[Note: some graphics & attachments are not available in this electronic version of document.]

September 29, 1995

MEMORANDUM

TO: Bill Albee, FAA
Rich Wilcox, EPA

FROM: Sandy Webb, EEA

SUBJECT: Technical Data to Support FAA's Advisory Circular on Reducing Emissions from Commercial Aviation

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Attached for your review is the draft document that presents technical data to support FAA's Advisory Circular on Reducing Emissions From Commercial Aviation. Data was collected and compiled in four main areas: commercial aircraft fleet emissions and strategies, conversion of GSE to alternative fuels (including electric), limiting the use of APUs, and fixed power and air conditioning systems at airport gates.

As discussed previously, many of the data elements are in draft form and would benefit from manufacturer and industry review. In particular, it would be advantageous to have industry representatives evaluate GSE use, brake horsepower, fuel consumption, and cost inputs. There are gaps in much of this data, which industry should be able to fill. For APUs, we appreciate FAA's assistance in contacting AlliedSignal to confirm the emission factors contained in ENSR's memorandum and to authorize inclusion of the data in the advisory circular. It would be useful to have AlliedSignal also review APU calculation procedures, and industry representatives review APU use and cost data.

Yesterday, EEA received average aircraft taxi data from FAA. These data were received too late to compile and review for incorporation into the attached draft document and airport database. Historical average taxi data was received from FAA's Office of Aviation Policy, Plans, and Management Analysis and includes airport location identification, OAG air carrier code, number of departures, number of arrivals, average taxi-in time, and average taxi-out time on a monthly basis. We do not have information on how the average taxi data was calculated. The file format and disk copy of the data file that FAA provided to EEA are included in Attachment 1. Because the data EEA requested of FAA on airports (Memorandum from S. Webb to B. Albee, FAA and R. Wilcox, EPA dated August 23, 1995) is coming from trade association surveys or hard copy reports filed with the FAA's Airports Division, data on only 50 airports is being provided for some data elements. As of today none of this information has been transmitted to EEA. Also, Airports Division was unable to provide other data elements, which we had originally hoped to compile. This includes the following data.

- Aircraft Gates
  - number of gates by airport
  - 400 Hz power/PCA status of gates by airport
  - 400 Hz power/PCA system installation, operating, and maintenance costs

- Helicopter Operations
  - number and type of helicopter operations by airport, county, or nonattainment area
- Enplanements
  - number of enplanements by airport for different aircraft categories (e.g., air carrier, air taxi, commuter, general aviation)
- Parking Spaces
  - the number of parking spaces by airport for employees and for passengers

In addition to the draft report, a diskette copy of the airport database covering 521 airports is attached. The information included in this database is discussed in the report. Please call me at (703) 528-1900 with any questions or comments.

Attachments:

Technical Data to Support FAA's Advisory Circular on Reducing Emissions from Commercial Aviation, draft report.

Airports Database Diskette

Average Aircraft Taxi Data Diskette and file format (Wilcox only)

cc: Annette Najjar, E.H. Pechan & Associates, Inc. (w/o attachments)

ATTACHMENT 1

FAA AVERAGE AIRCRAFT TAXI DATA

- **File Format**
- **Disk Copy of Data File**

ATTACHMENT 2

FAA AIRPORT GATE DATA

DRAFT

TECHNICAL DATA TO SUPPORT FAA'S ADVISORY CIRCULAR ON REDUCING EMISSIONS FROM COMMERCIAL AVIATION

Prepared for:

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September 29, 1995

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TECHNICAL DATA TO SUPPORT
FAA'S ADVISORY CIRCULAR
ON
REDUCING EMISSIONS FROM COMMERCIAL AVIATION

The U.S. Environmental Protection Agency (EPA) recently developed an interim final Federal Implementation Plan control strategy for aircraft operations in the Los Angeles, Sacramento, and Ventura areas of California. In its comments to the EPA on it's California FIP proposal, the Federal Aviation Administration (FAA) supported the reduction of emissions from commercial aviation through three methods: conversion of ground support equipment (GSE) to alternative fuels, reduced use of auxiliary power units (APUs), and installation of electric power and air conditioning at gates to reduce the need for operating APUs. FAA also agreed to encourage aircraft operators to operate the cleanest practical fleets into the FIP areas.

Although Congressional action deferred the proposed FIP for California, the EPA and FAA anticipate similar mandates in the forthcoming California State Implementation Plan (SIP) or a new EPA FIP if a conforming SIP is not produced before the scheduled deadline. Consequently, the EPA and FAA agree there is a need to continue the commercial aviation emission reduction initiative begun as part of the FIP. To this end, FAA plans to develop an advisory circular to encourage continuing progress in reducing emissions in the commercial aviation sector.

Under contract to EPA, EEA has collected and compiled technical data for use in developing the advisory circular. Data needed to evaluate the reduction of emissions through the conversion of GSE to alternative fuels is provided including GSE types, fuels, emissions, capital costs, and operating and maintenance costs. Emission reductions through limiting use of APUs is discussed and data needed to quantify this benefit is provided including APU models, emissions, and operating and maintenance costs. To allow limited APU use at airport gates, fixed power and air condition systems are necessary. Data is provided on system functions, operational and design parameters, emissions, and costs for existing and future fixed systems. Finally, an example fleet of U.S. commercial aircraft is ranked using several different measures of their relative emissions.

Data on U.S. airports having commercial air service has been compiled so that opportunities for reducing aviation emissions can be evaluated. This data includes information on each airport's local air quality (nonattainment status), the level of operational activity, and other indicators of the prospects for reducing aviation-related emissions. In addition, emissions from electric generation plants are discussed since these are important when considering electric GSE and fixed power and preconditioned air system emissions.

U.S. AIRPORTS WITH COMMERCIAL SERVICE

Using FAA Airport Master Records of U.S. and protectorate airports, EEA developed a preliminary database of 13,272 airports. The Airport Master Records are current as of 1990. Of the total, 521 airports in the lower-48 U.S. states had commercial service activity. Activity data (i.e., operations) from the Airport Master Records was supplemented with more current and detailed data using FAA fiscal year 1994 airport operations data for 435 airports (Reference 20). A list of the 521 commercial service airports and associated geographic and activity information is provided in Appendix 1.

The Clean Air Act and its various amendments established National Ambient Air Quality Standards (NAAQS) for several "criteria" pollutants, including ground-level ozone and carbon monoxide. Regions of the nation that fail to attain any of these standards are subject to a series of rigorous requirements designed to achieve attainment with the NAAQS. To identify those airports in nonattainment areas, baseline ozone and carbon monoxide nonattainment areas were identified and updated to include current redesignations. Boundaries of the Ozone Transport Region (OTR) also were defined. The Ozone Transport Region consists of the District of Columbia, Maryland, several northern Virginia counties, and all states north. Maps of the lower-48 states are included in Figures 1 and 2 that show the 521 commercial service airports and current ozone and carbon monoxide nonattainment designations, respectively. The ozone nonattainment area airport map in Figure 1 also includes the Ozone Transport Region boundary for the northeast states. A list of the 521 commercial service airports also is provided in Appendix 2 that identifies current ozone nonattainment status, current carbon monoxide nonattainment status, and whether it falls into the Ozone Transport Region.

EMISSIONS FROM ELECTRIC POWER PRODUCTION

Several options for reducing emissions from equipment operations at airports rely on the use of electric power. Use of electric GSE, electric air conditioners, or fixed power systems produces no emissions at the airport but generating the electricity needed to operate them does. Compared to APUs or GSE, power plants are very energy efficient and typically meet strict environmental standards through add-on controls and optimized operation. As a result, emissions from power production for use in electric equipment are much lower in total than emissions from equipment using internal combustion engines.

When electricity is used at an airport to power an aircraft on the ground or to recharge an electric vehicle, local or regional power plants are generating additional electricity to meet this demand. The emissions generated at the power plant depend on the power generation technology, fuel used, and emission controls. These factors vary from region to region throughout the US. Table 1 summarizes emissions factors for electric power

