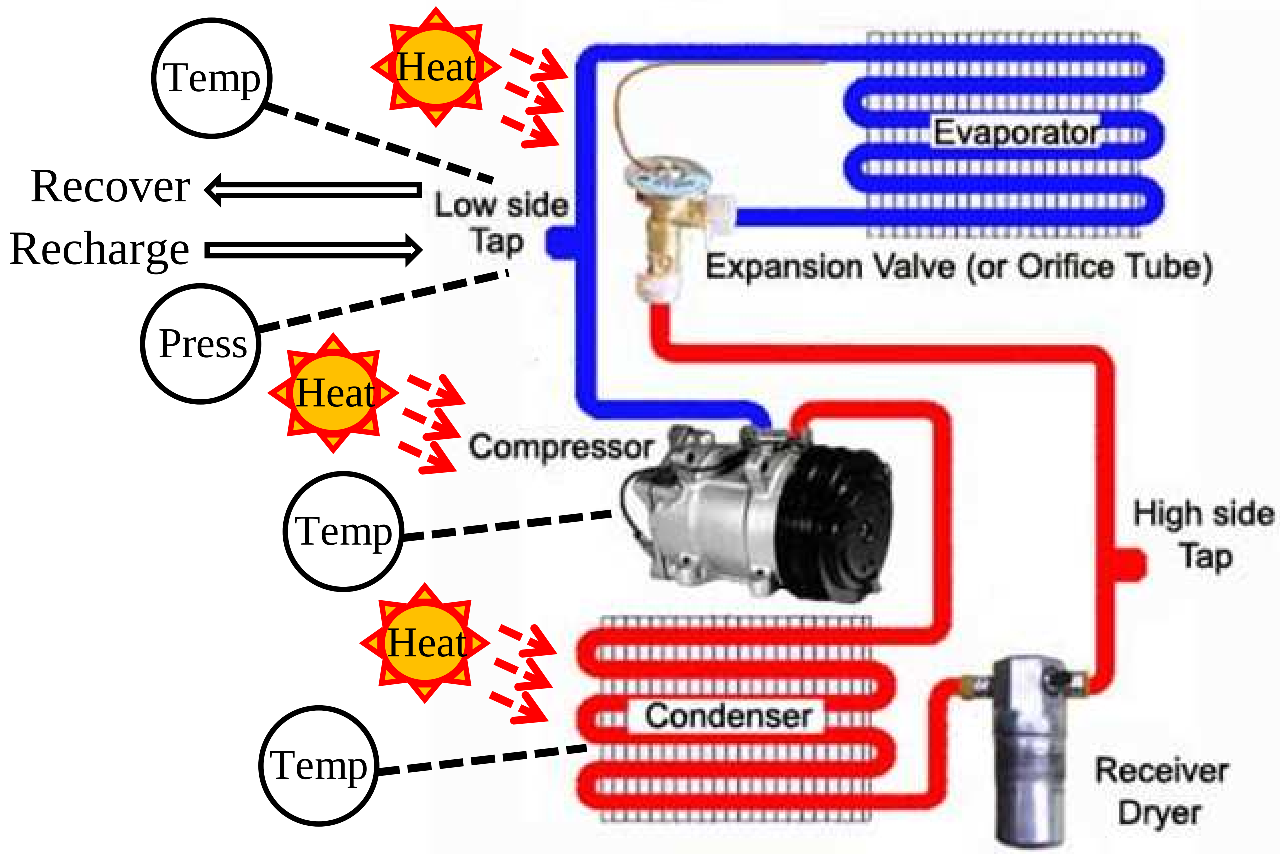
Gravimetric Method Overview

- Recover, evacuate and recharge MAC with known amount of R134a
  - Recover from MAC to 20 kPa with compressor
  - Distill R134a from oil and weigh
  - Evacuate recovery equipment to 20 Pa with vacuum pump
- Release to normal operations for several months at least
- Recover the R134a to determine leakage, if any, using same steps as above

Schematic of Gravimetric Method



Recovery Equipment List

Item	Notes
Vacuum pump, high vacuum gauge, hose	High capacity, 2-stage vacuum pump: Mastercool model 90067 with 212 LPM (7.5 CFM) capacity and 0.37 kW (0.5 HP) motor. High vacuum gauge: For reading vacuum at 20 Pa-absolute. Resolution of 0.1 Pa.
Recovery compressor and hose	Compressor (Bacharach model Stinger 2000) and dedicated hose used to recover R134a from the MAC into the Recovery tank.
Electronic scale	Electronic balance: Citizen model SSH 93 with capacity of 30 kg (66 lb) and resolution of 0.1 g (0.0035 oz).
Recovery tank	Cylinder used only to recover R134a from the MAC. After recovery R134a is transferred from this tank to the Recycling tank.
Manifold and 3 hoses	Service manifold with dedicated hoses and gauges for the low-pressure and high-pressure sides of the MAC and with a hose to transfer R134a from and to the MAC.
Charging tank and hose	Cylinder of new or recycled and purified (of air and water) R134a with a dedicated hose.
Recycling tank	Cylinder used only to receive R134a distilled from the recovery tank.
Thermocouples and displays	K-type thermocouples and readouts to monitor various temperatures.

