AIRCRAFT OPERATIONS AND REGIONAL AIR QUALITY IMPACTS: A CASE FOR CLEAN, ALTERNATIVE FUELS

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Abstract

The aviation transportation sector, both commercial jet and general aviation operations, exerts an increasingly important, but largely unacknowledged impact upon regional air quality. Emissions from these operations, which currently are uncontrolled, offset many of the emission reductions which are being achieved in the ground transportation sector. The regional air quality implications of aviation transportation will increase as the disparity between these uncontrolled emissions and those of the rapidly improving ground transportation sector widen. This paper discusses the magnitude of current and likely future petroleum-fueled aviation operations from a regional air emissions perspective. The potential for implementation of an alternative aviation fuel strategy to improve regional air quality also is addressed, and the characteristics of certain representative alternative fuels are discussed. Finally, a call is made to structure a research, demonstration, test, and evaluation (RDT&E) project to flight test and demonstrate this potential in the general and commercial aviation sectors.

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Aviation and Regional Air Quality

Like many highly urbanized areas, Los Angeles, Orange, Riverside, and San Bernardino Counties, which collectively comprise Southern California's South Coast Air Basin (Basin), are plagued with serious air quality problems. In the Basin's case, these problems are the most severe in the United States. The primary malefactor in this situation is the Basin's heavy reliance on an automotive transportation system fed almost exclusively by petroleum-based fuels. To deal with this pressing issue, innovative solutions have been proposed, including the mandatory phased introduction of low and zero emission vehicles (LEVs and ZEVs) into public and private automotive fleets and the trading of mobile source emission reduction credits through the mandatory early retirement of older, dirtier automobiles. (1,2)

These efforts are commendable, and some progress in improving regional air quality appears to be forthcoming. The aviation transportation sector, however, particularly commercial jet operations, also exerts an increasingly important, but largely unacknowledged impact upon urban regional air quality. Emissions from these operations, which currently are uncontrolled, have the potential to offset many of the emission reductions which are being achieved in the ground transportation sector.

Despite a few notable allusions to the contrary, on a national scale, aircraft emissions historically have been dismissed as insignificant contributors to adverse air quality impacts. This is due largely to the fact that aviation sources account for only a small portion of total emissions from all sources. (3,4) However, on a regional and local scale the picture is rather different.

Commercial Aviation

Currently, the Basin's five major commercial airports (Los Angeles-LAX, Ontario-ONT, Santa Ana-SNA, Burbank-BUR, and Long Beach-LGB) host one of the most intense areas of commercial air traffic activity in the country. Despite this intensity, reliable "census" data on commercial jet aircraft operations and fleets frequently are unavailable, inconsistent, or out-of-date. For example, consider the following range of commercial jet landing/takeoff cycles (LTOs) for the above mentioned airports during the same time period - 1987.

According to information provided by the South Coast Air Quality Management District (SCAQMD), as part of its 1991 Air Quality Management Plan, in 1987 domestic and international commercial jet air carrier operations at these airports averaged 821 LTOs daily. (5) This level of traffic agrees with that of the California Department of Transportation (Caltrans) Division of Aeronautics, which in its 1988 California Aviation System Plan (CASP), accounted for 1640 small, medium and large jet operations (or 820 LTOs) for these airports in 1987. (6) In contrast, however, the Southern California Association of Governments (SCAG) 1987 inventory totaled a daily average of 2168 operations or 1084 LTOs. (7) Finally, the U.S. Environmental Protection Agency (EPA), in developing its latest Federal Implementation Plan (FIP) for California, has utilized a 1990 "baseline" commercial jet LTO inventory for the five major airports of the region of 335,611, yielding a daily average of 919 LTOs. (8) Because commercial air carrier activity experienced significant changes during this period, 1990 data may not be representative of typical operations. For example, several air carriers, including Eastern Airlines, suspended or terminated operations in the South Coast area. Conversely, other airlines, such as Southwest, which had a minimal presence in this area prior to 1990, subsequently have undergone significant operational expansion. Clearly, lack of current, consistent, and verifiable LTO data complicates the assessment of commercial aviation's contribution to regional air quality problems.