FIGURE 1

U.S. Commercial Service Airports

— In Relation To U.S. Ozone Nonattainment Areas —

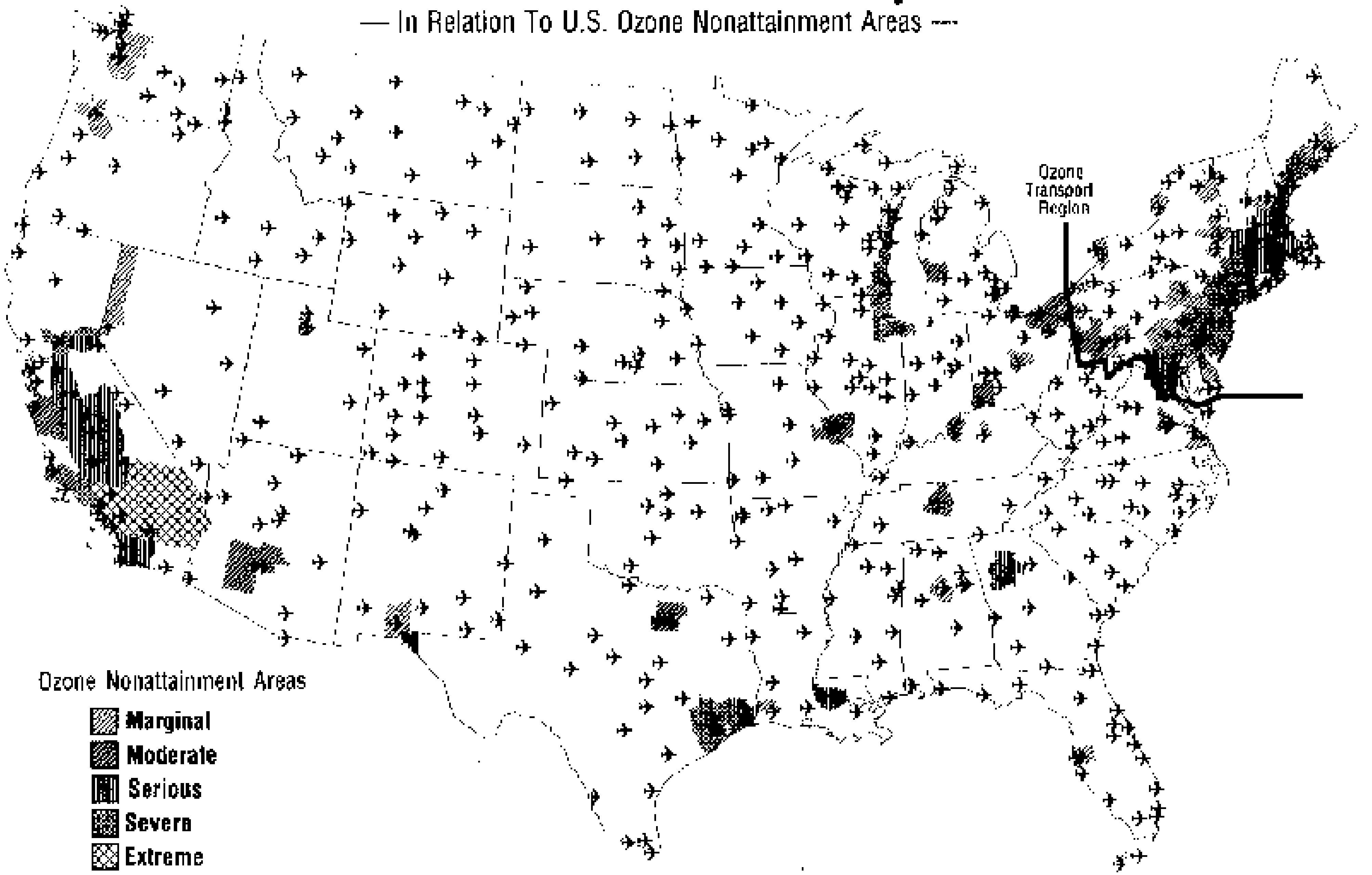
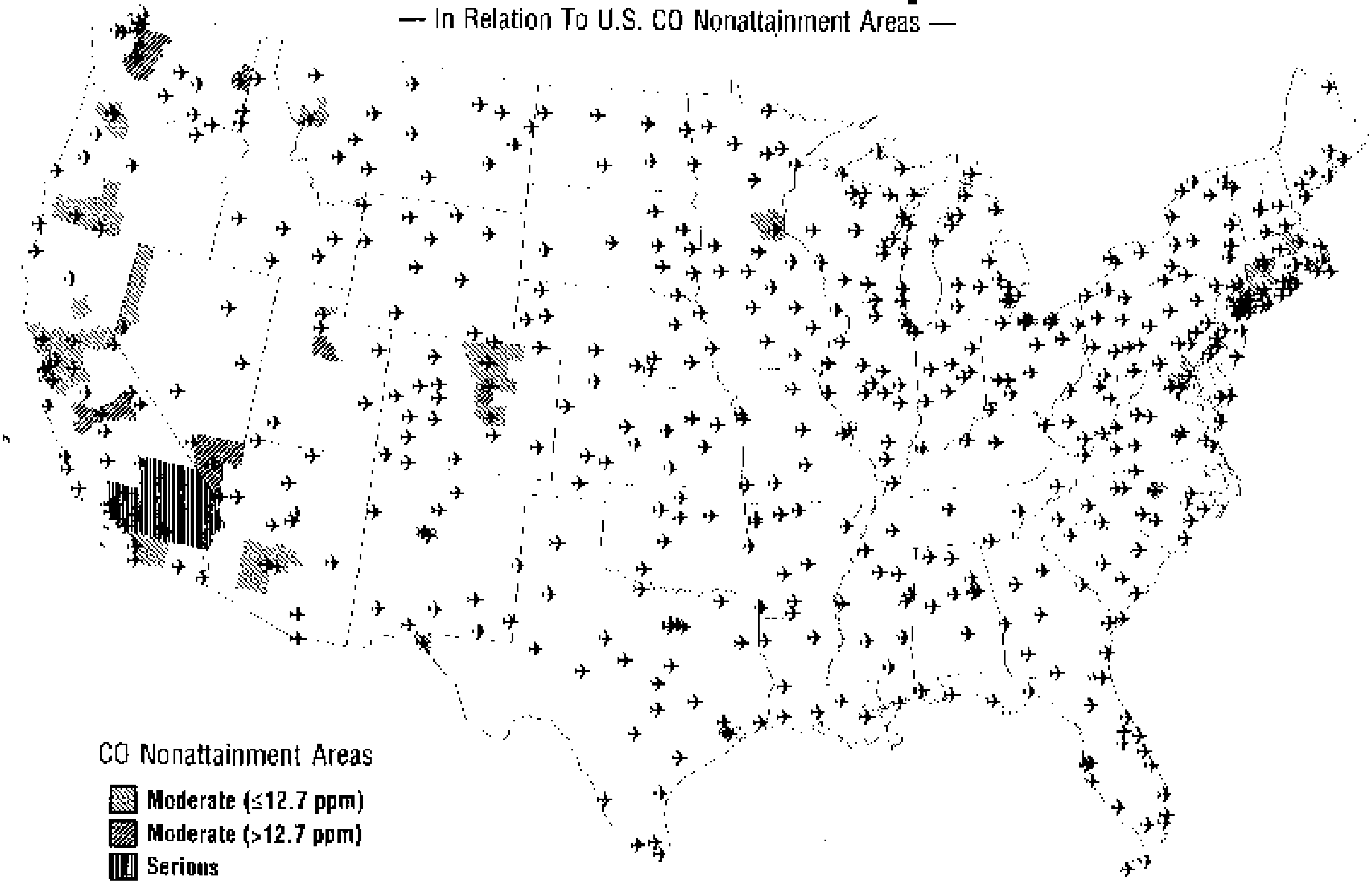


FIGURE 2

U.S. Commercial Service Airports

— In Relation To U.S. CO Nonattainment Areas —



production for the total US as well as for the OTR, California, and all areas of the US except the OTR and California. These factors relate emissions at a power plant to electricity use at an airport or other location connected to the power distribution system. They are based on the regional mix of electricity generation technology and assume an 8% power loss in the transmission and distribution system.

TABLE 1: EMISSIONS FROM ELECTRIC POWER CONSUMPTION[1]

Region	Emission Factor (lbs/MWh)[2]		
	HC	**CO**	**NO_x**
Ozone Transport Region[3]	0.03	0.33	0.88
California	0.04	0.44	0.31
Other U.S.	0.03	0.34	3.97
Total U.S.:	0.03	0.36	3.52

[1] Source: EEA unless otherwise noted. Data has been adjusted to account for 8% transmission and distribution losses.

[2] Represents pounds of pollutant emitted at the point of power generation per megawatt hour of electricity consumed in 2000.

[3] Source: *Impact of Battery-Powered Electric Vehicles on Air Quality in the Northeast States* (Reference 19)

COMMERCIAL AIRCRAFT

Several options exist for reducing aircraft emissions through operational control strategies. These include scheduling lower-emitting aircraft to operate in areas with air quality problems, minimizing the number of engines in operation during taxi-in and taxi-out (single engine taxi), derated-power takeoffs, and reducing use of reverse thrust upon landing, among others. Several of these options were analyzed as possible components of the FIP. For the present report, the only operational control analysis was evaluating different ways to rank aircraft according to their relative emissions.

The objective in scheduling lower-emitting aircraft to operate in areas with air quality problems is to move the maximum number of passengers and cargo (i.e., payload) with minimum emissions. For the purpose of this analysis, the minimum emissions per unit of payload moved is the figure of merit for "environmental efficiency" or "emissions productivity." Ranking aircraft simply according to their emissions per operation is not an appropriate measure since large aircraft generally have higher emissions than smaller aircraft because they have larger and/or more engines. Large aircraft are moving more payload since they (potentially) are transporting more passengers and cargo with each operation. A measure that more closely reflects emissions per unit of payload would be emissions per seat, however, this does not address cargo and airlines periodically change the configuration of their aircraft cabins, adding or removing seats, which would change value of this measure. Directly measuring emissions per unit of payload would be a better way to compare different aircraft. Consistently and accurately measuring payload is a problem, however, since it requires knowing the passenger and cargo load factors. This implies that a surrogate for emissions per unit of payload is needed. The best surrogate measure that EEA considered was emissions per unit of engine thrust. Conceptually, one ton of payload requires a similar amount of thrust for a single LTO regardless of the aircraft model or number or size of engines. Undoubtedly this measure does vary by aircraft model since the ratio of payload to gross weight varies somewhat between aircraft models. The benefit to this measure is that its value reflects the actual performance of the engines; engines with low emissions factors produce low emissions per unit of thrust . Another benefit is that engine manufacturers already calculate this value, based on default LTO times-in-mode, as part of the engine certification process. It is reported as Dp/Foo; where Dp is the mass of any gaseous pollutant emitted during the reference emissions landing and takeoff cycle and Foo is rated output, which is the maximum power/thrust available for take-off under normal operating conditions at sea level static conditions (without water injection). It is typically reported in grams/kiloNewton thrust.

An example fleet of U.S. commercial aircraft, listed in Table 2, was used to evaluate alternative means of defining lower-emitting aircraft. The aircraft were ranked from lowest- to highest-emitting based on total emissions per LTO, emissions per seat per LTO, emissions per engine per LTO, and Dp/Foo (expressed as pounds of emissions per 1000 pounds of thrust). Only the last measure appears to rank the aircraft where large and small aircraft appear throughout the ranking and newer aircraft are generally at the top of the list as one would expect since many have engines designed for low emissions. Other measures tend to distribute the aircraft poorly, biasing the ranking in favor of smaller aircraft. The aircraft rankings by different evaluation measure are shown in Appendix 3.