Gravimetric Method Considerations

- Maintain MAC system temperature
- Control recovery rate to recover only vapor (i.e., vaporize all liquid refrigerant before recovery)
- Minimize recovery hardware, procedural leak sources and fugitive losses

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Maintain MAC Temperature

- Warm up engine compartment
- Heat key components during recovery to counteract phase-change cooling
- Monitor temperatures during recovery (keep above 20°C)

Control Recovery Rate

- Recover only vapor (minimize liquid entrainment)
  - Lubricating oil is dissolved in liquid R134a
  - Oil is difficult to distill from recovered R134a and a source of error that can (mostly) be avoided
  - Watch recovery sight glass for liquid and recovery port temperature for rapid drop (due to liquid)

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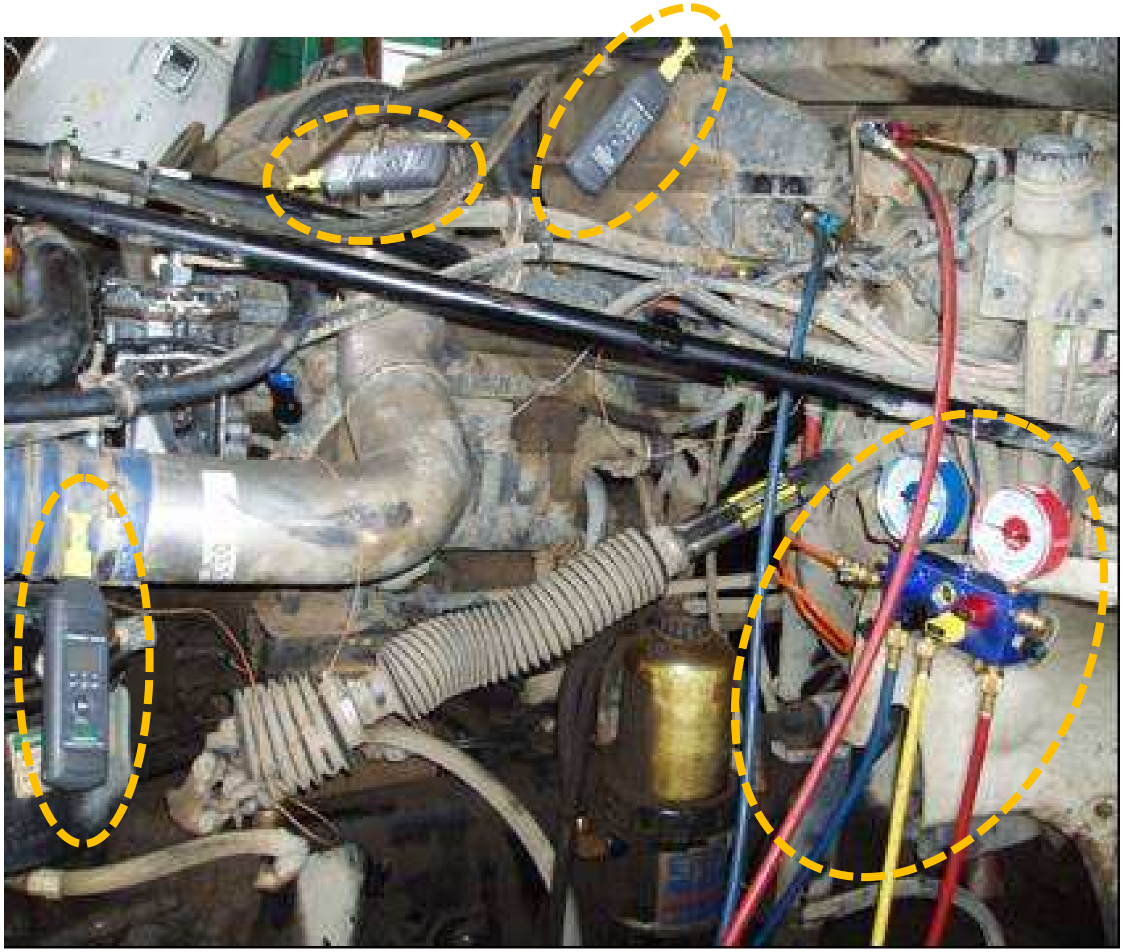
Evacuation of Recovery Unit and Hose before Test

Manifold & Thermocouples During Recovery



Weighing Recovery System after Recovery

Recharging MAC after R134a was Removed

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Anti-tamper Measures During a Test

Types of Participant Fleets

- Voluntary participation
- Government and private fleets in the Sacramento area
- Electric utilities, waste collection, heavy construction, universities, municipalities, and public and private transport

Maintenance Data vs. Direct Leak Rate Measurement

- Some fleets could only participate by supplying maintenance data
- Some of these data could be used to estimate total refrigerant consumption using a “mass balance” approach
- This approach was expanded to public transport fleets statewide

Issues with Mass Balance Approach

- Refrigerant consumption not typically tracked for each vehicle
- Useful mainly for homogenous fleets (e.g., large buses all using the same refrigerant)
- Estimates overall consumption of refrigerant (accounts for all leak sources, including technician practices, faulty service equipment, theft, etc.) instead of just longer-term, slow leaks from the MAC

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Mass Balance Data Requirements

- Quantities and types of buses
- Age range of the buses
- Type of refrigerant used in each type of bus
- Consumption rate of R134a for the fleet

Data Analysis

- Estimation of leak measurement accuracy and precision
- Quality Assurance
- Maintenance Data

Determining Accuracy of Leak Rate Measurement

- Evacuate and recharge a new vehicle
- Recover R134a to determine mass balance closure
  - Ideally recover 100% of recharge
- Perform on multiple vehicles
- Estimate accuracy and precision

Data Quality Assurance

- Written, step-by-step instructions and data sheets
- NIST traceable weights to check the scale at several points during the test
- “Sanity” checks of temperature and pressure readings compared to empirical observations
- Data post-processing included comparison to previous same/similar vehicles of capacities, transcription error checking, etc.
- Archival of raw data sheets

Results of Measurement Accuracy Tests

- Performed accuracy/precision test on 4 new vehicles
  - First one used a draft procedure
- 3 MACs tested with final procedure had mass closure of 99% or greater ("losses" ranging from 3.7 g to 14.6 g)
- Compare to results from a controlled, lab-like setting which achieved closure of 1 g for passenger car MACs(1)

(1) D. Clodic, "Research Study on the Definition of the Implementation of a Method of Measurement of Annual Leak Flow Rates (LFRs) of MAC Systems", ACEM/Armines Contract, January 2006.