For a final perspective on the complexity of accurately estimating Basin-specific commercial jet emissions, consider the LTO cycle, which incorporates all of the normal aircraft flight and ground operation modes that impact Basin air quality, including:

- descent/approach from 3,000 feet;
- touchdown and landing run;
- taxi in, idle and shutdown;
- startup, idle and checkout;
- taxi out, takeoff and climbout to 3,000 feet.

The LTO operational description is of importance to Basin air quality, since an inversion layer frequently exists at an altitude of approximately 3000 feet over much of the Basin, a situation which can exacerbate aircraft LTO emissions. The question then becomes whether or not this level of commercial aviation activity, and its associated emissions, is of a magnitude which can exert a potentially significant negative impact on regional air quality.

Both SCAG and SCAQMD have compiled LTO emission data on various commercial aircraft/engine combinations operating within the Basin, which account for aircraft-specific variations in time-in-mode for the LTO segments of approach, taxi/idle (arrival), idle/taxi (departure), takeoff, and climb. (7,23) Tables 1 and 2 illustrate SCAG and SCAQMD data, respectively, which have been averaged for carbon monoxide (CO), hydrocarbon (HC), and oxides of nitrogen (NOx) emissions for several commercial and general aviation (GA) aircraft classes.

TABLE 1
SCAG COMMERCIAL AIRCRAFT
AVERAGE EMISSION RATES (lb/LTO Cycle)

AIRCRAFT/ENGINE	NOx	CO	HC
CLASS 1			
B727/JT8D-17	25.29	29.75	6.71
B737/JT8D-17	16.86	19.84	4.47
B737-300/CFM56-3	14.69	14.33	0.80
BAE146/ALF502R5	7.47	12.82	1.54
DC9-30/JT8D-17	16.86	19.84	4.47
DC9-80/JT8D-217	23.07	8.23	2.50
CLASS 1 AVERAGE	**17.37**	**17.47**	**3.42**
CLASS 2			
B707/JT3D-7	22.65	163.75	130.81
DC8-63/JT3D-7	22.65	163.75	130.81
DC8-70/CFM56-2	35.90	30.71	1.39
B757-200/PW 2037	34.96	14.64	1.43
CLASS 2 AVERAGE	**29.04**	**93.21**	**66.11**
CLASS 3			
A300/GE CF6-50	56.64	50.98	19.58
B747-100/GE CF6-50	113.29	101.96	39.17
B747-200/JT9D-7	77.20	166.98	61.05
B747-SP/RB211-524	118.57	43.34	6.47
B767-200/GE CF6-80	50.51	21.48	2.23
DC10-10/GE CF6-6	61.00	58.41	20.07
DC10-30/GE CF6-50	84.96	76.47	29.38
DC10-40/JT9D-7	57.90	125.24	45.79
L1011-1/RB211-22	59.85	132.16	89.44
L1011-5/RB211-524	88.92	32.50	88.92
CLASS 3 AVERAGE	**76.88**	**80.95**	**40.21**

Source: SCAG. (7)

At this point, it is instructive to consider what this level of commercial aircraft activity and associated emissions means in terms of equivalent individual passenger vehicle (automotive) emissions, both now and in the future.

Aircraft vs. Autos

The SCAQMD provides guidance for estimating automotive emissions in support of California Environmental Quality Act (CEQA) Environmental Impact

Report (EIR) documents. (9) Drawing upon information provided by this guidance, we can estimate a Basin-specific emission rate for an "average" present-day (ca. 1991) individual passenger automotive vehicle, i.e. 0.15, 0.02, and 0.02 pounds per day of CO, HC, and NOx, respectively (Table 3).

