Hydrocarbon Refrigerant Risk in Car Air-Conditioners*

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Abstract

Ozone depletion and global warming require replacement of chlorofluorocarbon refrigerants like R12. The hydrofluorocarbon R134a is nonflammable, difficult to synthesize, has zero ozone depletion and high global warming. Hydrocarbon (HC) refrigerants are highly flammable, occur naturally, have zero ozone depletion and negligible global warming. HC mixtures have successfully replaced R12 and R134a in over 200,000 US car air-conditioners and many thousands in other countries. Some mechanics' organizations claim that hydrocarbon flammability make this so dangerous it should be discontinued.

On ten popular Australian cars, the engine and passenger compartment switches, wiring and hot surfaces have been tested with an extinguished hydrocarbon torch for ignition sources. Car cigarette lighters and lit cigarettes did not reignite the torch and neither did any other engine or passenger compartment components. A lit match or gas fueled lighter reignited the torch readily. For these cars, carbon dioxide was used as a tracer to measure outside air flow through the passenger compartment under many conditions. Outside air flows through late models fully closed and stationary were as high as 173 L/s. The measured air flows allowed revised estimates of the frequency of various accident scenarios.

The ignition and air flow measurements were combined with Australian collision data and US studies to estimate Australian insurance risk. The insurance risk increment for car air-conditioners is negative because of the high cost of R12 and R134a repairs.

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1 Car Air-Conditioner Requirements

The passenger compartment on automobiles is light, small and sealed to reduce fuel consumption and capital cost. Closed in summer sun, the compartment temperature can exceed 20 K above ambient, without cooling using vapour compression usually referred to as air-conditioning. The fuel consumption due to air-conditioning is usually less than that due to opening the windows above 60 km/hour.

Car air-conditioners use a simple reversed Rankine cycle (ASHRAE 1995). Power is most efficiently available if the compressor is bolted to the motor and driven through a belt and electrically operated clutch. A shaft seal is necessary which leaks. Flexible hoses must carry vapour to and from the compressor to reduce transmission of motor vibrations to the chassis and avoid fluctuating stresses causing fatigue fracture. Flexible hoses and their connections leak much more than metal pipe. Permanent Schrader valves are provided on both low and high pressure lines to the compressor, so refrigerant may be added, air released and pressure gauges attached for service. Schrader valves also leak. Typically total leakage rates from car air-conditioners vary from 0.1–l.0 L of liquid per year but is under 0.2 L/year for new, quality components, correctly installed. Either a liquid line receiver or suction line accumulator containing up to 0.5 L of extra refrigerant liquid allows continued operation for several years between recharging. A full charge is 0.6–1.0 L.

During recharging, the mass of refrigerant added is easily measured but only on older car air-conditioners with receivers having effective sight glasses can a full charge be detected. You add a correct full charge on other car air-conditioners by first releasing all refrigerant from the circuit and then measuring in the correct charge. In Australia, it was common to 'regas' once a year and release the refrigerant to the atmosphere. The effective leakage rate to the atmosphere with this efficient procedure was one charge per year or up to 1.0 L liquid per year even for new vehicles.

Hydrocarbon (HC) refrigerants were introduced to small applications in the 1920s. After R12 was invented in 1930, enthusiastic marketing of non-flammability allowed rapid expansion of R12 sales in applications where otherwise superior alternatives existed. Everyone was told that flammable refrigerants (or propellants) caused horrific fires and explosions. Ammonia, HC and other refrigerants disappeared from domestic systems. In the 1950s, many US states banned flammable refrigerants in car air-conditioners. A Society of Automotive Engineers standard first issued in 1953 still bans flammable refrigerants in car air-conditioners (SAE 1995). Despite these bans, we have found no record of HC refrigerants being used in car air-conditioners prior to their introduction in 1991 by US engineer and inventor, Gary Lindgren of OZ Technology Inc, Idaho.

2 Environmental Impact

In 1992, Australian CFC refrigerant consumption was estimated as 3204 tonnes with 1530 tonnes going into car air-conditioners (ANZECC 1994) and then into the atmosphere. With about four million car air-conditioners in Australia this could

Table 1: Environmental impacts of refrigerants (100 year basis, WMO 1991, IPCC 1994).