GROUND SUPPORT EQUIPMENT

A wide variety of equipment services large commercial aircraft while they are unloading and loading passengers and freight at an airport. Air taxi and smaller aircraft, unlike larger commercial aircraft, typically do not require this service equipment. As a group, the ground support equipment (GSE) for large commercial aircraft include primarily the following types of equipment.

- **Air Start Units -** Provide large volumes of compressed air to an aircraft's main engines for starting.
- **Air-Conditioning Units -** Provide conditioned air to ventilate and cool parked aircraft.
- **Aircraft Tugs -** Tow aircraft in the terminal gate area. They also tow aircraft to and from hangers for maintenance. These were broken into two categories: tugs for narrow body aircraft and tugs for wide body aircraft.

TABLE 2: U.S. COMMERCIAL AIRCRAFT EXAMPLE FLEET

AIRCRAFT NAME	AIRCRAFT MANUFACTURER	ENGINE NAME	EMISSIONS PER LTO* CO	NOx	HC	AIRCRAFT CLASS	LOW # SEATS	HIGH # SEATS
A-300-600	AIRBUS	CF6-80C2A5	61.60	56.15	13.08	2	267	267
A-300B	AIRBUS	CF6-50C2	30.29	52.40	3.48	2	262	262
A-310-300	AIRBUS	PW4152	16.52	47.36	1.21	2	218	280
A-320-100	AIRBUS	CFM56-5A1	15.03	23.75	1.45	1	150	150
A-320-200	AIRBUS	IAE V2500	7.38	34.02	0.32	1	150	150
A-321	AIRBUS	CFM56-5A1	15.03	23.75	1.45	2	186	200
A-330	AIRBUS	CF6-80C2A1	60.08	54.60	12.85	3	335	335
A-330	AIRBUS	CF6-80C2A1	60.08	54.60	12.85	3	335	335
A-330	AIRBUS	PW4158	32.62	57.00	2.75	3	335	335
A-340	AIRBUS	CFM56-5A1	15.03	23.75	1.45	3	262	440
B-727-200	BOEING	JT8D-17A	20.93	26.03	3.58	1	136	160
B-727-200	BOEING	JT8D-7B	53.88	20.35	15.31	1	136	160
B-727-200	BOEING	JT8D-15	60.49	26.38	17.94	1	136	160
B-727-200	BOEING	JT8D-17	52.91	28.33	17.50	1	136	160
B-737-200	BOEING	JT8D-9A	35.36	14.86	9.95	1	102	122
B-737-200	BOEING	JT8D-17	35.27	18.89	11.67	1	102	122
B-737-200	BOEING	JT8D-15A	13.51	16.09	2.60	1	102	122
B-737-200	BOEING	JT8D-15	40.33	17.59	11.96	1	102	122
B-737-300	BOEING	CFM56-3B	26.00	20.71	1.18	1	128	137
B-737-300	BOEING	CFM56-3C	29.48	20.59	1.83	1	128	137
B-737-400	BOEING	CFM56-3C	29.48	20.59	1.83	1	146	146
B-737-400	BOEING	CFM56-3B	26.00	20.71	1.18	1	146	146
B-737-500	BOEING	CFM56-3B	26.00	20.71	1.18	1	108	122
B-747-100	BOEING	JT9D-7A (MOD V)	167.66	127.19	79.85	3	410	431
B-747-200	BOEING	JT9D-7Q	175.89	109.18	40.20	3	410	410
B-747-400	BOEING	PW4056	31.55	115.02	2.54	3	412	412
B-757-200	BOEING	PW2037	23.78	35.75	2.34	2	187	194
B-757-200	BOEING	PW2040	26.75	49.87	2.65	2	187	194
B-757-200	BOEING	RB211-535E4	22.55	60.11	1.35	2	187	194
B-767-200	BOEING	JT9D-7R4D	15.93	59.57	2.04	2	184	210
B-767-200	BOEING	CF6-80C2B2	65.89	38.78	15.02	2	184	210
B-767-200	BOEING	CF6-80A2	32.62	52.37	7.32	2	184	210
B-767-200	BOEING	CF6-80A	32.66	48.79	7.21	2	184	210
B-767-300	BOEING	PW4460	31.88	62.16	2.62	3	204	254
B-767-300	BOEING	CF6-80A2	32.62	52.37	7.32	3	204	254
B-767-300	BOEING	CF6-80C2B6	61.60	54.51	13.08	3	204	254
B-777-200	BOEING	PW4056	15.78	57.51	1.27	3	350	400
BAE 146-200	BAE	ALF 502R-5	24.65	10.51	3.10	1	95	110
DC-9-30	MCDONNELL-DOUG	IAE V2500	7.38	34.02	0.32	1	98	108
DC10-10	MCDONNELL DOUG	CF6-6D	102.49	76.80	38.50	3	284	296
DC10-10	MCDONNELL DOUG	CF6-6D	102.49	76.80	38.50	3	284	296
DC10-30	MCDONNELL DOUG	CF6-50C2	148.19	88.75	88.14	3	258	298
DC10-40	MCDONNELL DOUG	JT9D-59	131.92	81.89	30.15	3	298	298
DC8-60	MCDONNELL DOUG	JT3D-7	262.74	25.65	218.35	2	189	259
DC8-70	MCDONNELL DOUG	CFM56-2B	53.65	34.70	2.99	2	189	259
DC9-30	MCDONNELL DOUG	JT8D-7B	35.92	13.57	10.21	1	98	108
DC9-40	MCDONNELL DOUG	JT8D-11	39.61	16.49	10.83	1	107	107
DC9-50	MCDONNELL DOUG	JT8D-17	35.27	18.89	11.67	1	122	122
DC9-80	MCDONNELL DOUG	JT8D-219	14.24	26.92	4.19	1	135	146
DC9-80	MCDONNELL DOUG	JT8D-209	15.33	22.38	4.62	1	135	146
DC9-80	MCDONNELL DOUG	JT8D-217C	14.26	26.39	4.13	1	135	146
DC9-80	MCDONNELL DOUG	JT8D-217A	14.26	26.39	4.13	1	135	146
DC9-80	MCDONNELL DOUG	JT8D-217	14.26	26.39	4.13	1	135	146
F-28	FOKKER	SPEY MK555	75.04	10.38	75.66	1	63	68
F100-100	FOKKER	TAY MK650	30.52	12.70	3.17	1	97	103
F100-100	FOKKER	TAY MK620-15	19.58	12.41	3.01	1	97	103
L-1011-50	LOCKHEED	RB211-22B	248.27	65.68	160.60	3	275	296
L-1011-500	LOCKHEED	RB211-524B4	33.20	112.00	6.17	3	226	226
MD11-11	MCDONNELL DOUG	CF6-80C2D1F	93.35	81.99	20.65	3	314	314
MD11-11	MCDONNELL DOUG	PW4460	47.83	93.24	3.93	3	314	314
MD11-11	MCDONNELL DOUG	CF6-80C2D1F	93.35	81.99	20.65	3	314	314

* LTO - Landing/Take-Off cycle

- **Baggage Tractors -** Haul baggage between the aircraft and the terminal.
- **Belt Loaders -** Mobile conveyor belts used to move baggage between the ground and the aircraft hold.
- **Buses -** Shuttle personnel between airport locations.
- **Cargo Moving Equipment -** Various types of equipment employed to move baggage and other cargo around the airport and to and from aircraft. This category includes forklifts, lifts, and cargo loaders.
- **Cars** - Move personnel around the airport.
- **Deicers -** Vehicles used to transport, heat, and spray deicing fluid.
- **Ground Power Unit (GPU) -** Mobile ground-based generator units that supply aircraft with electricity while they are parked at the airport.
- **Other -** Small miscellaneous types of equipment commonly found on airports such as compressors, scrubbers, sweepers, and specialized units.
- **Pickups -** Move personnel and equipment around the airport.
- **Service Vehicles -** Specially modified vehicles to service aircraft at airports. This category includes fuel trucks, maintenance trucks, service trucks, lavatory trucks, and bobtail tractors (a truck body that has been modified to tow trailers and equipment).
- **Vans -** Move personnel and equipment around the airport.

GSE OPPORTUNITY FOR EMISSION REDUCTIONS

While GSE are commonly fueled by gasoline or diesel, it is possible to use other fuels that result in lower emission operation. Alternatives to gasoline and diesel include compressed natural gas, liquefied natural gas, liquefied petroleum gas (commonly propane), and electricity. This discussion refers to these fuels excluding electricity as alternative fuels.

Many different types of GSE are commercially available that operate on alternative fuels or electricity. From an emissions perspective, equipment originally designed to use these fuels gives much better environmental performance than equipment that is converted from a conventional fuel to use an alternative fuel or electricity. This report describes the benefit of using GSE designed to use alternative fuels or electricity.

The following sections discuss how to determine emission reductions achieved and the cost (or savings) incurred through purchasing, operating, and maintaining equipment that operates on alternative fuels or electricity. First, GSE emissions and operating cost discussions address calculation methodologies, sample calculations, and data inputs. Then the methodology for calculating emission reductions, costs (or savings), and cost effectiveness are discussed.

GSE EMISSIONS

This section discusses the calculation methodology and data inputs for determining the pollutant emissions from GSE. In the case of electric GSE, emissions attributable to the generation of electricity for use by the equipment are taken into account. GSE emissions of significance are hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), particulates (PM), and sulfur dioxide (SO_2). For conventional and alternative fuel GSE, the factors that determine the quantity of pollutant emitted are the emission factor, average rated brake horsepower, load factor, and usage. For electric GSE, the quantity of pollutant emitted due to the generation of electricity for recharging the equipment is determined by the emission factor of the electric power plant and the amount of electricity consumed as described earlier.