TABLE 2
SCAQMD TURBINE-FUELED AIRCRAFT AVERAGE EMISSION RATES (lb/LTO Cycle)

AIRCRAFT CLASS	NOx	CO	HC
C1 Small Jet Transport	19.98	30.24	5.92
C2 Med. Jet Transport	33.98	64.06	36.78
C3 Large Jet Transport	72.59	66.48	16.62
C4a Small/Med. Turboprop	1.55	6.51	5.51
C4b GA Turboprop/jet	2.57	22.62	9.04

Source: SCAQMD. (5)

TABLE 3
CURRENT SOUTH COAST AIR BASIN DAILY PASSENGER VEHICLE EMISSION RATES

	(Trips/Miles per trip)	
COUNTY	WORK	NONWORK
Los Angeles	0.95/9.6	4.35/5.6
Orange	1.07/10.9	4.32/5.6
Riverside	0.90/17.7	4.48/7.8
San Bernardino	0.91/13.0	4.79/7.0
Regional Average	0.96/13.0	4.48/6.5

TRIP BREAKDOWN	39.27%	60.73%
REG. AVG. VMT	5.11	3.95
TOTAL AVG. VMT	9.06 miles @ 25.4 mph	

EMISSION FACTORS	CO	ROC	NOx
(g/mile)	7.65	0.98	1.1
(g/vehicle)	69.33	8.88	9.97
(lb/vehicle)	0.15	0.02	0.02

Source: SCAQMD (9)

Turbine Aircraft

Information provided by SCAQMD indicates that daily LTOs in 1987 for turbine-fueled, fixed-wing operations (commercial and GA jets and turboprops) at the Basin's five major airports averaged 1466, apportioned approximately as shown in Table 4. (5) By comparing automotive emissions data with those previously estimated for the aviation sectors, we may roughly approximate Basin commercial turbine-fueled emissions, weighted by aircraft class, in terms of passenger vehicle equivalents. Table 5 illustrates these passenger vehicle equivalent approximations (ca.1987-1990) for the previously presented range of LTOs.

Note that the passenger vehicle equivalent values of Table 5 are for the Basin's five major commercial airports only. As such, they do not reflect the additional emission contributions at other Basin airports, from turbine-engined helicopter or military aviation operations, nor do they take into consideration emissions from such commercial aviation ancillary sources as auxiliary power units (APUs) or other ground service equipment (GSE) which utilize turbine fuel.

TABLE 4
SCAQMD* TURBINE-FUELED AIRCRAFT 1987 AVERAGE DAILY OPERATIONS

AIRCRAFT CLASS	LTO %
C1 Small Jet Transport	22.27
C2 Med. Jet Transport	23.60
C3 Large Jet Transport	10.07
C4a Small/Med. Turboprop	22.20
C4b GA Turboprop/jet	21.87
Total Turbine-fueled LTOs	100.00

*LAX, SNA, ONT, BUR, LGB only
Source: SCAQMD. (5)

TABLE 5
DAILY SOUTH COAST AIR BASIN* TURBINE-FUELED AIRCRAFT EMISSIONS WEIGHTED BY AIRCRAFT CLASS (X 10^4 lb)

LTO Emission Data	NOx	CO	HC
SCAG (Class 1-3)	2.5	3.3	1.5
SCAQMD (Class 1-4b)	3.0	5.1	2.2

PASSENGER VEHICLE EQUIVALENTS

NOx	1.3-1.5 x 10^6
CO	2.2-3.4 X 10^5
HC	7.4-10.9 X 10^5

*LAX, BUR, SNA, LGB, ONT only
Source: SCAQMD (5); SCAG (7); Webb (8)

For perspective, it is constructive to consider that, under proposed Rule 1601, the SCAQMD had originally proposed to target a scant 51,000 nontransit fleet cars and light trucks for mandatory conversion to clean alternative fuels.(11) Considered from a slightly different perspective, the level of commercial aviation generated NOx is several times higher than that of all pre-1972 vehicles estimated to be present and on the road in the Basin, which are candidates for emission trading early retirement. (2) This gives rise to yet another observation. Over time, the ground transportation fleet will continue to benefit from overall emission reductions as newer, cleaner vehicles are introduced (Table 6).