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Mass Based Leak Sample Overview

- Leak measurements occurred from Jan 2009 to Apr 2010
- Total of 65 samples, 3 invalid due to servicing or failure during intervening period
- 3 converted from R12 to R134a
- 1 (heavy construction) had electric compressors

Sample Counts by Sample Bin and Model Year

Sample Bin Key
1 – Full-Sized Transit Buses
2 – Shuttle Buses
3 – Medium-duty Trucks
4 – Heavy-duty Tractor Trucks
5 – Other Heavy-duty Trucks (e.g., waste haulers)
6 – Construction Equipment
7 – Agricultural Equipment

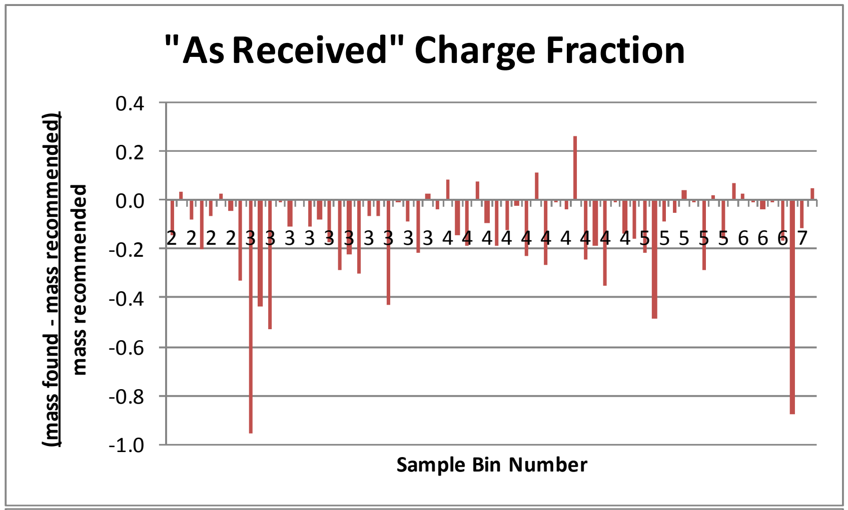
Sample Bin / Model Year	1	2	3	4	5	6	7
1989			1				
1990				1			
1991			1	1			
1993				1			
1995				1			1
1996			1				
1997		1					
1998		1	1	1			
1999			1	3	1	1	1
2000		2	1	2	2		
2001				2			
2002			1	1		1	1
2003		2	1			1	
2004		1	2	2	1	1	
2005			2	1		1	
2006			1		3		
2007			6	2	1		
2008				1	1		

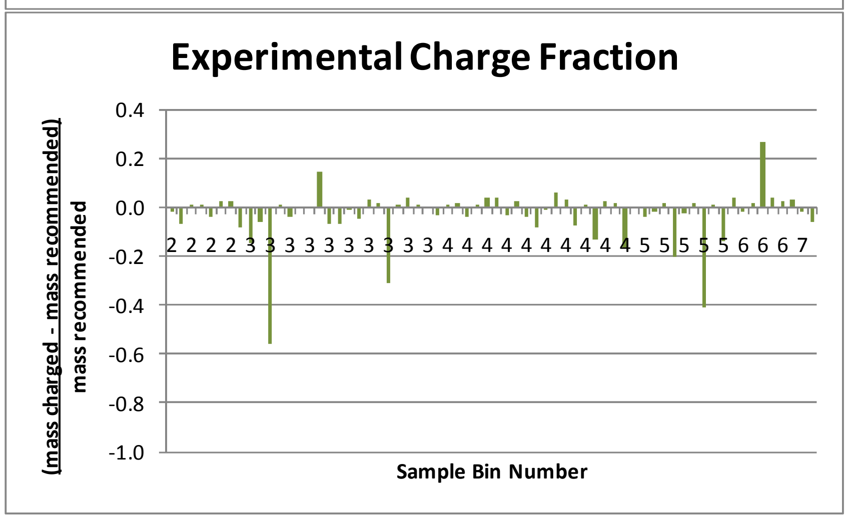
Sample Counts by Sample Bin and MAC Capacity

<u>Sample Bin Key</u>
1 – Full-Sized Transit Buses
2 – Shuttle Buses
3 – Medium-duty Trucks
4 – Heavy-duty Tractor Trucks
5 – Other Heavy-duty Trucks (e.g., waste haulers)
6 – Construction Equipment
7 – Agricultural Equipment