GSE Emissions - Calculation Methodology (Conventional and Alternative Fuel GSE)

The following equation calculates the pollutant emissions from an individual unit of equipment.

$$E_{it} = (BHP_t \text{ x } LF_t \text{ x } U_t \text{ x } EI_{it}) \text{ x } CF$$

Where: E_{it} - emissions per year of pollutant i, in pounds, produced by GSE type t
BHP_t - average rated brake horsepower (BHP) of the engine for equipment type t
LF_t - load factor utilized in ground support operations for equipment type t
U_t - annual hours of use for equipment type t
EI_{it} - emission index (or emission factor) for pollutant i, in grams per BHP-hr, which is specific to a given engine size (and engine vintage for diesel engines) and fuel type
i - pollutant type (HC, CO, NO_x, PM, SO_2)

t - equipment type (e.g., diesel baggage tug)
CF - 0.0022046 unit conversion factor from grams to pounds

GSE Emissions - Calculation Methodology (Electric GSE)

The following equation calculates the pollutant emissions attributable to the generation of electricity used by a particular piece of electric GSE. The emissions are determined based on usage and emission indices of the electric power plant. Since emissions associated with electric GSE occur at the power plant rather than at the point where the equipment is used, the equation defined above is modified somewhat.

$$E_{it} = U_t \text{ X } EI_{it}$$

Where: E_{it} - emissions of pollutant i, in pounds, attributable to the use of GSE type t (e.g., electric baggage tug) for a given time period
U_t - megawatt hours of electricity used by equipment type t
EI_{it} - emission index (or emission factor) for pollutant i, in pounds per megawatt hour of electricity consumed
i - pollutant type (HC, CO, NO_x, CO_2)
t - equipment type (e.g., electric baggage tug)

GSE Emissions - Example Calculation (Conventional and Alternative Fuel GSE)

This sample calculation illustrates the procedure for determining the pollutant emissions from a particular GSE type. For this example, emissions will be calculated for a diesel baggage tug with a 78 horsepower engine, which is used for 1,021 hours per year.

Pollutant	BHP	Load Factor	Usage (hr/yr)	Emission Index (grams/BHP-hr)	Emissions (lbs)
HC	78 x	55% x	1,021 x	1.2 x 0.0022046 =	115.88
CO	78 x	55% x	1,021 x	4.0 x 0.0022046 =	386.25
NO_x	78 x	55% x	1,021 x	11.0 x 0.0022046 =	1,062.20
PM	78 x	55% x	1,021 x	0.5 x 0.0022046 =	48.28
SO_2	78 x	55% x	1,021 x	0.25 x 0.0022046 =	24.14

GSE Emissions - Example Calculation (Electric GSE)

This example calculation illustrates the procedure for determining the pollutant emissions attributable to the generation of electricity used by a particular GSE type. This example assumes a baggage tug consumed 60,000 kilowatt-hours (or 60 Mwh) of power during the year at an airport in California.

Pollutant	Power Consumption (Mwh)		Emission Index (lbs/Mwh)		Emissions (lbs)
HC	60	x	0.04	=	2.4
CO	60	x	0.44	=	26.4
NO_x	60	x	0.31	=	18.6

GSE Emissions - Data Inputs

The data needed for calculating pollutant emissions from GSE include GSE type, engine BHP, engine load factor, GSE usage, engine emission factors, population, and electric generation emission factors; emission factors from electric power generation were presented above in Table 3. These data inputs, as well as GSE economic life, are discussed below.

- **GSE Type -** GSE type refers to the equipment (e.g., baggage tug) and fuel (e.g. diesel) type. A list of GSE types is included in Table 3.

- **Brake Horsepower (BHP) -** Brake horsepower refers to the average rated brake horsepower of an equipment type's engine. Typical brake horsepower data by GSE type is included in Table 3.

- **Load Factor -** The load factor is the average operational horsepower output of the engine divided by its rated BHP. Load factors by equipment type are included in Table 3.

TABLE 3: GSE EQUIPMENT AND ENGINE DATA

Equipment Type	Economic Life[1]	Load Factor	Use Per Year[2]	Fuel Type	Coolant	BHP	Fuel Consumption[3]
Aircraft Tug (Narrow Body Aircraft)	10	80%	1,721	Diesel	Water	175	0.061
				Electric	Water		
				Gasoline	Water	130	0.089
				LPG	Water	130	
				CNG	Water	130	
Aircraft Tug (Wide Body Aircraft)	10	80%	1,721	Diesel	Water	500	0.053
				Gasoline	Water	500	0.089
				CNG	Water	500	
Air-Conditioning Unit	8	75%	271	Diesel	Water	300	0.053
				Electric[4]			
				Gasoline	Water	130	0.089
				CNG	Water	130	
Air Start Unit	8	90%	181	Diesel	Water	600	0.053
				Electric	Air		
				Gasoline	Water	130	0.089
				Jet Turbine	Air	140	0.156[5]
				CNG	Water	130	
Baggage Tug	8	55%	1,021	Diesel	Water	78	0.064
				Electric	Air		
				Gasoline	Water	100	0.089
				LPG	Water	100	
				CNG	Water	100	
Belt Loader	8	50%	887	Diesel	Water	45	0.076
				Gasoline	Water	60	0.089
				LPG	Water	60	
				CNG	Water	60	

TABLE 3: GSE EQUIPMENT AND ENGINE DATA
(Continued)

Equipment Type	Economic Life[1]	Load Factor	Use Per Year[2]	Fuel Type	Coolant	BHP	Fuel Consumption[3]
Bobtail	8	55%	434	Gasoline	Water	100	0.089
				CNG	Water	100	
Bus	8	25%	1,678	Diesel Truck	Water	180	0.095
				Gasoline Truck	Water	130	0.123
				CNG Truck	Water	130	
Car	8	25%	486	Gasoline Car	Water	130	0.123
				LPG Car	Water	130	
				CNG Car	Water	130	
Cargo Loader[6]	10	50%	1,250	Diesel	Water	76	0.064
				Gasoline	Water	70	0.089
				LPG	Water	70	
				CNG	Water	70	
Cart	8	50%	340	Electric	Air		
				Gasoline	Air	12	0.162
				LPG	Air	12	
				CNG	Water	12	
Deicer	8	95%	156	Diesel	Water	93	0.064
				Gasoline	Water	93	0.089
				CNG	Water	93	
Forklift	8	30%	1,028	Diesel	Water	52	0.064
				Electric	Water		
				Gasoline	Water	50	0.089
				LPG	Water	52	
				CNG	Water	52	

TABLE 3: GSE EQUIPMENT AND ENGINE DATA
(Continued)

Equipment Type	Economic Life[1]	Load Factor	Use Per Year[2]	Fuel Type	Coolant	BHP	Fuel Consumption[3]
Fuel Truck	8	25%	1,117	Diesel Truck	Water	180	0.095
				Gasoline Truck	Water	130	0.123
				LPG Truck	Water	130	
				CNG Truck	Water	130	
GPU	8	75%	2,240	Diesel	Water	145	0.061
				Electric	Air		
				Gasoline	Water	150	0.089
				CNG	Water	150	
Lav Cart	8	50%	725	Gasoline	Air	12	0.162
				CNG	Water	12	
Lav Truck	8	25%	735	Gasoline	Water	130	0.089
				CNG	Water	130	
Lift	8	50%	1,357	Electric	Air		
				Gasoline	Water	100	0.089
				LPG	Water	100	
				CNG	Water	100	
Maintenance Truck	8	50%	563	Diesel	Water	130	0.061
				Gasoline	Water	130	0.089
				LPG	Water	130	
				CNG	Water	130	
Other[7]	8	50%	771	Diesel	Water	50	0.064
				Gasoline	Water	50	0.089
				LPG	Water	50	
				CNG	Water	50	
Pickup	8	25%	1,722	Gasoline Truck	Water	130	0.123
				LPG Truck	Water	130	
				CNG Truck	Water	130	

TABLE 3: GSE EQUIPMENT AND ENGINE DATA
(Concluded)

Equipment Type	**Economic Life[1]**	**Load Factor**	**Use Per Year[2]**	**Fuel Type**	**Coolant**	**BHP**	**Fuel Consumption[3]**
Service Truck	8	20%	563	Diesel	Water	170	0.061
				Gasoline	Water	180	0.089
				LPG	Water	180	
				CNG	Water	180	
Van	8	25%	1,987	Gasoline Truck	Water	130	0.123
				CNG Truck	Water	130	
Water Trucks	8	20%	567	Gasoline	Water	150	0.089
				CNG	Water	150	

SOURCES:

Economic Life - American Airlines, Inc.

Load Factor - TWA *South Coast & Sacramento Federal Implementation Plans* correspondence (see Appendix GSE 1), supplemented with information from GSE and engine manufacturers and the ground service operations supervisors of United and Alaska Airlines

Use Per Year - *Comments of the Air Transport Association on EPA's Proposed FIP: Measures for Commercial Aviation* (Reference 1)

Fuel Type - American Airlines, Delta Airlines, Federal Express, Northwest Airlines, Southwest Airlines, Trans World Airlines, and United Airlines

BHP - Delta Airlines, Trans World Airlines, and United Air Lines, supplemented with data from *Jane's Airport and ATC Equipment, 1992 - 1993* (Reference 18) and discussions with equipment manufacturers

Fuel Consumption - On-road vehicle fuel consumption is based on the national average fleet mix of on-road vehicles; off-road vehicle fuel consumption was estimated using data from *Documentation of Input Factors for the New Off-Road Mobile Source Emissions Inventory Model* (Reference 6)

[1] Economic Life in years

[2] Average Use Per Year in hours

[3] Fuel Consumption in gallons per BHP-hour

[4] Add on to an existing gate

[5] Fuel consumption is for APU model GTC85-72 with 200 HP and 210 lb/hr fuel flow.

[6] Lower Lob Cargo Loader (15,000 lbs)

[7] Includes compressors, scrubbers, sweepers, and specialized units

- **Usage -** The specific hours of operations for a particular piece of equipment should be used where available. If the specific usage is not known, an average operation, as shown in Table 3, can be used.

- **Off-Road GSE Emission Factors -** There is no single, acknowledged source of emission factors for the specific engines found on most conventional and alternative fuel GSE that is endorsed by EPA. Table 4 summarizes emission factors compiled from various sources and represent a typical GSE fleet mix.