Refrigerant	R12	R22	R134a	R600a	R290
Class	CFC	HCFC	HFC	HC	HC
Atmospheric lifetime (years)	130	15	16	<1	<1
Ozone depletion potential	1.0	0.07	0	0	0
Global warming potential	8500	1700	1300	8	8

have been worse. Regulations at that time prohibited service people from releasing CFCs to the atmosphere and required obvious leaks to be repaired. The Ozone Depletion and Global Warming Potentials of refrigerants in car air-conditioners cannot be ignored. Table 1 compares them.

Table 1 shows R22 and R134a are clearly more environmentally acceptable than R12. R600a and R290 not only have outstandingly low ODP and GWP but they are naturally occurring requiring no chemical plants to produce. Is the outstanding environmental performance of hydrocarbon refrigerants necessary in car air-conditioners for warm countries?

The advanced countries committed themselves at Rio de Janeiro in 1992 to maintaining their contribution to global warming at 1990 levels. For most sectors of the economy this can only be done with massive investment like a national solar electric program. Clearly the car industry must contribute with increased fuel efficiency on new vehicles but it will be many years before this has an impact. No politician wishes to talk about increasing fuel taxes. Kroeze (1995) calculates that volatile fluorine compounds will be 8 to 14% of global 1990 greenhouse gas inventory by 2040.

Consider a car traveling 20,000 km per year with a fuel efficiency of 10 km/L. The annual carbon dioxide emissions or equivalents for a car which consumes 2000 L of fuel in a year and emits only 0.4 L of refrigerant which includes emissions during service:

Emission of 0.4 L of liquid	R12	R134a	R290/600a
is equivalent to CO_2 in kg	4400	630	2

2000 L of petrol burns to 4300 kg CO_2

If R12 were the refrigerant the global warming due to refrigerant emissions is greater than that from combustion of the fuel. R134a as refrigerant reduces this to 15% of the fuel but hydrocarbons reduce it to only 0.04%.

Dieckmann *et al.* (1991) predicted an additional environmental benefit of HC refrigerants, up to 4% reduction in fuel consumption. Abboud (1994) and Parmar (1995) measured the performance of natural HC refrigerants relative to R12 on ten typical Australian cars. The cars were stationary with engines idling and in a shaded and sheltered outdoor position. The average ratio of HC to R12 cooling capacity was 1.00 with the average energy consumption for HC cooling 13% less than R12. The scatter from differences in charge, ambient and instrumentation was considerable for these results. If air-conditioning adds 10% directly to fuel consumption, Abboud and Parmar's results suggest a 1.2% saving in fuel from converting from R12 to HC. Reduced vehicle mass due to reduced refrigerant mass gives about an 0.1% further saving in fuel.

Maclaine-cross and Leonardi (1995) attempted to explain theoretically the outstanding performance of isobutane in small refrigerators. They proposed that isobutane would also give superior energy savings in car air-conditioners to other HCs. The advantages they identified stem from its low molecular mass, lower vapour pressure and larger molecule.

HC refrigerants are compatible with standard seals, driers and oils. No retrofitting is necessary. Pollution in manufacturing and fitting new components and disposing of old components is eliminated. Despite data (Dekleva *et al.* 1993) indicating that retrofitting may be irrelevant for R134a, Australia mechanics are mainly of the opinion that it is a necessary nuisance and costs about $1000. They are happy to pay 30–100 $/kg for HC refrigerants and then replace R12 for about $100. Over 5000 Australian cars had HC 'drop-in' replacements in Spring 1995.

3 Hazards and precautions for refrigerants

All refrigerants are dangerous. The principal hazards are:

Explosion in space Any refrigerant with vapour pressure above ambient can flash to a larger volume. The potential increase in volume is greater if combustion of lubricant or refrigerant occurs. Explosion venting may be necessary to limit pressure rise to what the space can safely withstand. 2 kPa can blow window glass off a building.

Fire Combustible lubricant and refrigerant must be discharged safely outside a building when a fire occurs especially if the heat of combustion exceeds 200 MJ.