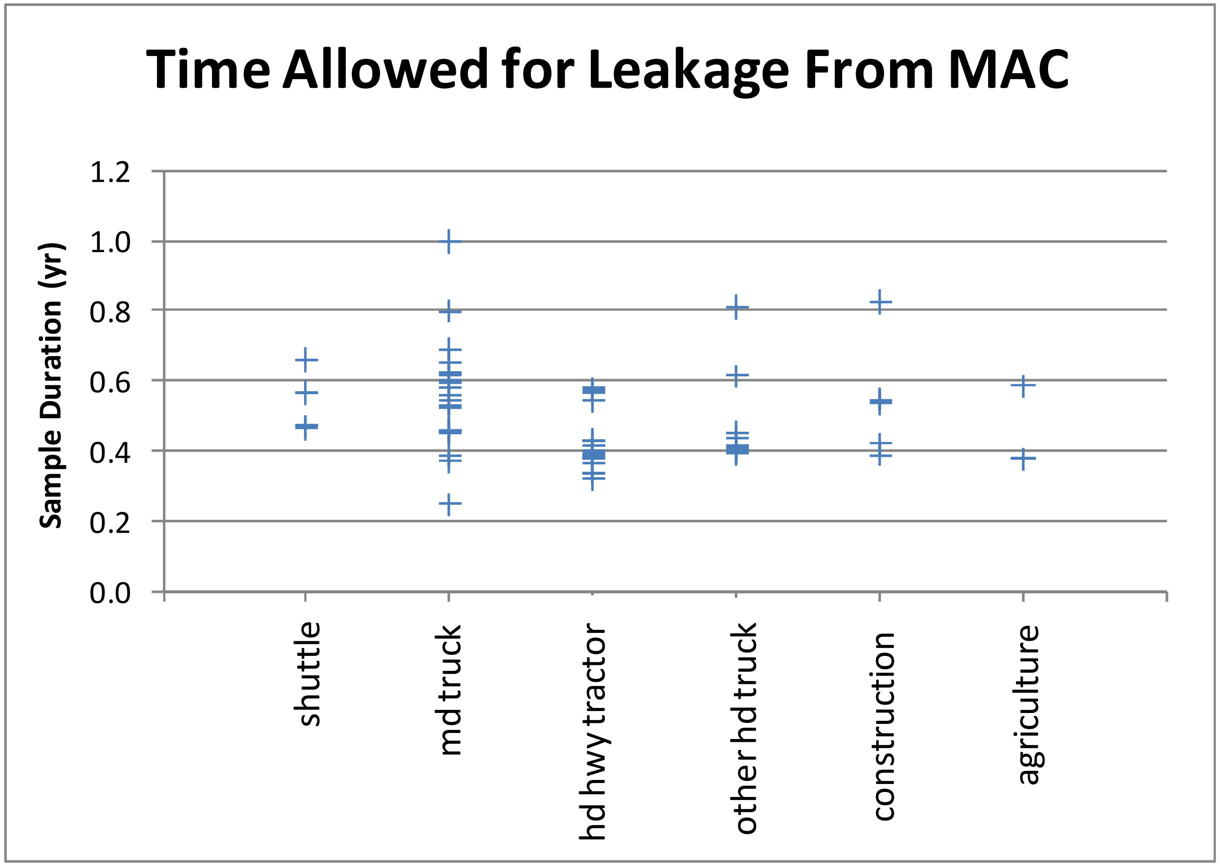
Sample Bin	1	2	3	4	5	6	7
Capacities (g)							
650		1					
907			1		1		
1080			4	2			
1134		1	1	2	1		
1190		1	3		2	1	
1247			1				
1280			1				
1310			5	5	2	2	2
1360		1	1	2	2		1
1400						1	
1474			2	6			
1700						1	
1950				2	1		
2495		3					