- **On-Road GSE Emission Factors -** On-road emission factors are based on the national average fleet mix of on-road vehicles. On-road emission factors in grams per BHP-hour are provided in Table 5.

- **Population -** When calculating an emissions inventory, the specific population of the inventory should be used.

- **Economic Life -** The economic life, or planning life, refers to the average number of years a new piece of equipment is projected to be used. In reality, the useful life of a piece of equipment is much longer than its initial economic life due to rebuilding and remanufacture options. The economic life of equipment used for the cost benefit calculations in this report, in years, is listed by equipment type in Table 3.

GSE OPERATING COSTS

This section discusses the calculation methodology and data inputs for calculating the cost of purchasing, operating, and maintaining a piece of GSE. The factors that determine the cost of purchasing, operating, and maintaining a piece of equipment are the capital cost(s), usage, hourly operating cost, and hourly maintenance cost.

GSE Operating Costs - Calculation Methodology

The following discusses the calculation methodology for determining the cost of purchasing and operating and maintaining a piece of GSE. The cost of purchasing a piece of equipment is simply the sum of all capital costs. For most types of GSE, the only capital cost is the actual cost of the piece of GSE. For electric GSE, the cost of purchasing a piece of GSE also includes the cost of purchasing an electric recharger station. Calculating the cost of operating and maintaining a piece of GSE is more

TABLE 4: OFF-ROAD GSE EMISSION FACTORS

Engine Type	Coolant Type	Horsepower Range	EMISSION FACTORS (grams per BHP-hr)				
			HC	NO_x	CO	PM	SO_2
Gasoline	Air Cooled	1 to 24	10.0	2.0	360.0	0.2	0.21
		25 to 50	7.0	3.0	400.0	0.0	0.21
	Water Cooled	25 to 50	4.0	4.0	240.0	0.0	0.21
		≥ 51	4.0	4.0	240.0	0.0	0.26
Diesel	Water Cooled	1 to 50	1.0	11.0	4.0	0.7	0.29
		≥ 51	1.2	11.0	4.0	0.5	0.25
OEM Optimized CNG	Water Cooled	1 to 24	5.0	4.0	180.0	0.0	0.00
		25 to 50	2.0	6.0	120.0	0.0	0.00
		≥ 51	1.0	3.5	2.1	0.0	0.00
Existing CNG or LPG	Air Cooled	1 to 24	5.0	4.0	180.0	0.0	0.00
		25 to 50	4.0	6.0	200.0	0.0	0.00
	Water Cooled	1 to 24	5.0	4.0	180.0	0.0	0.00
		25 to 50	2.0	6.0	120.0	0.0	0.00
		≥ 51	2.0	6.0	120.0	0.0	0.00

SOURCE: *Regulatory Strategies for Off-Highway Equipment* (Reference 8) and *Feasibility of Controlling Emissions from Off-Road, Heavy-Duty Construction Equipment* (Reference 7)

TABLE 5: ON-ROAD GSE EMISSION FACTORS

Vehicle Type	Engine Type	EMISSION FACTORS (grams per BHP-hr)				
		HC	NO_x	CO	PM	SO_2
Light Duty Vehicle	Gasoline	4.18	1.57	8.98	0.03	0.21
Light Duty Truck	Gasoline	4.10	1.87	13.05	0.04	0.26
	Diesel	0.88	2.02	2.60	0.43	0.25

SOURCE: MOBILE5a and PART5 model runs at GSE-equivalent mileage accumulation and age distribution involved. The following equation calculates the cost to operate and maintain a particular piece of GSE and fuel type. If the hourly operating cost is not known, it can be estimated using the equipment's fuel consumption and a fuel cost.

$$C_t = U_t \text{ x } (OC_t + MC_t)$$

Or

$$C_t = U_t \text{ x } [(FF_t \text{ x } BHP_t \text{ x } LF_t \text{ x } FC_t) + MC_t]$$

Where:
C_t - total operating and maintenance cost per year of GSE type t
U_t - annual hours of use for equipment type t
OC_t - cost, in dollars per hour, of operating equipment type t
MC_t - cost, in dollars per hour, of maintaining equipment type t
FF_t - fuel flow (or fuel consumption), in gallons per brake horsepower-hour, of equipment type t; for electricity the fuel consumption is in megawatt hours
BHP_t - average rated brake horsepower (BHP) of the engine for equipment type t
LF_t - load factor utilized in ground support operations for equipment type t
FC_t - cost, in dollars per gallon, of fuel type (e.g., diesel) of equipment type t (e.g., diesel baggage tug); for electricity the cost is in dollars per megawatt hour
t - equipment type t (e.g., diesel baggage tug)

GSE Cost Sample Calculation

This sample calculation illustrates the procedure for determining the cost of purchasing, operating, and maintaining a particular GSE type and usage. For this sample, costs are calculated for a new diesel baggage tug. The cost of purchasing the equipment is assumed to be $28,000. To calculate an annual O&M cost for the baggage tug, the equation identified above is used. The hourly operating cost is estimated using the equipment's fuel consumption and an average fuel cost of $0.53, based on an average cost of jet fuel (assumed to be representative of the cost an air carrier would pay for diesel fuel).

Usage (hr/yr)	Fuel Flow (gal/BHP-hr)	BHP	Load Factor	Fuel Cost ($/gal)	Maintenance Cost ($/hr)	Annual O&M Cost ($)
1,021 x [(		0.064	x	78 x	55% x	0.53) +8.06] =9,715

GSE Cost Data Inputs

The data needed for calculating the cost of purchasing, operating, and maintaining a piece of GSE include GSE type, BHP, usage, capital cost(s), operating cost, maintenance cost, and population. If the operating cost is not known, it can be estimated using the equipment's fuel flow (or fuel consumption), usage, and a given fuel cost. The GSE type, BHP, usage, fuel flow (under the GSE emission data inputs' emission factor discussion), and population are addressed under the GSE emission data inputs section. The remaining GSE cost data inputs are discussed below.

- **Capital Cost(s) -** Capital costs are a one-time expenditure, incurred when a new piece of equipment is purchased. If the capital costs are fully realized in the first year of the equipment's life, then for subsequent years of the equipment's operation the capital costs would be zero and the only cost is for operating and maintenance. For the purposes of these calculations, capital costs will be realized over the life of a piece of equipment (annualized) as is discussed in further detail in the following GSE cost/benefit section. Capital costs for replacement, converted, and modified GSE were compiled from industry sources. Capital costs per unit for conventional, alternative fuel, and electric GSE are provided in Tables 6 and 7.

  For electric GSE, total capital costs include the cost of purchasing electric recharger stations. If the number of recharger stations needed per piece of electric equipment is not known, it can be assumed that one recharger station is installed for each new piece of electric GSE. The recharger capital cost is assumed to be an additional cost of $2,500 and includes a minimum for additional wiring from the terminal to each recharger station. In general, an electric GSE and recharger cost more to purchase than a conventional GSE, although for most GSE types it costs less to operate and maintain an electric GSE and recharger than a conventional GSE. Also benefits such as tax credits for the purchase of electric vehicles at either the federal or state level, may be available. Such credits would improve the economic feasibility of purchasing an electric piece of equipment.

- **Operating Cost -** Operating costs are a recurring expenditure for the life of the equipment. Elements of the operating costs include fuel and operating labor. Since operating labor costs are assumed to be the same for both conventional GSE and alternatively fueled or electric, they are excluded from these cost calculations. The actual local cost of operating equipment should be used where available. If no direct source of operating costs is available, operating costs can be estimated based on fuel consumption rates (or fuel flow), usage, and a given fuel cost. Estimated operating costs are provided in Table 6.

TABLE 6: REPLACEMENT GSE
CAPITAL, OPERATING AND MAINTENANCE COST INPUTS[1]

	Replacement Conventional GSE Cost			Replacement Electric GSE Cost[2]			Replacement CNG GSE Cost			Replacement LNG GSE Cost		
Equipment Type	**Cap. ($000)**	**Maint. ($/hr)**	**Op. ($/hr)**	**Cap. ($000)**	**Maint. ($/hr)**	**Op. ($/hr)**	**Cap. ($000)**	**Maint. ($/hr)**	**Op. ($/hr)**	**Cap. ($000)**	**Maint. ($/hr)**	**Op. ($/hr)**
Aircraft Tug (Narrow Body)	$100.0	$16.67		$120.0	$12.50							
Aircraft Tug (Wide Body)	$190.0	$26.41		$250.0	$19.71							
Air Conditioner[3]	$60.0	$12.15		$55.0	$9.11							
Air Start	$80.0	$33.76		N/A	$25.32							
Bag Tug	$15.5	$8.06		$28.0	$6.04							
Belt Loader	$23.0	$6.63		$35.0	$4.97							
Bobtail	$24.0	$13.82		$35.0	$10.37							
Bus	$110.0	$9.58		N/A	$9.58							
Car	$15.0	$2.10		N/A	$2.10							
Cargo Loader[4]	$150.0	$9.84		$180.0	$7.38							
Cart	$6.0	$1.69		$6.0	$1.27							
Deicer	$5.0	$4.63		$5.0	$3.47							
Forklift	$18.0	$10.32		$20.0	$7.74							
Fuel Truck	$65.0	$16.83		N/A	$16.83							
GPU	$32.0	$10.44		N/A	$7.83							
Lav Cart	$7.0	$2.44		$7.0	$2.44							
Lav Truck	$35.0	$12.15		$42.0	$9.11							
Lift	$45.0	$13.73		$54.0	$10.30							
Maintenance Truck	$25.0	$12.82		$30.0	$9.62							
Other	$20.0	$10.97		$30.0	$8.23							
Pickup	$18.0	$9.65		$27.0	$7.24							
Service Truck	$25.0	$12.82		$30.0	$9.62							
Van	$22.0	$10.09		N/A	$10.09							
Water Truck	$32.0	$14.04		$38.5	$10.53							

Abbreviations: Cap. refers to Capital; Maint. refers to Maintenance; Op. refers to Operating

[1] Data is compiled from industry sources.