Asphyxiation or poisoning All refrigerants except air and oxygen are asphyxiants. Ventilation must prevent serious injury or death on a sudden total release of refrigerant. The quantity of ventilation necessary varies greatly between refrigerants.

Flying metal System must comply with piping and pressure vessel codes.

Corrosion or chemical reaction HC refrigerants are non-reactive and chemically stable at refrigeration temperatures.

Chemical or cold burns Accidental contact between skin and cold metal must be prevented by insulation. Accidental releases of liquid refrigerant must drain safely.

All refrigerants require safety measures to prevent hazards causing injury to persons or damage to property. The safety measures depend on the mass of the refrigerant, the design of the system and the individual properties of the refrigerants. Grouping refrigerants as in AS 1677–1986 results in excessive safety for some refrigerants and inadequate for others. AS 1596–1989 and material safety data sheets from suppliers give more relevant information for HC refrigerant safety.

Table 2: Fire and explosion data for HC refrigerants and RC270 (Perry and Chilton 1973 Table 9-20). P50 consists of equal parts of R290 and R600a by mass and is representative of HC refrigerants which replace R12.

Code	Liquid 25°C sat.	Mol. mass	Expl. limits	Stoch. mixture	Spont. ignit.	Max. flame	Flame temp.	Heat comb.
Units	kg/m^3	g/mol	vol. %	vol. %	°C	m/s	°C	MJ/kg
R290	493	44.1	2.1 to 11.4	4.02	504	0.40	2232	50.3
R600a	551	58.1	1.9 to 10.0	3.12	477	0.37	2241	49.3
R600	573	58.1	1.7 to 10.3	3.12	431	0.37	2238	49.5
P50	523	50.1	2.0 to 10.8	3.58	490	0.38	2236	49.8
RC270	621	42.1	2.6 to 12.3	4.44	498	0.49	2310	49.7

A German standard (DIN 7003) allows up to 150 g HC charge with no special safety precautions, up to 1 kg if the system can resist excess compressor pressures and up to 2.5 kg with specified pressure relief devices and above ground. Beyond this the equipment should be outdoors or in a plant-room designed for safety (Krug *et al.* 1993). Table 2 and refrigerant tables (ASHRAE 1993, Gallagher *et al.* 1993) give data for calculating explosion venting and whether a discharge line is necessary on the pressure relief valve. The long term exposure limit for HC refrigerants is 1000 ppm and for RC270 400 ppm. The ventilation in an unoccupied plantroom should be sufficient to return concentrations below these levels one hour after a complete release of refrigerant. When a plantroom is occupied ventilation must prevent serious injury at floor level on complete discharge of refrigerant. No standards exist. Ventilation which lowers HC refrigerant concentration below 25% by volume in one minute and RC270 below 10% is a possible precaution.

Refrigerant and lubricant combinations can be compared by the cost of precautions necessary to give the same standard of safety or cost of injury. The cost of precautions should not be used to select combinations by safety authorities. Their responsibility to the public is to make sure the precautions are made.

Including all six hazards mentioned previously and all common combinations of refrigerant and lubricant, we believe R600a and mineral oil require the least expenditure on precautions for car air-conditioners. Low vapour pressure reduces the explosion and flying metal hazard which anyone working on the engine is exposed to; low leakage (Maclaine-cross and Leonardi 1995) greatly reduces the necessary charge of refrigerant; and low vapour pressure also greatly reduces the initial rate of leak from a large hole in the circuit.

For R600a under cold winter conditions more air leaks into a car air-conditioner than for refrigerants with a higher vapour pressure. This air can be easily discharged in spring. For the R600a and air mixture to reach the upper explosive limit (Table 2) the temperature must drop below -58°C which is possible only in the Arctic or Antarctic.

The R600a and mineral oil combination has become a world-wide standard for refrigerators but suitable car air-conditioner components are not available and we know of no plans to make them available. Given the environmental and other advantages previously mentioned this is disappointing.

4 Car mechanics' accident scenarios

The first commercial hydrocarbon refrigerant for car air-conditioners (OZ-12) was introduced in 1991. Since then a small but international team of mechanics have been inventing and publicizing accident scenarios for flammable refrigerants in car air-conditioners. Some of these have appeared in the trade press (Keebler 1993, MACS 1993) and others in government publications (Gallagher 1993).