"As Received" Charge Versus Experimental Charge

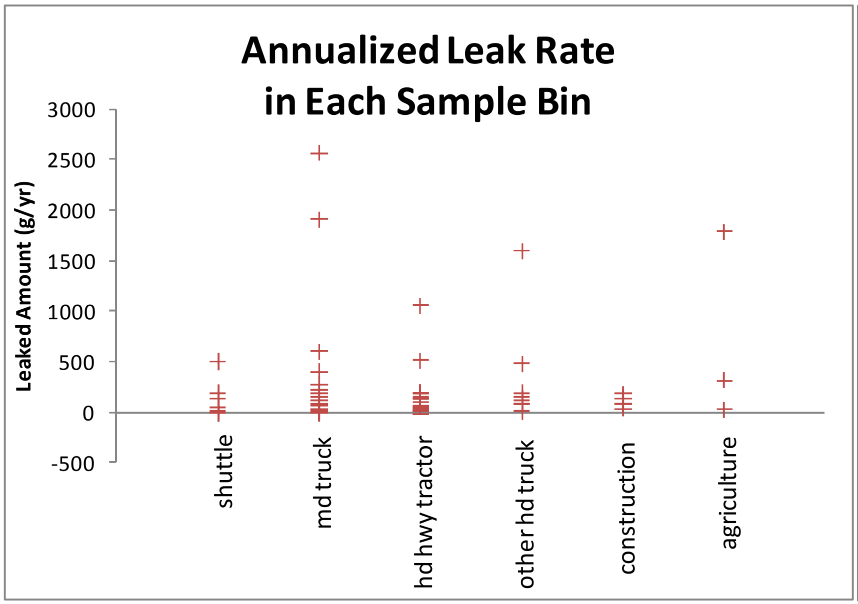


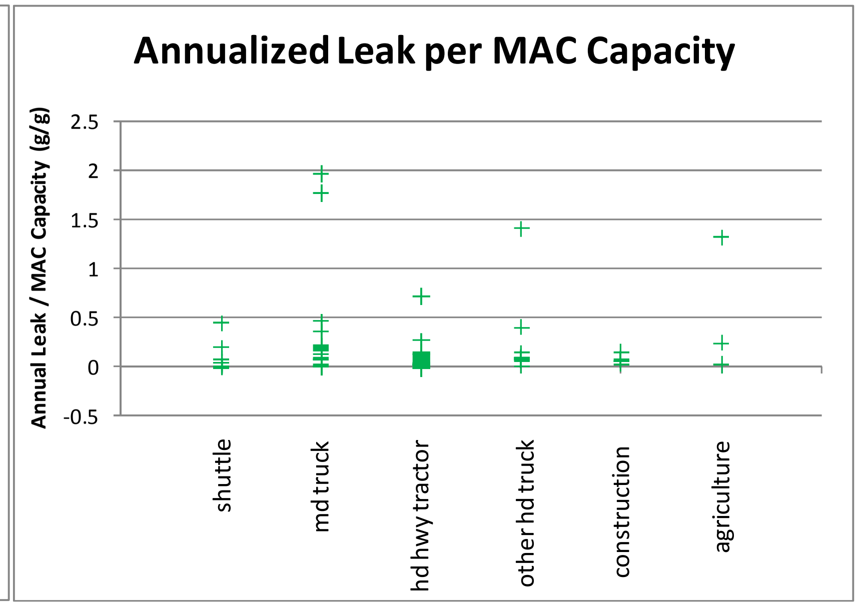


Length of Sample Time, Grouped by Sample Bin



Annualized Leak Rate: Each Data Point, by Sample Bin





Leak Rate Projection Analysis

- Linear interpolation used to extrapolate from actual sample period to 12 months
- Linear assumption probably results in over-estimate of leak rate because rate would taper off as system working pressure decreases
  - Note that several high leak rate systems are projected to empty in less than 1-year

Measured Leak Rate Modeling

- The measured (annualized) leak rate data were plotted by various parameters to find obvious modeling variables (e.g., model year, MAC capacity, etc.)
- Given the variability of the data and the small sample size, statistical rigor was not possible
- A model year split at 2006 was selected because of the voluntary IMAC leak standards the onroad manufacturers agreed to follow (1)
  - This is not applicable to offroad equipment, which are assumed to have the pre-2006 leak rate

(1) Personal communication with Gary Hansen, Red Dot Corporation, April 2008.