TABLE 6
2010 SOUTH COAST AIR BASIN DAILY PASSENGER VEHICLE EMISSION RATES

	(Trips/Miles per trip)	
COUNTY	**WORK**	**NONWORK**
Los Angeles	0.96/10.8	4.34/6.3
Orange	1.09/11.6	4.36/6.5
Riverside	0.89/17.0	4.35/9.6
San Bernardino	0.89/13.6	4.59/7.9
Regional Average	0.96/13.2	4.41/7.6

TRIP BREAKDOWN	39.39%	60.61%
REG. AVG. VMT	5.2	4.6
TOTAL AVG. VMT	9.8 miles @ 23.2 mph	

EMISSION FACTORS	CO	ROC	NOx
(g/mile)	1.49	0.07	0.27
(g/vehicle)	14.65	0.72	2.62
(lb/vehicle)	0.03	0.002	0.01

Source: SCAQMD (9)

Although the aviation sector may show minor emission reductions, due primarily to improvements in turbine engine combustor technology or retirement of older aircraft, the penetration into the overall aircraft fleet likely will be slow as a result of high costs and lengthy certification requirements. Concurrent with this generally static emissions scenario, commercial aviation activity is forecast to increase. For example by 2010, SCAG projects an increase over 1990 levels of approximately 53% in domestic and international commercial air carrier operations within the Basin. (10) The EPA, as part of California's latest FIP, is forecasting growth in these operations from 1990-2010 of approximately 31%. (8)

Regardless of which projection is accurate, the net result will be an increased disparity in aircraft/automotive emissions. For example, assuming a 31% growth in the LTOs of Table 4 (and no change in turbine-fueled aircraft fleet emission or class composition characteristics), when combined with SCAQMD's projected 2010 automotive emissions data, the result yields jet transport emissions equivalent to a significant number of 2010-model year automobiles (Table 7). Note that, once again, none of these approximations take into account the emissions contributed at other Basin airports, nor by APUs, GSE, turbine-powered helicopter or military aircraft operations within the Basin. A similar situation exists for gasoline-fueled, piston engine general aviation aircraft.

TABLE 7
2010 SOUTH COAST AIR BASIN* DAILY TURBINE-FUELED AIRCRAFT EMISSIONS WEIGHTED BY AIRCRAFT CLASS (X 10^4 lb)

LTO Emission Data	**NOx**	**CO**	**HC**
SCAG (Class 1-3)	5.1	7.0	3.5
SCAQMD (Class 1-4b)	5.5	9.3	3.9

PASSENGER VEHICLE EQUIVALENTS

NOx	5.1-5.5 x 10^6
CO	2.4-3.1 X 10^6
HC	17.5-19.7 X 10^6

*LAX, BUR, SNA, LGB, ONT only
Source: SCAQMD (5); SCAG (10)

General Aviation

General aviation is a vital and important segment of personal and business transportation. For example, it has been estimated that in California approximately 70 percent of all flying is business related, while the figure nationally approaches 85 percent. The sharp fuel price rises of recent years have adversely affected the general aviation industry by curtailing not only discretionary, but also business and commercial flying. For example, between 1977 and 1982, the average retail price of aviation gasoline increased more than 400 percent from approximately $0.48 per gallon to more than $2.00 per gallon -- a level where it has remained. In addition, supplies of aviation gasoline are in jeopardy and future shortages loom, since aviation gasoline represents a limited, specialty market to oil refiners.

By utilizing data on general aviation operations provided by the California Department of Transportation and piston engine aircraft emission rates from EPA and SCAQMD, repetition of the above comparisons for general aviation shows that in 1987 these operations contributed NO_x, CO, and HC emissions equivalent to 9.6 x 10^4, 1.4 X 10^6, and 2.5 x 10^5 automobiles, respectively (Table 8). (5,6,12) Like its larger commercial aviation brethren, the regional air quality implications of the general aviation sector will increase as the disparity between these uncontrolled emissions and those of the rapidly improving ground transportation sector widen (Table 9).

Clearly, the aviation sector not only is a significant consumer of petroleum-based fuel, but also represents a significant and expanding source of uncontrolled annual emissions within the Basin. With momentum building for analysis and implementation of alternative fuels and low emission vehicles for air quality improvement within the automotive sector, the time appears ripe to conduct similar investigations in the aviation sector.