Many of these claims are exaggerated or misreported or made in the absence of any attempt to substantiate them with experiment. The claimants appear totally unaware of the literature on hydrocarbon refrigerant safety (Section 3). Unscientific assertions are an unsafe basis for public policy and worldwide the vast majority of safety authorities have ignored them.

There are now over 200,000 car air-conditioners using HC refrigerant and over 400,000 operating years have been accumulated. No accidents in which hydrocarbon refrigerant caused damage or injury due to its flammability have been reported to manufacturers or safety authorities yet.

In 1993, our students had tested just one car with hydrocarbon refrigerant (Maclaine-cross 1993, Giobran 1994). The performance had been encouraging, the mechanics claims were known to be unscientific (Maclaine-cross 1994) and Dieckmann *et al.* (1991) had estimated most risks as very low but they had not considered the 'bomb in the passenger compartment'. More data was necessary to estimate the probability of this and other scenarios.

5 Hydrocarbon ignition sources

Razmovski (1994) and Rajasekariah (1995) searched for ignition sources using a propane welding torch attached to a cylinder of hydrocarbon refrigerant. The car was parked in a sheltered outdoor position with fine weather. They started the engine and allowed idling until it reached normal operating temperature *i.e.,* typically for ten minutes. They ignited the welding torch then adjusted it to give a stable yellow flame about 70 mm long. They extinguished the flame with an air blast and tested for easy reignition with lighted matches and cigarette lighter.

The extinguished torch was played over the hot engine, electricals, ignition and exhaust. Then the door, light and brake switches, fan motor, relays and cigarette lighter were tested in the passenger compartment. Each test took over fifteen minutes and 50 to 100 g of flammable refrigerant were used for each test depending on the car. Table 5 lists the model and year of manufacture of the ten cars. They found no ignition sources either inside or outside the passenger compartment on any of the cars tested.

Leakage of fuel into the passenger compartment is not uncommon. A manufacturer would be negligent to use open relays, switches or motors which could ignite a fuel/air mixture. Enclosed electrical components are also more reliable saving on warranty claims. The incidental effect is a match or cigarette lighter is the only ignition source for a refrigerant mixture in the passenger compartment as Razmovski and Rajasekariah found. The consumption of cigarettes over the whole driving population is equivalent to about ten cigarettes a day (Department of Community Services and Health 1990). We will assume that half the cigarettes consumed in cars are lit with the car's cigarette lighter and would not cause ignition. We then have five potential ignitions per driver per day.

6 Passenger compartment volume and air flows

Razmovski (1994) and Rajasekariah (1995) measured the volume of and fresh air flows into the passenger compartments of ten Australian cars using carbon dioxide as a tracer. Carbon dioxide was selected as a tracer because its molecular mass is close to propane, it is safe and instrumentation to measure its concentration was available.

The procedure was to purge, fill and weigh a 2 L fire extinguisher with typically 300 g of carbon dioxide. The extinguisher was fitted with a 90°ball valve with 300 mm handle extension. The car was parked in a sheltered, shaded, outdoor position. The extinguisher was held upside down by a laboratory stand on the floor in front of the passenger seat and opened by a string passing under the passenger door. The extinguisher discharged fully in less than 3 s. The air in the passenger compartment was sampled at 0.5 L/minute through a Beckman infrared analyzer outside the passenger compartment. The readings of the analyzer were recorded on a personal computer through a YEW datalogger every 9 s. The maximum wind velocity was always less than 3 m/s.

Table 3 gives the passenger compartment volume and fresh air flows calculated for various configurations of the ten Australian cars tested. The Kingswood and the Volvo air-conditioners did not have a fresh air vent and the Berlina had a fixed fresh air vent.

Razmovski (1994) also used this apparatus with a door switch and electronic timer to measure the loss in concentration when the driver's door was opened fully and closed again quickly without entering the vehicle. Table 4 shows this concentration loss is significant for many vehicles.