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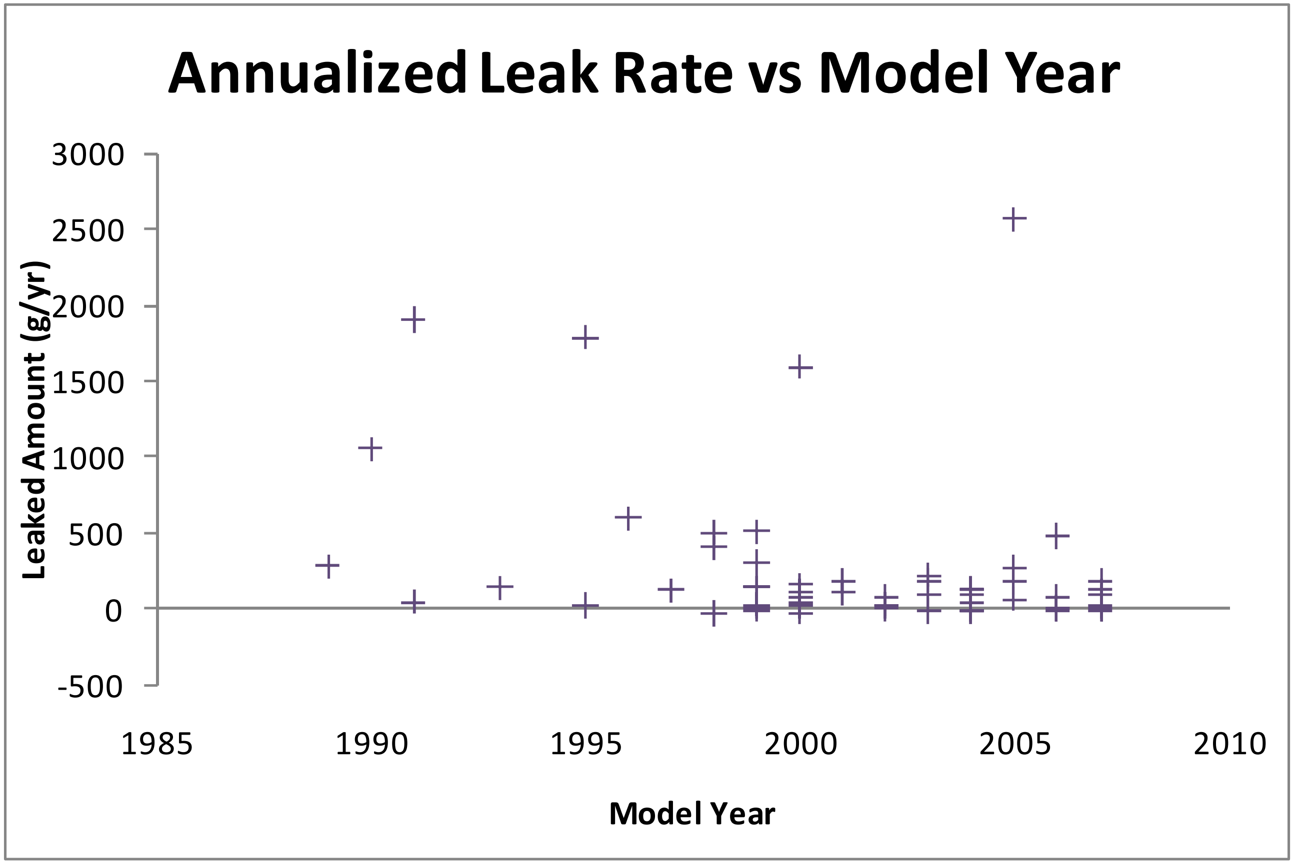
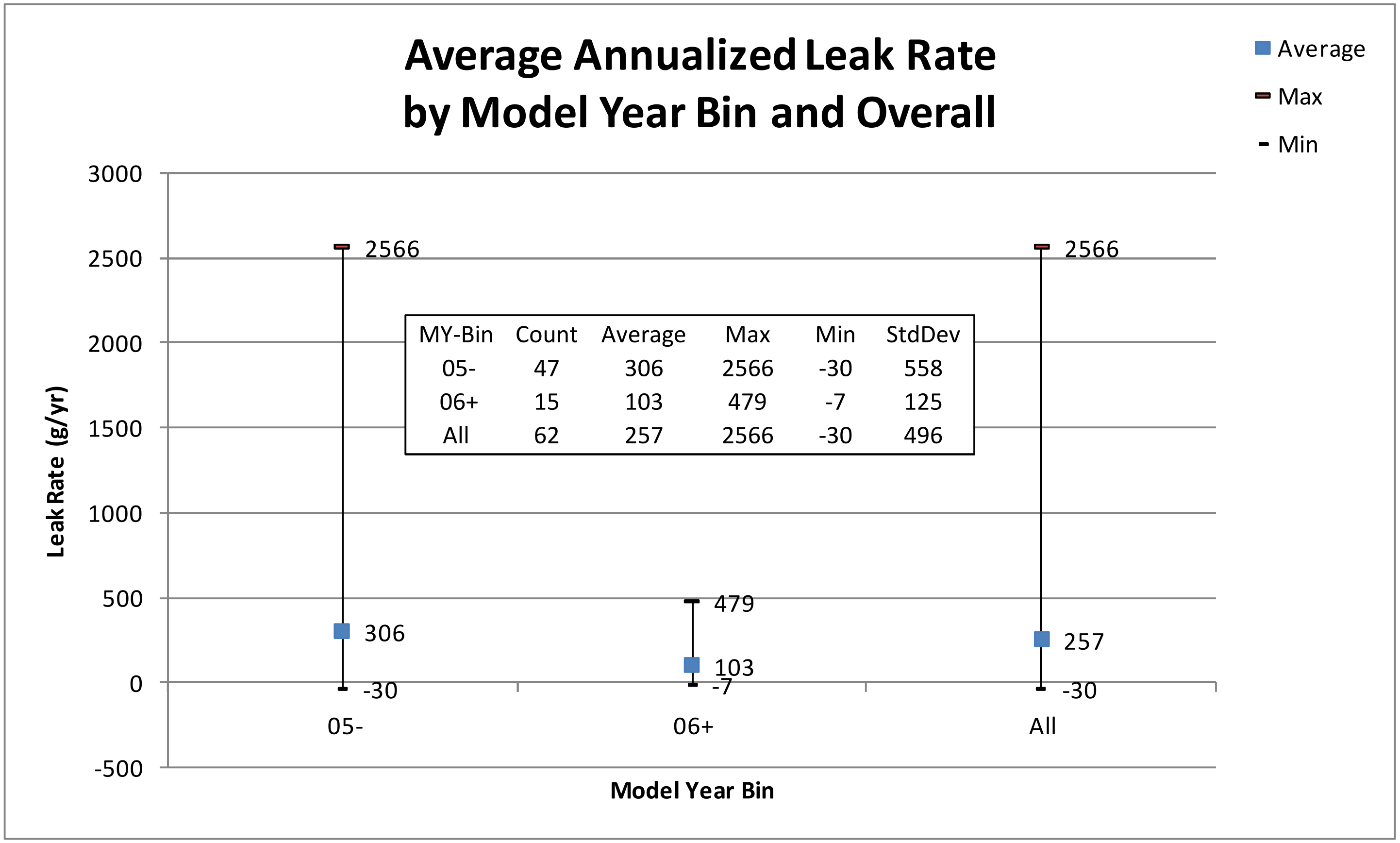
Annualized Leak Rate, by Model Year



Average Results by Age Group, and for All Vehicles



MY-Bin	Count	Average	Max	Min	StdDev
05-	47	306	2566	-30	558
06+	15	103	479	-7	125
All	62	257	2566	-30	496

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Analysis of Maintenance Data

- Assumptions
  - Accurate tracking of R134a purchases and recycling
  - Accurate records of which vehicles use R134a
  - Average annual R134a purchases equal average annual R134a leaks (mass balance)

Maintenance Record Leak Rate Sample

- Five transit bus fleets participated
- Operated all across California
  - Los Angeles air basin
  - Northwest coastal
  - Northern in-land
  - Sacramento region
  - San Joaquin Valley

Maintenance Record Leak Rate Analysis

- 329 buses in these fleets were 29- to 45-foot long coaches
  - 181 used R134a
  - The rest used R22 or R407c or none
- Fleet-average leak rate (all buses using R134a) was 1,340 grams per year
  - All types of “leaks” from maintenance equipment, maintenance practices, recycling, slow leaks from MAC, MAC system failure, etc.