TABLE 8
1987 DAILY SOUTH COAST AIR BASIN GENERAL AVIATION PISTON ENGINE AIRCRAFT EMISSIONS

		(x 10^3 lb)		
COUNTY	LTOs	NOx	CO	HC
Los Angeles	2,960	1.02	111.0	2.62
Orange	786	0.27	29.3	0.70
Riverside	878	0.30	32.8	0.78
San Bernardino	975	0.34	36.4	0.86
TOTAL	5,599	1.93	209.5	4.96

PASSENGER VEHICLE EQUIVALENTS

NOx	9.63×10^4
CO	1.39×10^6
HC	2.48×10^5

Source: CALTRANS (6); EPA (12); SCAQMD (5)

Alternative Aviation Fuel Issues

Is there a market for alternative commercial aviation fuels? Despite the attractive potential environmental benefits of alternative aviation fuels, development of both piston and turbine engine alternatives face a number of obstacles in the form of resource, technical development, investment, regulatory and marketing impediments. (13) These development barriers include:

- Availability;
- Distribution;
- Compatibility;
- Economics;
- Energy density;
- Handling;
- Safety; and
- Quality control.

TABLE 9
2000 DAILY SOUTH COAST AIR BASIN GENERAL AVIATION PISTON ENGINE AIRCRAFT EMISSIONS

			(x 10^3)	
COUNTY	LTOs	NOx	CO	HC
Los Angeles	2,901	1.00	108.0	2.57
Orange	865	0.30	32.3	0.77
Riverside	983	0.34	36.7	0.87
San Bernardino	808	0.28	30.1	0.71
TOTAL	5,556	1.92	207.0	4.91

PASSENGER VEHICLE EQUIVALENTS

NOx	1.91×10^5
CO	6.91×10^6
HC	2.46×10^6

Note: Totals shown may not add due to rounding
Source: CALTRANS (6); EPA (12); SCAQMD (5)

Availability and supply affect both conventional and alternative fuels. For example, refiners are reluctant to gear up for low-volume fuel production in the absence of a large existing or perceived market, while manufacturers are unwilling to commit resources to develop aircraft/engine designs for specialty fuels which have no long-term production commitment.

Alternative aviation fuel market penetration depends on its ability to use the existing fuel distribution system. An alternative which is compatible with an existing or developing fuel distribution system will enjoy a significant advantage over one which requires complex and expensive storage and handling facilities. A substitute fuel also must be compatible with current aircraft engine/fuel systems.

The fuel/direct operating cost ratios of civil aircraft have increased during the past two decades from approximately 0.25 to over 0.60. (14) The price of jet fuel rose 40% between August 1989 and January 1990. (15) The cost effectiveness of alternative aviation fuels is, therefore, a key factor in the future viability of aviation in general, and the airline industry in particular. Consequently, a substitute fuel must compete cost-effectively with conventional fuel.

Energy density is another important consideration when screening alternative aviation fuels. Aircraft turbine engines are heat engines, transforming heat released during combustion into useful mechanical work. One result is that aircraft range is, more or less, proportional to fuel-energy density expressed in BTUs per pound or gallon. Lower energy density also can exact a penalty in payload and range.

Studies of alternative aviation fuels are concerned primarily with both quantity and quality as they affect availability, handling, performance and overall economy in terms of both energy and costs. A prime consideration for any aircraft fuel is handling ease and safety. Fuel quality control translates as a need for an American Society for Testing and Materials (ASTM) or similar technical specification or standard.

Aviation Fuel Alternatives

The use of alternatives such as methyl and ethyl alcohols (methanol and ethanol), either as stand-alone substitute fuels or in combination with conventional jet fuel, presents not only an opportunity for reductions in dependence on imported petroleum, but also significant potential as environmentally attractive options to conventional turbine aircraft fuel.

Methanol Methanol is considered to be a "near-term" alternative to conventional petroleum-based fuels in the automotive sector. In addition, methanol already has received considerable attention as an alternative aviation fuel. For example, a Supplemental Type Certificate (STC) already has been obtained from the FAA for piston engine applications of methanol, based on a significant amount of flight testing by former astronaut Gordon Cooper and his partner William Paynter.