7 The slightest spark

Front to rear collisions are the commonest accident. Keebler (1993) quotes this description of the scenario with HC refrigerant:

> "GM's pickup gas tank problems are nothing compared to this," says Simon Oulouhojian, who is president and executive director of the Mobile Air Conditioning Society.
>
> "You've got that stuff in the condenser at 200 to 400 psi in the front of the vehicle. And you have an accident with the slightest spark and you've got a serious problem."

Hydrocarbons refrigerants are flammable like paint, plastic, antifreeze, engine oil and petrol. In the open air hydrocarbons refrigerants may catch fire but they will not explode. The recommended 300 g mass of hydrocarbon refrigerant is about 1%

Table 3: Measured passenger compartment volume and total fresh air flows for ten Australian passenger cars (Razmovski 1994, Rajasekariah 1995). The first three configurations have all windows closed and the last three have the fan operating at full flow. The third has the fresh air vent open and the last has the driver's window open.

Model	Year	Vol.		Fresh air (L/s)		
		m^3/s		Fan	F.V.	F.W.
Kingswood	1970	5.81	1.05	2.52	2.52	
Volvo	1978	6.48	4.00	20.8	22.0	1363
Commodore	1979	3.81	5.78		85.0	
Pulsar	1984	4.16	0.61	20.2	77.4	
Corolla	1985	5.68	3.00	20.0	149.7	262.2
Falcon	1987	4.44	38.03	164.0	134.5	151.2
Laser	1988	3.48	1.42	4.56	85.1	41.0
Berlina	1989	4.36	2.95	173.0	173.0	
Magna	1989	6.12	6.00	37.0	100.7	987
Astron	1989	5.50	50.0	143.0	136.0	312

Table 4: Loss in tracer concentration in the passenger compartment when driver's door briefly opened fully and closed with fan off and vent closed (Razmovski 1994).

Model name	King.	Comm.	Pulsar	Laser	Berlina
Year of manufacture	1970	1979	1984	1988	1989
Time door open (s)	5.70	3.60	3.27	3.60	3.70
Tracer conc. loss (%)	10.3	33.6	29.8	21.8	19.7

of the petrol in a full tank. Any refrigerant fire from a condenser leak is so small and far away that it cannot cause injury directly to occupants.

For fire to occur, four conditions must be satisfied. There must be a leak, the leak must mix with air to form a flammable mixture, the velocity of the flammable mixture must somewhere be less than the flame velocity and the flammable mixture must coincide in space and time with an ignition source. Because of the high pressures, leak velocity is initially close to the velocity of sound in the refrigerant. When the velocity has dropped to less than the flame velocity (Table 2) the refrigerant has almost always been diluted to less than the lower explosion limit. No fire is possible without a permanent ignition source touching the refrigerant jet before it is diluted. This is why no such fire has yet been reported despite the many condenser puncturing accidents which would have occurred in 400,000 operating years (Section 4).

This argument does not apply to large refrigerant jets possible from systems containing more than 2.5 kg of hydrocarbon refrigerant.

8 A bomb in the passenger compartment

Keebler (1993) describes this as follows:

> Late this summer, International Association of Arson Investigators conducted tests with as little as $5\frac{1}{2}$ ounces of the OZ-12 material introduced into a vehicle interior.
>
> "When the ignition source was activated, the result was an explosion that blew the windows out of the car," said a source with the state of Florida.

This standard movie stunt is usually performed with 600 g of liquefied petroleum gas not $5\frac{1}{2}$ ounces (156 g) of OZ-12. Anything less than 600 g makes it very hard to ignite and does not give the brilliant yellow flame so beloved by directors of B-grade gangster movies.

An accident scenario resulting in such an explosion is the following. The evaporator and frequently the expansion valve are between the dashboard and firewall on the passenger's side. A complete and instantaneous rupture of the liquid line just upstream of the expansion valve could release a white cloud of perhaps 300g of LPG refrigerant into the passenger compartment. Opening a window would create a safe situation in seconds. If all occupants ignored the cloud and one lit a match, the windows would blow off the car in a second. Replacing the glass may cost $1000 and LPG explosion accidents with domestic appliances show occupants' exposed skin would be red and sting for a few days. The glass flies away from the occupants and the resulting in-rush of cool fresh air limits burns and importantly prevents asphyxiation.