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R134a Emission Inventory from Heavy-Duty Fleet

- Use to get an initial estimate of the contribution from MD and HD vehicles while acknowledging the uncertainties of the method
- Estimate number of medium-duty and heavy-duty vehicles with air-conditioned cabs
- Multiply the estimated annual leak rate per vehicle by the number of vehicles

Onroad Heavy-Duty Fleet for 2010

- EMFAC default fleet
  - About 55% of urban and “other” buses use R134a (per fleet manager estimates)
  - About 100% of the rest of the MD & HD fleet use R134a
- Total estimated fleet = 3,857,000 (2,684,000 model year 2005-, 1,173,000 model year 2006+)

Offroad Heavy-Duty Fleet for 2010

- OFFROAD default fleet
  - Equipment types with enclosed cab options (per ERG knowledge)
  - Assume only equipment with engines 50 HP or larger would have MAC
- Total estimated fleet = 316,600

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Estimate: 2010 Leaks of R134a directly from HD MACs

EMFAC Vehicle Category	Pre-2006 Mg/yr (short ton/yr)	2006+ Mg/yr (short ton/yr)	All Model Years Mg/yr (short tons/yr)
On-Road Equipment [Pre-2006: 2,684,000*306=821 Mg] [2006+: 1,173,000*103=121 Mg] [All: 3,857,000 * 257=991 Mg]	821 (905)	121 (133)	991 (1,089)
Off-Road Equipment [Age Basis[1]: 316,600*306=97 Mg] [All: 316,000*257=81 Mg]	97 (107)		81 (89)
Grand Total	**1,039** **(1,145)**		**1,072** **(1,178)**

Note: These estimates account only for in-use leaks directly from the MAC. Leaks from other sources, such as maintenance procedures, are not included and are probably significant for certain vehicle types.

[1] Assumes offroad MAC systems emit at the same rate as pre-2006 on-road systems.

CO_2-Equivalent Emissions 2010

- Assume R134a greenhouse warming potential of 1,300 (IPCC guidelines)
- 1,039 Mg/yr * 1,300 CO2E = <u>1,350,000 CO_2E Mg/yr</u> from HD equipment
- Compare to CARB estimate of 4,000,000 CO_2E Mg/yr from all sources

Sources of Uncertainty in this Estimate

- Undocumented measurement error (e.g., impact of "difficult" MAC layouts not assessed in QA)
  - A few systems difficult to evacuate without entraining liquids
- Linear projection for annualized leak rate (assumes no tapering of leak rate)
  - Regional ambient differences may play a role here since cooler areas tend to use more for defogging windows, less for summer cooling, which may impact driver tolerance of low refrigerant levels
- Only attempts to account for in-use leakage from MAC
  - Maintenance/service leaks for public transport might be significant due to complexity and "preventative" nature (e.g., quarterly) of service
- The impact of the measurement method has not been empirically assessed
  - Clodic has not seen adverse impacts on systems tested by Ecol des Mines
  - Some evidence from this study indicate that impacts are possible
    - Some systems may be "pushed" to leak more due to higher than normal vacuum conditions during testing – especially older systems
    - One system could not be tested due to in-leakage of air at high vacuum (higher than service vacuum levels)

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Summary & Main Conclusions

- MACs in heavy-duty equipment appear to be significant in the R134a leak inventory
- This leak estimate does not account for leaks due to maintenance, equipment failure, etc
- Linear projection of leak rate to annual rate is probably an over-estimate
- Gravimetric leak measurement method accurate to about 20 g or 2% of original MAC charge
- A possibly significant source (not accounted for with this method) is the frequent, preventative maintenance on large MACs in public transport vehicles
- Regional usage differences may impact leak rates (MAC for defrost-only is effective at lower charges than MAC for comfort)

Primary Recommendation

- Survey large fleet operators and certified technicians to find obvious sources of leaks other than during typical MAC system operation
  - Estimate leak rate ranges from sources other than the in-use MAC (e.g., maintenance) using a mass-balance approach (net R134a purchased = total leaked)
  - Compare to leak rates measured in this study and use to update the inventory
  - Use results to prioritize future studies aimed at improving the inventory

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End of Presentation

Q&A

Supplementary Slides

- The following slides have some details behind the summaries in the main presentation...

Supplementary Slide – Equipment Customization

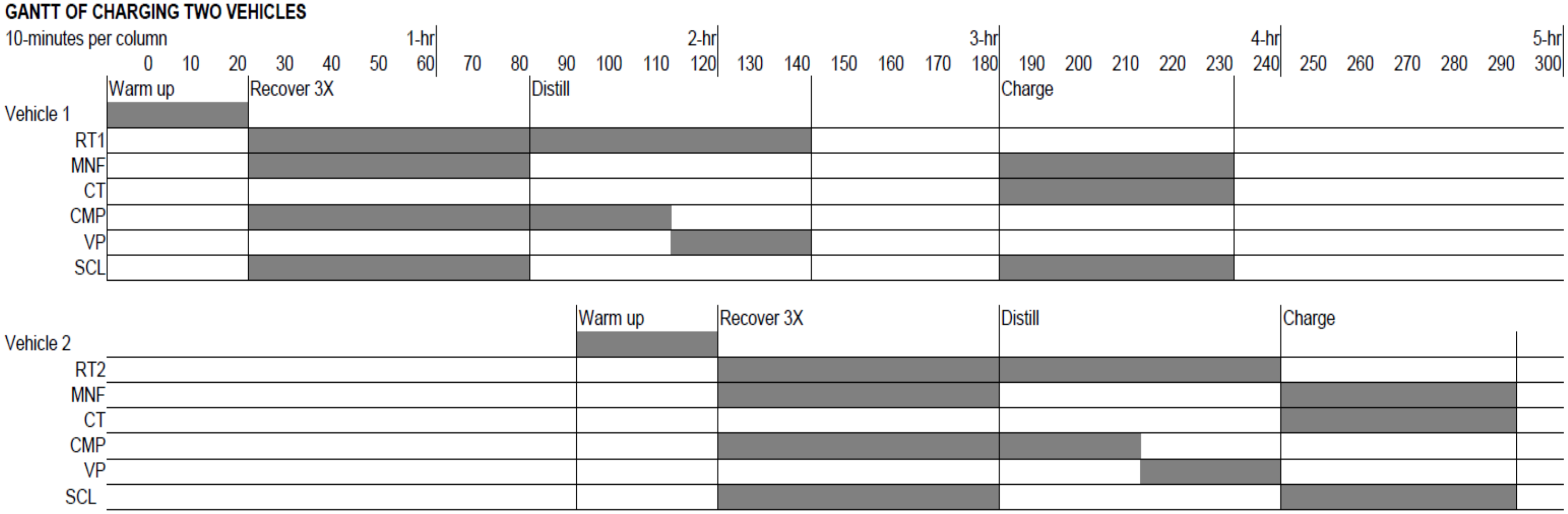
- Permanent joints wherever possible
- Custom hose with heavy-duty compression fittings
- Ball valves at hose ends
- Frequent replacement of gaskets and vacuum oil