The California Energy Commission (CEC) has demonstrated that methanol is an environmentally attractive alternative to conventional turbine fuel for stationary peaking turbines, with engine/fuel system conversion relatively straightforward. (16) Operation of methanol-fueled commercial jet aircraft would be anticipated to realize the same types of positive environmental benefits as determined by the CEC's Clean Coal Stationary Engine Demonstration Project, specifically:

- Significantly reduced NOx emissions relative to conventional Jet A;
- Negligible particulate emissions; and
- Reduced emissions of carbon monoxide and aldehydes during full power operation, such as take-off and climb-out, with a possibly slight increase in these emissions during low power operation, such as descent and taxi.

Should a methanol-fueled commercial jet realize NOx emission reductions consistent with the approximate 5-fold reduction noted in the CEC Clean Coal Stationary Engine Demonstration Project for methanol vs. Jet A, the resultant extrapolation indicates that a commercial aircraft methanol fuel strategy implemented within the Basin could result in substantial daily NOx emission reductions. For example, a 25% methanol fleet penetration by 2010, would be equivalent to eliminating approximately 1.1×10^6 2010-model year passenger vehicles from the Basin.

Somewhat more limited testing has been conducted with methanol in aircraft turbine engines. For example, early in 1983 General Electric performed an altitude simulation test of methanol in a combustor segment of one of its CF 680 aircraft turbines for the National Aeronautics Association (NAA). (17) The test established that methanol as an aircraft turbine fuel would produce low NOx emissions, little smoke and operating temperatures lower than with Jet A. Furthermore, with its lower vapor pressure, methanol could diminish the impact of evaporative emissions from fuel storage and transfer.

The primary operational impacts likely to arise from conversion to methanol will be in the areas of aircraft range and cost. The oft heard "rule of thumb" regarding alternative-fueled aircraft range is that it will be proportional to the Btu content of the fuel relative to conventional Jet A. In the case of methanol, this assumed range reduction would be approximately 50%. However, this "rule of thumb" does not take into account such factors as the increased turbine power and mass flow which result from methanol combustion, yielding the flexibility to operate at decreased power, increased altitude, and/or increased airspeed, with a resultant positive impact on range.

CEC performed a preliminary assessment of the potential for methanol as a commercial jet fuel in California nearly a decade ago. (18) This analysis was widely distributed and reviewed within the established aviation industry. Despite the passage of time, the study's basic conclusions remain unchallenged. A few of these conclusions are:

- Intrastate commercial airlines represent California's largest "captive fleet";
- On typical intrastate flights, the methanol weight penalty (resulting from its lower per pound Btu content relative to jet fuel) does not significantly increase fuel consumption; and
- Present airline operation and refueling practices could accommodate methanol.

Ethanol As with methanol, ethanol has received substantial attention over the years as a potentially viable piston engine aircraft alternative fuel. The primary efforts in this regard have been led by Dr. Max Shauck of Baylor University. Dr. Shauck's efforts recently culminated with the first trans-Atlantic flight using an alternative fuel and his receipt of the prestigious Harmon Trophy.

Recent ground-based turbine engine performance tests using ethanol in various percentage mixtures with conventional jet fuel, indicate some potentially attractive reductions in exhaust emissions. For example, Alabama Aviation and Technical College recently conducted a series of "probe tests" of various alternative aircraft fuels, including a 10% ethanol/90% Jet A fuel mixture in a Pratt & Whitney PT-6 turbine engine. (19) These tests resulted in the following observations relative to conventional jet fuel: reduced odor; 0 ppm (parts per million) HC; and 0% CO at rated power under simulated cruise conditions. Although ethanol has a lower energy content (BTUs per gallon) than Jet A, no appreciable loss of power was detected. All temperatures were observed to remain within acceptable limits.

Somewhat more complex and intensive investigations of ethanol/jet fuel blends were conducted recently at Southern Illinois University (SIU). (20) Although these tests were unable to duplicate the dramatic reductions in HC and CO emission observed in the Alabama tests, the SIU investigation did result in the following observations relative to conventional jet fuel: dramatic reductions in soot (particulate) formation; reduced CO_2 production; and substantial reductions in NOx and nitric oxide (NO) formation.