[2] Add an additional $2,500 per piece of electric equipment for the electric GSE recharger capital cost.

[3] Add on to an existing gate.

[4] Refers to a lower lob cargo loader (15,000 lbs).

TABLE 7: CONVERSION AND MODIFICATION GSE CAPITAL, OPERATING, AND MAINTENANCE COST INPUTS[1]

	Conversion Electric GSE Cost[2]			Conversion CNG GSE Cost			Modification LNG GSE Cost			Conversion LNG GSE Cost		
Equipment Type	**Cap. ($000)**	**Maint. ($/hr)**	**Op. ($/hr)**	**Cap. ($000)**	**Maint. ($/hr)**	**Op. ($/hr)**	**Cap. ($000)**	**Maint. ($/hr)**	**Op. ($/hr)**	**Cap. ($000)**	**Maint. ($/hr)**	**Op. ($/hr)**
Aircraft Tug (Narrow Body)							$20.0					
Aircraft Tug (Wide Body)							$35.0					
Air Conditioner[3]										$55.0		
Air Start							$35.0					
Bag Tug										$5.0		
Belt Loader										$5.0		
Bobtail												
Bus							$35.0[5] $10.0[6]					
Car										$5.0		
Cargo Loader[4]							$35.0[7]			$10.0		
Cart												
Deicer										$40.0		
Forklift										$5.0		
Fuel Truck										$5.0		
GPU							$35.0					
Lav Cart	$1.0									$1.0		
Lav Truck										$5.0		
Lift												
Maintenance Truck										$5.0		
Other												
Pickup										$5.0		
Service Truck										$5.0		
Van										$5.0		
Water Truck										$5.0		

* Footnotes contained on the following page

TABLE 7: CONVERSION AND MODIFICATION GSE CAPITAL, OPERATING, AND MAINTENANCE COST INPUTS[1]

FOOTNOTES

Abbreviations: Cap. refers to Capital; Maint. refers to Maintenance; Op. refers to Operating

[1] Data is compiled from industry sources. Unit conversion is defined as converting a unit's existing engine for use with an alternative fuel power plant. Unit modification is defined as replacing a unit's existing power plant with an alternative fuel power plant.

[2] The electric GSE recharger capital cost is assumed to be an additional $2,500 per piece of equipment, excluding air conditioners, air starts, GPUs, lav carts, and on-road vehicles.

[3] Add on to an existing gate.

[4] Refers to a lower lob cargo loader (15,000 lbs).

[5] Cost applies to a 42 passenger bus.

[6] Cost applies to a 16 passenger bus.

[7] Refers to a main deck cargo loader (30-40,000 lbs).

- **Maintenance Cost -** Maintenance costs are a recurring expenditure for the life of the equipment. Elements of the maintenance costs include replacement parts, general upkeep of the equipment body and engine, and labor costs. A specific maintenance cost for a piece of equipment should be used where available. The estimated hourly maintenance costs for conventional and electric GSE are listed in Table 6.

GSE COST/BENEFIT ANALYSIS

This section discusses the emission reductions and cost (or savings) of purchasing, operating, and maintaining equipment that operates on alternative fuels or electricity instead of gasoline or diesel. In performing a cost/benefit analysis, the costs (or savings) and emission reductions of equipment are evaluated over the life of the equipment. The remainder of this section discusses the emission reduction and cost analyses, including calculation methodologies and sample calculations for purchasing an electric vehicle in place of a conventional fueled vehicle. Finally, the cost/benefit calculation methodology and sample calculations are provided.

Emission Reduction Analysis

Cost Analysis

To determine the cost of purchasing, operating, and maintaining one piece of equipment (e.g., electric baggage tug) over another piece that is the same type of equipment but a different fuel type (e.g, diesel baggage tug), the total costs of the equipment over a lifetime are evaluated. To evaluate the total cost of a piece of equipment over a lifetime, the capital, operating, and maintenance costs have to be combined. As discussed previously in the GSE cost section, the two costs have different characteristics: the capital cost is a one-time expenditure, while the annual operating and maintenance cost is a recurring expenditure.

A method of evaluating the total (i.e., capital plus operating and maintenance) cost of a piece of equipment over its lifetime is the Annualized Cash Flow (ACF) method. The ACF method annualizes costs. The capital cost is multiplied by a capital recovery factor (CRF) to obtain an equivalent end-of-year annual capital cost payment necessary to repay the investment over the life of the equipment given a specified interest rate. The resulting annualized capital cost is added to the annual operating and maintenance costs to obtain an annualized total cost.

If the annual cost or the interest rate changes from year to year, capital costs occur beyond the first year, or risk factors have to be addressed, an alternative method should be used to evaluate costs. The Discount Cash Flow (DCF) method can be used to calculate costs and address such complexities. The DCF method calculates the cost by determining the present value of the costs of buying, operating, and maintaining a piece of equipment over the equipment life. The CRF then can be applied to determine the annualized cost. For this report it will be assumed that the ACF method can be used to evaluate the cost of purchasing, operating, and maintaining a piece of equipment with one fuel type versus another.

Cost Analysis - Calculation Methodology

To compare the cost of owning and operating one type of GSE versus another, the total costs of each type are first determined on an annualized basis and then compared. As mentioned above, the annualized capital cost is added to the annual O&M cost to get a total annual cost of operation.

The capital cost is multiplied by the capital recovery factor (CRF) to obtain the equivalent end-of-year annual capital cost payment necessary to repay the investment over the life of the equipment given a specified interest rate. The CRF is a function of the interest rate and equipment life. The following equation is used to determine the CRF.

$$CRF = \frac{i \times (1 + i)^n}{(1 + i)^n - 1}$$

Where: CRF - capital recovery factor
i - interest rate
n - economic life, in years

After the CRF has been determined, the following equation is used to determine the annualized capital cost of a piece of equipment.

$$ACC = CC \times CRF$$

Where: ACC - annualized capital cost, in dollars per year, of a piece of equipment
CC - capital costs, in dollars, of a piece of equipment

The annualized capital cost is then added to the annual O&M cost for each type of GSE. The two equipment types can be compared and the annual cost of using an alternative type of equipment is simply the difference in annualized costs. The following equation calculates the annual cost (or savings) of converting to an alternative fueled or electric GSE.

$$C_{t1,t2} = (ACC_{t2} + OMC_{t2}) - (ACC_{t1} + OMC_{t1})$$

Where: $C_{t1,t2}$ - total annual cost (or savings), in dollars per year, of purchasing, operating, and maintaining a piece of GSE operating on one fuel type t2 (e.g., electric baggage tug) instead of another t1 (e.g., diesel baggage tug)
ACC_{t1} - annualized capital cost, in dollars per year, of equipment type t1
ACC_{t2} - annualized capital cost, in dollars per year, of equipment type t2
OMC_{t1} - annual O&M cost, in dollars per year, of equipment type t1
OMC_{t2} - annual O&M cost, in dollars per year, of equipment type t2
t1 - GSE type operating on first fuel type (e.g., diesel baggage tug), which is to be replaced with t2
t2 - GSE type operating on second fuel type (e.g., electric baggage tug), which is to be purchased, operated, and maintained in place of t1 for emission benefits

Cost Analysis - Sample Calculation

This example evaluates the replacement of a diesel baggage tug with an electric baggage tug. The diesel tug is assumed to have a 78 horsepower engine and is used for 1,021 hours per year. From Table 6, the capital cost of the diesel tug is $15,500 and the O&M cost is $8.06 per hour. An electric replacement tug has a capital cost of $30,500 ($28,000 for the tug and $2,500 for the recharger) and an O&M cost of $6.04 per hour. Both vehicles have an 8 year economic life. The capital recovery factor is based on an interest rate of 10%.

$$\begin{aligned} CRF &= i \times (1 + i)^n / [(1 + i)^n - 1] \\ &= 0.10 \times (1 + 0.10)^8 / [(1 + 0.10)^8 - 1] \\ &= 0.187 \end{aligned}$$

The CRF is used to annualize the GSE capital costs, which is then added to the O&M cost.

Diesel Baggage Tug (t2)
= (0.187 x $15,500) + ($8.06/hr x 1,021 hr/yr)
= ($2,898.50) + ($8,229.26)
= $11,127.76/yr

Electric Baggage Tug (t1)
= (0.187 x $30,500) + ($6.04/hr x 1,021 hr/yr)
= ($5,703.50) + ($6,166.84)
= $11,870.34/yr

For this example, conversion to an electric baggage tug to reduce GSE emissions costs $742.58 per year.

$$\begin{aligned} C_{t1,t2} &= \$11{,}870.34/\text{yr} - \$11{,}127.76/\text{yr} \\ &= \$742.58/\text{yr} \end{aligned}$$

The earlier sample emissions calculations for these GSE showed NO_x emissions of 1,062 lbs/yr for the diesel and 19 lbs/yr for the electric for an emissions reduction of 1,043 lbs/yr. The cost/benefit ratio can be calculated:

= $742.58/yr ÷ (1,043 lbs/yr ÷ 2,000 lbs/ton)

= $1,424/ton

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AUXILIARY POWER UNITS

An auxiliary power unit (APU), which is a component of a large aircraft, is essentially a small turbine engine. An APU generates electricity and compressed air to operate the aircraft's instruments, lights, ventilation, and other equipment and for starting the aircraft main engines. If a ground-based power or air source is unavailable, the APU may be operated for extended periods when the aircraft is on the ground with its engines shut down. APUs burn jet fuel and create exhaust emissions like larger engines. There are different models and series of APUs to meet the needs of various civil aircraft. APUs are not common on smaller civil aircraft.