Supplementary Slide – Evacuate-Recharge Schedule

LIST OF EQUIPMENT

each	item
2	recovery tank (RT1, RT2)
1	manifold & 3 hoses (MNF)
1	charging tank and hose (CT)
1	compressor, hose and mid-vacuum gauge (CMP)
1	vacuum pump, hose and high-vacuum gauge (VP)
1	Scale (SCL)

GANTT OF CHARGING TWO VEHICLES



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Supplementary Slide – Data from Accuracy Tests

Vehicle ID	Model Year	System Capacity (g)	Charge (g)	Recovered (g)	Difference (g)	% Difference	Note
Util2-01	2007	907	907.6	871.7	35.9	4.0	Draft Procedure
Garb2-02	2006	1,190	1,217.9	1,214.2	3.7	0.3	Final procedure
Priv4-1	2002	1,080	1,104.7	1,094.1	10.6	1.0	Final procedure
Priv5-1	2003	1,758	1,784.4	1,769.8	14.6	0.8	Final procedure

Supplementary Slide – Bus Fleet and R134a Maintenance Data Summary

Fleet	Location	Peak Month Avg. Daily High	Avg. Annual R134a Purchase	R134a Fleet	Estimated R134a Leak Rate (per vehicle)	Notes
Fleet 1	LA Basin	32°C (90°F)	27 kg (60 lb)	40-ft coaches: 170 total; 51 use R134a, 119 use R407c	540 g/yr (1.2 lb/yr)	Approx. 180 lb of R134a used in 3 years for 51 buses. 150 lb purchased, 30 lb already in stock.
Fleet 2	NW CA	18°C (64°F)	2.0 kg (4.3 lb)	40-ft coaches: 33 total; 5 w/o AC, 28 use R134a	68 g/yr (0.15 lb/yr)	30 lb cylinder of R134a purchased 7/18/2006. About ½ used so far.
Fleet 3	N CA	37°C (99°F)	55 kg (120 lb)	Shuttle buses: 23 total; all use R134a	2,400 g/yr (5.2 lb/yr)	Purchase approx. 120 lb R134a per year for shuttle buses
Fleet 4	Sacramento region	34°C (93°F)	Not provided	40-ft coaches: 22 total; all use R134a	1,100 g/yr (2.4 lb/yr)	Maintenance records: average of 103 lb R134a per year total for 40-ft coach buses
Fleet 4	Sacramento region	34°C (93°F)	Not provided	Shuttle buses: 21 total; all use R134a	2,700 g/yr (5.9 lb/yr)	Maintenance records: average of 138 lb R134a per year total for cutaway buses
Fleet 5	San Joaquin Valley	34°C (94°F)	180 kg (390 lb)	Shuttle buses: 32 total; all use R134a. 29 ft to 45 ft coaches: 104 total; 80 using R134a, 24 using R22.	1,600 g/yr (3.5 lb/yr)	Projected “year to date” use as of Nov 4 (325.7 lb R134a & 147.1 lb R22) to end of year.

Supplementary Slide – Estimate of 2010 On-road HDVs with R134a

EMFAC Vehicle Category	Pre-2006 Count	2006+ Count
04 - Medium-Duty Trucks (T3)	1,722,000	746,000
05 - Light HD Trucks (T4)	239,000	188,000
06 - Light HD Trucks (T5)	119,000	49,000
07 - Medium HD Trucks (T6)	188,000	70,000
08 - Heavy HD Trucks (T7)	179,000	51,000
09 - Other Buses	9,000	3,000
10 - Urban Buses	7,000	1,000
12 - School Buses	23,000	4,000
13 - Motor Homes	198,000	61,000
Total	**2,684,000**	**1,173,000**

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Supplementary Slide – OFFROAD Equipment With MAC

- Rollers
- Trenchers
- Cranes
- Rough Terrain Forklifts
- Rubber Tire Loaders
- Tractors/Loaders/Backhoes
- Skid Steer Loaders
- Other Construction Equipment
- Forklifts
- Sweepers/Scrubbers
- Other General Industrial Equipment
- Other Material Handling Equipment
- Agricultural Tractors
- Combines
- Balers
- Sprayers
- Swathers
- Other Agricultural Equipment
- Cargo Tractor
- A/C Tug, Narrow Body
- A/C Tug, Wide Body
- Air Conditioner (GSE)
- Baggage Tug
- Bobtail
- Fuel Truck
- Lavatory Truck
- Maintenance Truck
- Passenger Stand
- Sweeper
- Service Truck
- Catering Truck
- Hydrant Truck
- Scrapers
- Excavators
- Graders
- Off-highway Trucks
- Rubber Tire Dozers
- Crawler Tractors
- Off-Highway Tractors
- Skidders
- Fellers/Bunchers
- Other GSE
- Other Workover Equipment
- Drill Rig
- Military Tactical Support Equipment
- Dredger
- Other Dredging

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