Liquified Petroleum Gas (LPG) Preliminary investigations by the author and others indicate that LPG displays a significant potential as an alternative fuel for general aviation aircraft in California, nationally, and internationally. LPG is a commercially available transportation fuel, suitable to most applications for which gasoline currently is used. When used as a motor vehicle fuel, LPG exhibits a higher octane level than gasoline. Additional infrastructure requirements for LPG fueling are minimal. In contrast to other alternative fuels, there is an LPG distribution network in place capable of scale modifications if significant demand for LPG as a transportation fuel develops.

Although LPG is considered to be a commercially available fuel substitute for conventional gasoline in certain stationary and ground transportation sectors, it is not so considered in the aviation transportation sector, necessitating technical demonstrations leading to FAA approval. However, LPG already has received attention as an alternative aviation fuel. For example, research efforts continue in the former Soviet Union aimed at converting aircraft to operate on LPG. This effort is being pushed with great urgency because of anticipated increasing shortages of aviation fuel. Additional development work, including wider industry involvement and development, is needed to establish performance, cost, and emissions characteristics before commercial applications of LPG in the aviation sector can commence.

The principal advantages for an LPG aviation application include, but are not necessarily limited to:

- Substantially lower fuel costs relative to aviation gasoline, combined with low-cost, off-the-shelf conversion technology;
- High octane rating, which results in viable performance potential, and an established technical fuel specification (HD-5);
- Current and projected future LPG surplus availability, with concurrent projected declining traditional end-use markets for LPG wholesalers and retailers;
- Existing national (U.S.) LPG supply system infrastructure, with many established wholesale/retail refueling locations proximate to airports in California; and
- Decreased engine/fuel system maintenance costs associated with a clean, low-emitting fuel.

As a substitute fuel which must be compatible with current aircraft engine/fuel systems, LPG appears to be a realistic alternative to gasoline for general aviation operations. There is no insurmountable technical barrier to this application. Automotive experience has shown that LPG is an excellent piston engine fuel and that engine/fuel system conversions are straight forward. LPG appears to be equal or superior to gasoline in the following key performance areas:

- Antiknock properties;
- Preignition and deposit ignition;
- Vapor lock;
- Icing;
- Cold start;
- Hot restart;
- Fuel safety;
- Valve sticking and wear;

- Material incompatibility and corrosion;
- Maldistribution;
- Spark plug operation; and
- Fuel storage stability.

The antiknock property of a fuel is its octane rating -- its ability to resist autoignition and preignition. Aviation gasoline has an octane rating of approximately 80-100, depending upon grade. LPG's octane rating is 110+ without the octane boosters typically blended with gasoline. Consequently, LPG appears to have an attractively high octane rating for modern aircraft engines.

Combustion chamber deposits can aggravate knock-induced preignition. Further, some aromatic compounds tend to preignite easily. These problems are especially prevalent when using automobile gasoline with its higher aromatic content and higher volume of low boiling point constituents. With LPG there is no buildup of deposits in the combustion chamber or on spark plugs, precluding the potential for preignition and deposit ignition. This lack of deposit formation also can lead to significant extension of spark plug life. With compression ratio increased, lower heat range plugs can be used. The clean burning nature of LPG leaves no lead, sludge, varnish, or carbon deposits that can cause valve sticking and wear from lubricant contamination.

Vapor lock can be a problem even with conventional aviation gasoline. Vapor lock is probably the most important safety-related problem facing substitute aircraft fuels. Because LPG is a gaseous fuel, vapor lock hazard is eliminated. Further, because of the absence of deposit ignition and vapor lock, hot restart should be facilitated both on the ground and at altitude. Since LPG vaporizes completely, it enters and distributes within engine cylinders much more readily and evenly than gasoline.