APUs are used on a routine basis throughout much of the time when an aircraft is on the ground. Operating practices largely are determined by individual airlines and vary considerably among aircraft types and airlines. Some airlines start the APU when the aircraft is on approach and keep it on during the entire taxi-in phase as a precaution to insure its availability if needed for engine restart. Some airlines only operate their APUs on taxi-in if they are practicing single/reduced engine taxiing. Again, this is to insure its availability if the main engine(s) shuts down and must be restarted. Some airlines do not operate APUs during the taxi-in phase at all or only for particular aircraft types. During quick turnaround flights or where electricity is unavailable the APU typically also is operated while docked at a passenger gate.

If a ground power system (400 Hz) and source of ventilation air are available at the docking location, the APU may not be needed. To connect the aircraft to a ground power system, a cable is plugged into an electrical connector on the aircraft. This commonly is done on arrival as soon as the aircraft comes to a stop, requiring less than one minute of APU operation after the aircraft has come to a full stop. The ground-based air system is then connected to the aircraft cabin via a flexible hose.

Prior to main engine start for departure the cockpit crew goes through their departure checklist and readies their flight plan. During this time, course settings and communication frequencies are programmed into the on-board avionics. If an aircraft is relying on electric power provided from a ground-based system that must be disconnected, it is possible that the on-board power may be interrupted or perturbed. If the aircraft electrical system is interrupted while the avionics are being programmed, some of the data may be lost. For this reason, most airlines prefer to have the APU running for approximately 10 minutes to provide the electric power for the aircraft during flight preparation.

On departure, the critical service provided by the APU is main engine start. This requires a large volume of air to initiate rotation of the turbine and mass flow through the combustor. For routine operation this takes less than one minute. Once the main engine(s) are started they provide the electric power and ventilation to the aircraft. Again, some airlines prefer to keep the APU running during taxi-out as a back-up. An APU also is operated during taxi out if the aircraft must temporarily park away from the gate due to a delayed departure.

In addition to the time the aircraft is docked at a gate for passenger loading and unloading, aircraft also can be docked at remote gates or hardstand areas for cargo or passenger loading and unloading and for maintenance. For these locations the needs for APU operation are similar, except that passengers typically are not aboard the aircraft in these locations and thus the ventilation needs for passenger comfort may not exist.

OPPORTUNITY FOR EMISSION REDUCTIONS

Emissions from APUs can be reduced by turning off the APU while an aircraft is docked at the gate. Turning off an APU reduces fuel combustion. When available at the gate, a 400 Hz ground power system and ventilation air source often provide a reasonable alternative to using an APU to support normal aircraft operations. These fixed systems operate at a greater energy efficiency than an APU and substantially reduce pollutant emissions. In addition, the emissions attributable to the generation of electricity for use by the fixed systems are generated at an off-airport electric power plant. The emissions generated at the power plant are lower due to higher efficiency and emission controls. Often, the cost of the fuel saved is greater than the cost of electricity. Therefore, a project to reduce emissions by substituting fixed systems for APU use actually may save money. The following section discuss how to determine emission reductions and costs (or savings) through the use of ground-based power and preconditioned air instead of an APU. The balance of this section discusses APU emissions and operating costs including calculation methodologies, sample calculations, and data inputs. APU emissions and costs described in this section will be compared later with the emissions and costs of fixed systems, and a cost/benefit analysis will be performed.

APU EMISSIONS

This section discusses the calculation methodology and data inputs for calculating the emissions from APUs. APU engines burn jet fuel and create exhaust emissions like larger engines. APU emissions of significance are hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and sulfur dioxide (SO_2). The factors that determine the quantity of pollutant emitted are the pollutant's emission index (pounds of pollutant per 1000 pounds of fuel consumed), the fuel consumption rate, and the duration of APU operation.

APU Emissions - Calculation Methodology

The methodology for calculating emissions from APUs is adapted from the U.S. EPA's *Procedures for Emission Inventory Preparation* (Reference 21). The following equation calculates the pollutant emissions from an APU on a particular aircraft based on APU operating time, fuel flow, and the emission indices for the specific APU.

$$E_{ij} = T \text{ X } (FF_j/1000) \text{ X } (EI_{ij})$$

Where: E_{ij} - emissions of pollutant i, in pounds, produced by the APU model installed on aircraft type j for one LTO cycle
T - operating time per LTO cycle, in minutes
FF_j - fuel flow, in pounds per minute, for each APU used on aircraft type j
EI_{ij} - emission index for pollutant i, in pounds of pollutant per one thousand pounds of fuel, for each APU used on aircraft type j
i - pollutant type (HC, NO_x)
j - aircraft type (e.g., B-737, MD-11)

To calculate APU emissions for multiple aircraft at an airport, the above equation also would be used to calculate APU emissions for each operating condition (e.g., aircraft type or operating time per LTO). Then, to calculate the total APU emissions for multiple aircraft the following equation would be used. This second equation multiplies the APU emissions per LTO for a given aircraft type and operating time by the number of corresponding LTOs, then sums the emissions over all aircraft types.

$$E_{Ti} = \sum (E_{ij} \text{ X } LTO_j)$$

Where: E_{Ti} - total APU emissions of pollutant i, in pounds, produced by all aircraft types in question
LTO_j - number of landing and takeoff cycles by aircraft j for the inventory time period

APU Emissions - Sample Calculation

This sample calculation illustrates the procedure for determining the pollutant emissions from an APU while it is docked at an airport gate. This is the target operating period for using a low emission, ground-based system instead of the APU. This calculation is based on a Boeing B-737-300 aircraft with APU model GTCP85-129ck. The LTO is assumed to occur at Los Angeles International Airport (LAX) in California at the 1990 average APU operating time for LAX of 105.34 minutes per LTO. Since the APU operating time includes APU operation during aircraft taxi, the average taxi time for LAX, 23.8 minutes as determined by FAA, is subtracted to obtain the estimated APU operating time at the gate of 81.54 minutes (105.34 - 23.80 = 81.54).

Pollutant	Time (min)		Fuel Flow (lb/min)		Emission Rate (lb/1000 lb)		Emissions (lb)
HC	81.54	x (	3.92	/ 1000) x	1.03	=	0.329
CO	81.54	x (	3.92	/ 1000) x	17.99	=	5.750
NO_x	81.54	x (	3.92	/ 1000) x	4.75	=	1.518

APU pollutant emissions from multiple aircraft and/or LTOs are determined using the same calculation as above, applying the corresponding number of LTOs, and summing over all aircraft.

APU Emissions - Data Inputs

In addition to knowing aircraft type and number of operations, the data needed for calculating pollutant emissions from an APU include APU model, APU emission factors, and APU operating time.

- **APU Model -** The specific APU model that is installed on an aircraft must be determined to select the emission factors used in calculating the emissions. Table 8 lists APUs and the aircraft on which they are installed. For some aircraft, an APU model is listed (e.g., GTCP 85), but a particular series (e.g., -300) is not indicated. In general, one set of emission factors is not available for all series of an APU model. In these cases, a possible APU series for which emission factors are available is noted in a footnote. For some aircraft models, information on their APUs may not be available. For these aircraft an APU can be assigned based on APUs used on similar aircraft. This gives a reasonable estimate of APU power requirements since typically there are only one or two APUs available in a particular size range. This assumption gives reasonable and repeatable results.

- **Emission Factors -** Emission factors for several APUs have been compiled from various sources into Table 9. Emission factors are listed where available for hydrocarbon, carbon monoxide, nitrogen oxides, and sulphur dioxide. Where emission factors are unavailable for a specific APU, factors for an alternative unit of the same or similar horsepower should be used. Engine manufacturers also may be contacted for specific emission data not available in Table 9.

- **Operating Time -** The APU operating time at the gate must be known to calculate emissions. If the specific APU operating time is unavailable, an airport average APU operating time or aircraft time at the gate can be used. Table 10 lists 1990 average APU operating times for several airports in the South Coast Air Basin of California. These operating times include any time the APU was operating at the gate as well as during aircraft taxi, safety, and maintenance operations.

  To determine emission reductions possible through the use of ground-based systems, the APU operation while at the gate is the period of interest. Since the APU operating times shown in Table 10 include APU operation during aircraft taxi (i.e., operation away from the gate), the aircraft taxi time should be subtracted from the total APU operating time to obtain the APU operating time while at the gate. If the particular aircraft's taxi time is not available, an airport average aircraft taxi time

TABLE 8: APUs AND COMMERCIAL AIRCRAFT MODELS[1]

Auxiliary Power Unit (Shaft Horsepower)	**Aircraft Model**
AlliedSignal, Inc.	
GTP 30 Series[2]	Fairchild F-27[3]
GTCP 30 Series[2]	Dassault-Bregue Falcon 20[3] Jet Commander[3]
GTCP 35-300[2]	Airbus A-321[4]
GTCP 36 Series[5] (80 HP)	Airbus A320 Airbus A-320-100[6] Airbus A-320-200[6] Airbus A-321[6] Aerospatiale ATR-42[3] Beechcraft Beech 18[7] Brit. Aero. 111-400[7] Brit. Aero. BAe 146 Brit. Aero. BAe 146-100[6] Brit. Aero. BAe 146-200[6] Brit. Aero. Jetstream 31[7] Brit. Aero. Super 31[7] Canadair CL600/CL601[3] Cessna C-208[7] Dassault-Bregue Falcon 50[3] DeHavilland Dash 7[7] DeHavilland DHC-6/300[7] DeHavilland DHC-8[7] DeHavilland DHC-8-100[7] Embraer EMB-110[6] Embraer EMB-120[3] Embraer EMB-145[6] Fokker F-27 Series[6] Fokker F-28 Fokker F-100 Fokker F-100-100[6] NAMC YS-11[3] Saab Fairchild 340[3] Saab Fairchild 340A[6] Short Brothers SHT-360[7] Swearingen SA227[7]

TABLE 8: APUs AND COMMERCIAL AIRCRAFT MODELS[1] (Continued)