We wish to know an upper limit for the insurance risk so we will assume here that either a pedestrian is walking by at the wrong time and gets horribly injured by flying glass or the vehicle is moving and the driver is so distracted that he crashes the car. BTCE (1992) gives the average cost of a hospitalization accident in Australia as $95000 and allowing for inflation we have used $100,000.

Table 5: Measured HC refrigerant charge (Abboud 1994, Parmar 1995) with Table 3 gives the maximum time a flammable concentration exists in the passenger compartment with fan and vent operating. HC refrigerant suppliers recommend 300 g charge gives lower values from which explosion frequency and insurance risk increment have been calculated.

Model	Year	Charge (g)	Max. HC (%)	Flam. time (s) M. C.	Flam. time (s) R. C.	E. F. 10^{-10}/year	Risk ($/year)
Kingswood	1970	298	2.50	519	0	0	0
Volvo	1978	405	3.05	124	0	0	0
Commodore	1979	460	5.90	48	11.1	6	0.00006
Pulsar	1984	425	4.99	49	8.6	5	0.00005
Corolla	1985	295	2.54	9	0	0	0
Falcon	1987	985	10.83	56	0	0	0
Laser	1988	315	4.42	32	13.9	8	0.00008
Berlina	1989	840	9.41	39	0	0	0
Magna	1989	370	2.95	24	0	0	0
Astron	1989	420	3.73	25	0	0	0

Fatigue fractures of pipes which do not leak before the sudden and complete parting of the metal are so rare, that we have never heard of it happening between the firewall and the expansion valve. The unmistakable sign is a sudden white cloud emerging from behind the dashboard on the passenger's side. We will assume here that such fractures occur once per million operating years which implies several occur in Australia every year. Tables 2, 3 and 5 show that assuming all the charge used for performance testing enters the passenger compartment the maximum hydrocarbon concentration for each of the ten cars is a flammable mixture.

We also assume a smoker ignores the cloud and does not wind down a window. Figure 1 shows the concentration profile assumed in the passenger compartment to calculate the time which the concentration remains above the 2.0% lower flammability limit for the Pulsar. Table 5 gives this maximum flammable time as 48s. Hydrocarbon refrigerant suppliers are recommending charges of only 300 g for all car air-conditioners. This is easily measured by using preweighed canisters or a cylinder equipped for liquid delivery on an electronic balance. This is much lower than some charges used for performance testing (Table 5). From a liquid line receiver the maximum refrigerant discharge to the break in the first minute will certainly be less than 200 g. The Berlina and Falcon had suction line accumulators which can discharge only vapour to the passenger compartments. For suction line accumulators the initial mass will be less than 150 g. Our thermodynamic calculations and laboratory experiments all give lower values than this.

The flammable times are then zero for all but three vehicles. The Pulsar has its flammable time reduced to 8.6 s. The explosion frequency for the Pulsar in Table 5 is thus $5 \times 8.6/(86400 \times 1000000) = 5.0 \times 10^{-10}$.

The insurance risk increment in Table 5 is negligible.

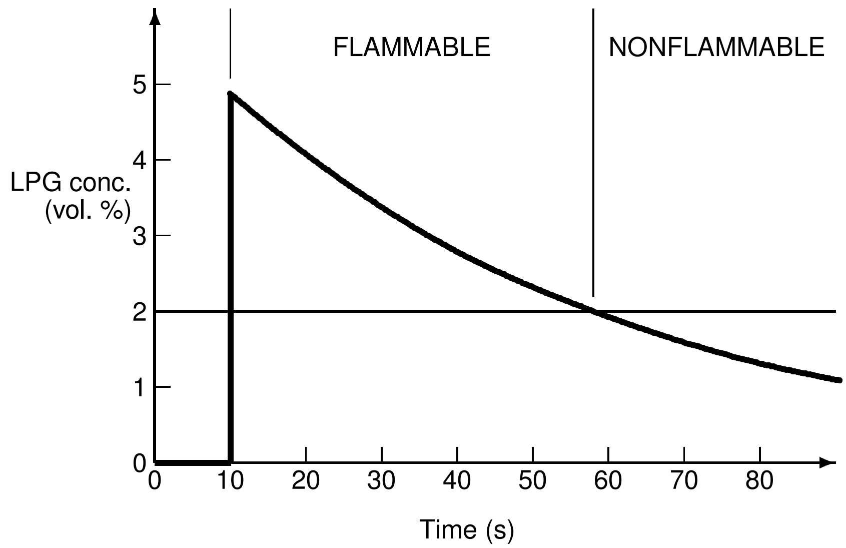

Figure 1: HC refrigerant concentration assumed in passenger compartment to calculate maximum flammable time for Pulsar in Table 5.