Conventional aviation gasoline contains additives which inhibit the onset of carburetor icing. With LPG, standard industrial practice is to introduce minute quantities of methanol to inhibit icing (about 1 pint per 100 gallons). There is also a limit to the content of water allowed in the fuel quality specifications. Icing should not be a greater problem with LPG than with avgas. In addition, since LPG enters the combustion chamber as a dry gas, cold starting is facilitated. Recently, a 50-hour test of LPG in a Lycoming O-320 aircraft piston engine, conducted at the Alabama Aviation and Technical College, confirmed that, even under ambient freezing conditions, an LPG-fueled engine starts and runs all the way up to full power with no roughness such as that experienced with conventional avgas. (19)

LPG engine fuel has an excellent safety record as noted by the EPA. Further, crash tests have shown LPG storage tanks to be more durable and safer than conventional gasoline tanks. From an environmental standpoint, the sealed fuel system prevents evaporative loss, and engine emissions are considerably lower than from gasoline.

Unlike alcohols and autogas, LPG will not degrade aircraft engine/fuel system components. Further, since an LPG storage system is a sealed system, losses due to spillage, pilferage, and evaporation are eliminated. As a gaseous fuel, LPG is not prone to the deteriorations and disassociations typical of liquid blended fuels over time.

From a performance perspective, internal combustion engine power output and fuel consumption actually are dependent on the energy density of the fuel-air mixture ratio, rather than that of the fuel itself. The energy density of typical propane-air mixtures is only 2.3-3.1 percent lower than that of gasoline-air mixtures. Further, the high octane characteristics of LPG allow the potential for increasing engine compression ratio and improving overall combustion efficiency. Finally, the latent heat of vaporization capacity of LPG could be utilized to cool induction air, thus increasing charge density and resultant power as much as 12 percent. Consequently, the energy density of LPG relative to conventional aviation gasoline does not appear to offer a significant impediment to use in terms of reduced range.

Various industry and government sector ground transportation tests have demonstrated the attractive emission reduction benefits of LPG in comparison with conventional gasoline. For example, recent tests by IMPCO Carburation, Inc., and the California Air Resources Board (CARB) indicate that LPG hydrocarbon (HC) emissions were 16 percent lower than gasoline and 42 percent lower than indolene, 48-60 percent lower than CARB 1988 emission standards and 68-75 percent less than 1989 federal emission standards. LPG carbon monoxide (CO) emissions were 11 percent less than with gasoline, 70-84 percent lower than CARB standards and 73-75 percent less than federal standards. Nitrogen oxide emissions were 7 percent less than gasoline, 73-74 percent lower than CARB and 84-86 percent lower than federal. These emission gains were exceeded in high altitude demonstrations conducted at Environmental Testing Corporation in Aurora, Colorado. LPG-fueled operation also results in less carbon dioxide CO2 emission than gasoline, with demonstrations indicating a reduction of 11-13 percent. LPG emission products are also approximately 47 percent less reactive in terms of the potential for ozone formation than gasoline.

Aviation Fuel Development Plan

Additional development work, including wider industry and public agency involvement, is needed to establish the performance, cost, and emissions characteristics of any of these alternative aviation fuels before commercial applications can commence. (22) In this light, the author suggests structuring a research, demonstration, test, and evaluation (RDT&E) project to concurrently:

- Flight test and demonstrate the potential for the alternative fuel LPG to replace conventional aviation gasoline in aircraft piston engines; and
- Flight test and quantify the potential for regional air quality improvement through the use of various alternative fuel(s) in the turbine engine, commercial aviation sector.

The proposed effort would be structured to develop the data necessary to recertify a conventional single engine aircraft for operation on LPG. Concurrently, a series of various alternative fuel/fuel blend performance and emission "probe" tests, under actual LTO cycle flight conditions, could be conducted simultaneously using a small aircraft turbine engine (e.g. Microturbo TRS-18) mounted on the piston engine test aircraft. It is anticipated that such an approach can garner technical data at significantly lowered engineering, development, test, and logistic costs associated with a flight test program of this magnitude relative to a program focused on a large commercial or corporate jet aircraft.

Implementation of alternative fuels within the air transport sector will help keep California competitive by lowering operation and maintenance costs for flight schools, FBOs, business and agricultural aircraft. These cost savings will have a direct effect on business and commercial aviation "bottom line" profitability and, consequently, tax revenues. In addition, successful completion of the program, resulting in STC approval would result in a viable energy export technology. Finally, transitioning to clean aviation fuels would help ensure that this critical transportation sector proactively seeks to become more compatible with regional and federal air quality goals.

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