9 Insurance risk increment

A fatigue fractures occurring in the engine bay during operation may be as common as one in ten thousand operating years. The experiment described in Section 5 shows that ignition sources are not usually present and ignition sources are believed present on less than 1% of the vehicle population. Experiments by Maclaine-cross (1994) show that the quantity of flammable mixture present from a leak is at any time about 10%. The probability of an ignition source contacting and igniting leaking flammable mixture is estimated as less that one in ten. A flammable mixture might be created and ignited in this manner once in ten million operating years. The damage due to ignition would be less than $1000 on average and it will be assumed to be covered by the policy.

Low velocity front collisions create about one insurance claim every twenty operating years (RTA 1992). About one fifth of these are likely to involve loss of refrigerant in the collision. Another fifth will require the refrigerant to be removed before repairs can commence. These less serious collisions are more expensive to repair if R12 is used because the law requires that R12 be recovered by trained and licensed operators before repairs commence. R12 replacement is estimated at $50 and recovery and later replacement at $100 more than hydrocarbon refrigerant. Conversion to R134a after an accident creates even greater costs.

Ignition is unlikely from fracture of the refrigerant circuit and Section 5 that ignition is unlikely from an intact engine. I expect damage to electrical wiring and components to create an ignition source for one in ten accidents. A flammable fraction of the leaking refrigerant might contact such an ignition source one in ten times (Dieckmann *et al.* 1991). Ignition of hydrocarbon refrigerant is expected once in a hundred refrigerant loss accidents. Such fires would frequently add nothing to damage and injury but it will be assumed here to add $1000.

Table 6: Annual insurance risk increment on conversion of R12 car air conditioner to HC refrigerants.

Scenario	Payout Increment	Frequency $year^{-1}$	Risk Incr. \$/year
Engine bay fatigue fire	\$1000	1×10^{-7}	+0.0001
Slow collision fire	\$1000	1×10^{-4}	+0.10
Fast front/rear fire	\$100,000	1×10^{-6}	+0.10
Slow collision R12 loss	-\$50	1×10^{-2}	-0.50
Slow collision R12 recovery	-\$100	1×10^{-2}	-1.00
		Total Risk Increment	-1.30

Front to rear collisions rarely occur at sufficient velocity to fracture the fuel tank of the vehicle in front. This may occur once in five thousand operating years (RTA 1992). Ignition of hydrocarbon refrigerant is expected once in a hundred such accidents and it will be assumed this ignites the fuel 50% of the time with a major fire. On average this increases the cost of the accident by $100,000 (BTCE 1992).

Table 6 shows a rough estimate after Maclaine-cross (1994) of the annual insurance risk increment from converting an R12 car air-conditioner to HC refrigerants. The high cost of crash repairs to R12 air-conditioners results from the price of R12 and the legal requirement to recover it. HC refrigerants reduce insurance risk over R12 by 1.3$/year.

Dieckmann *et al.* (1991) made an earlier, independent and more detailed investigation of HC in car air-conditioners. They concluded that the risk of injury from HC refrigerant was 3.5×10^{-7} per year in the US. This is three times lower than the fast front/rear frequency assumed in Table 6 confirming the low insurance risk of HC refrigerants.

No slow collision fires have been reported to manufacturers or safety authorities despite 400,000 operating years of HC car air-conditioners. The slow collision fire frequency suggests that up to 40 such incidents should have occurred.

10 Conclusion

Hydrocarbon refrigerants are especially attractive environmentally for car air conditioners offering about 14% reduction in radiative forcing over their best competitor. The new experimental data incorporated into this study has lowered the upper limits estimated previously for injury and damage due to flammability. Field experience suggests that these upper limits are far too high.

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