Auxiliary Power Unit (Shaft Horsepower)	**Aircraft Model**
AlliedSignal, Inc. (Continued)	
GTC 85[2]	Convair CV-580[3]
GTCP 85 Series[8] (200 HP)	Boeing B-707 Boeing B-707-300[6] Boeing B-727 Boeing B-727-100[6] Boeing B-727-200[6] Boeing B-737[9] Boeing B-737-100[9] Boeing B-737-200[9] Boeing B-737-300[10] Boeing B-737-400[10] Boeing B-737-500[10] Lockheed L-100[3] McDonnell Douglas DC-8 McDonnell Douglas DC-8-50F[6] McDonnell Douglas DC-8-60[6] McDonnell Douglas DC-8-62[6] McDonnell Douglas DC-8-63F[6] McDonnell Douglas DC-8-70[6] McDonnell Douglas DC-8-71[6] McDonnell Douglas DC-8-73[6] McDonnell Douglas DC-9 McDonnell Douglas DC-9-15F[6] McDonnell Douglas DC-9-30[6] McDonnell Douglas DC-9-40[6] McDonnell Douglas DC-9-50[6] McDonnell Douglas MD-80
GTCP 331 Series[11] (143 HP)	Airbus A-300-600 Airbus A-310 Airbus A-310-200[6] Airbus A-310-300[6] Airbus A-330[4] Airbus A-340[4] Boeing B-757[12] Boeing B-757-200[12]

TABLE 8: APUs AND COMMERCIAL AIRCRAFT MODELS[1] (Continued)

Auxiliary Power Unit (Shaft Horsepower)	Aircraft Model
AlliedSignal, Inc. (Continued)	
(GTCP 331 Series[11] - Continued) (143 HP)	Boeing B-767[12] Boeing B-767-200[12] Boeing B-767-200ER[12] Boeing B-767-300[6,12] Boeing B-767-300ER[6,12] Boeing B-777[4,13] Boeing B-777-200[6,13]
GTCP 660[14] (300 HP)	Boeing B-747 Boeing B-747-100[6] Boeing B-747-200[6] Boeing B-747-300[6]
TSCP 700[15] (142 HP)	Airbus A-300B[6] Airbus A-300-B2 Airbus A-300-B4 McDonnell Douglas DC-10 McDonnell Douglas DC-10-10[6] McDonnell Douglas DC-10-30[6] McDonnell Douglas DC-10-40[6] McDonnell Douglas MD-11 McDonnell Douglas MD-11-11[6]
Hamilton Standard	
ST-6[16]	Lockheed L-1011 Lockheed L-1011-100[6] Lockheed L-1011-50[6] Lockheed L-1011-500[6]
Pratt & Whitney	
PW 901A	Boeing B-747 Boeing B-747-400[6] Boeing B-747-SP[6]

* Footnotes contained on the following page.

TABLE 8: APU'S AND COMMERCIAL AIRCRAFT MODELS[1]
(Continued)

FOOTNOTES

[1] SOURCE: *Federal Express Fleet Guide* (Reference 10), unless otherwise noted.

[2] No emission factor data available.

[3] SOURCE: *Reference Guide - Auxiliary Power Systems* (Reference 11).

[4] New aircraft scheduled to enter production.

[5] Emission factors for the GTCP36-300 Series can be used for calculation purposes as representative of all series of the APU model.

[6] APU for a particular aircraft model assumed to be the same as other aircraft in that series or for similar aircraft.

[7] GTCP 36 Series assumed to be representative for this aircraft.

[8] Emission factors for the GTCP85-98ck Series can be used for calculation purposes as representative of all series of the APU model, unless otherwise noted.

[9] Emission factors for the GTCP85-129 Series should be used for calculation purposes.

[10] Emission factors for the GTCP85-129ck Series should be used for calculation purposes.

[11] Emission factors for the GTCP331-200/250 Series can be used for calculation purposes as representative of all series of the APU model, unless otherwise noted.

[12] Emission factors for the GTCP331-200ER Series should be used for calculation purposes.

[13] Emission factors for the GTCP331-500 Series should be used for calculation purposes.

[14] Emission factors for the GTCP660-4 Series can be used for calculation purposes as representative of all series of the APU model.

[15] Emission factors for the TSCP700-4B Series can be used for calculation purposes as representative of all series of the APU model.

[16] Emission factors for the ST-6 L-73 Series can be used for calculation purposes as representative of all series of the APU model.

TABLE 9: MODAL EMISSION RATES - AUXILIARY POWER UNITS

Model - Series (Shaft HP)	Mode	Fuel Flow (lb/hr)	Emission Rates (lb/1000 lb)			
			HC	CO	NO_x	SO_2
GTC85-72[1] (200)	Load	210.00	0.13	14.83	3.88	0.54
GTCP100-544[1] (400)	Load	412.80	0.16	5.89	5.95	0.54
GTCP30-300[2]		282.20	0.20		10.10	
GTCP331-200/250[2] (143[3])		267.92	0.43		9.51	
GTCP331-200ER[2] (143[3])		267.92	0.43	4.13[6]	9.51	
GTCP331-500[2] (143[3])		536.00	0.13	0.09[6]	14.67	
GTCP36-300[2] (80[3])		282.20	0.20	2.05[6]	10.10	
GTCP660-4[2] (300[3])		862.92	0.28	8.65[6]	5.33	
GTCP85[2] (200[3])		235.28	1.03		4.75	
GTCP85-129[2] (200[3])		235.28	1.03	17.99[6]	4.75	
GTCP85-129ck[2] (200[3])		235.28	1.03	17.99[6]	4.75	
GTCP85-98ck[2] (200[3])		235.28	1.03	17.99[6]	4.75	
GTCP95-2[1] (300)	Load	292.80	0.36	3.20	5.65	0.54
PWC 901A[4]	No Load	510	2.00	20.50	1.8	
PWC 901A[4]	Max. Load	899	0.00	5.60	6.5	
PWC 901A[2]		862.92	1.50	16.78[6]	3.15	

TABLE 9: MODAL EMISSION RATES - AUXILIARY POWER UNITS (Continued)

Model - Series (Shaft HP)	Mode	Fuel Flow (lb/hr)	Emission Rates (lb/1000 lb)			
			HC	CO	NO_x	SO_2
ST6/ST6 L-73[5]		440.00	0.02	0.05	8.90	
T-62T-27[1] (100)	Load	102.00	7.79	42.77	3.94	0.54
T-62T-47C1[6]		235.28	0.16	40.20	4.30	
TSCP 700[2] (142[3])		323.68	0.26		8.55	
TSCP 700-4B[2] (142[3])		323.68	0.26	1.48[6]	8.55	
WR27-1[1] (85)	Load	139.80	0.21	5.66	4.63	0.54

[1] SOURCE: *Summary Table of Gaseous and Particulate Emissions from Aircraft Engines* (Reference 2)

[2] SOURCE: *Proposed Federal Implementation Plan for California, Docket No. A-94-09* memorandum (Reference 9)

[3] SOURCE: *Federal Express Fleet Guide* (Reference 10) (note: the APU model's horsepower was assumed to be representative for all series of the APU model)

[4] SOURCE: *PW901A Gaseous Exhaust Emissions* memorandum (Reference 15)

[5] SOURCE: *AIA Exhaust Emissions Data Sheet* letter (Reference 5)

[6] SOURCE: United Air Lines' APU Emissions Database (note: data for LAX 1991) (Reference 22)

TABLE 10: SUMMARY OF APU OPERATING TIMES - 1990
(min/LTO)

Airport	Time in Mode
South Coast Air Basin	
Burbank	44.28
John Wayne	33.48
Long Beach	98.99
Los Angeles Intl	105.34
Ontario Intl	115.62

Source: *Comments of the Air Transport Association on EPA's Proposed Federal Implementation Plan: Measures for Commercial Aviation* (Reference 1) can be used. Average aircraft taxi times for several California airports during the period of June to December 1992 were estimated by FAA, and are included in Table 11. Information on aircraft taxi times is available from FAA's Office of Aviation Policy, Plans, and Management Analysis for some airports. If unavailable from FAA, it may be necessary to calculate taxi times for the airport of interest.

If the APU operating time is unavailable, an airport average operating time can be estimated by considering the services APUs provide. APUs sometimes are used during aircraft taxi for safety reasons. APUs also are used to provide power and ventilation for aircraft at a docking location (e.g., passenger, cargo, maintenance) that have shut down their engines. If either of these services is provided at the docking location, APU operating time can be reduced.

On departure the essential preparations and main engine start can be accomplished in three to five minutes. (Most air carriers do not start their main engines until they have been pushed back from the gate. Since this takes less than one minute, the time of main engine start has only a small effect on the minimum time needed to operate the APU on departure.) The need for pneumatic air sets the lower boundary of APU use. Approximately 10 minutes is a reasonable minimum APU operating period for a single LTO. This estimate is applicable to aircraft docked at a gate for passenger loading and unloading, as well as aircraft docked for cargo loading and unloading and for maintenance.

If only 400 Hz is available (i.e., no PCA), some additional APU operation may be required depending on ambient temperature and weather conditions. If only PCA is available, the APU must run for the entire turnaround.

APU COSTS

This section discusses the calculation methodology and data inputs for calculating the cost of operating and maintaining APUs. The factors that determine the cost of operating and maintaining an APU are fuel consumption, fuel cost, maintenance costs, and the duration of APU operation.

APU Cost - Calculation Methodology

The cost of operating and maintaining APUs is calculated by adding the hourly operating cost to the hourly maintenance cost, and multiplying the total cost per hour times the APU operating time per LTO cycle. If the APU operating cost is not known, it can be calculating using the APU fuel flow (or fuel consumption) and fuel cost. The following equation calculates the cost to operate and maintain an APU on a particular aircraft.

TABLE 11: AVERAGE AIRCRAFT TAXI TIMES

Airport	**Average Taxi-Out Time (minutes)**	**Average Taxi-In Time (minutes)**	**Average Total Taxi Time (minutes)**
Burbank	10.8	2.7	13.5
Fresno Air Terminal	7.7	4.4	12.1
Los Angeles Intl	15.0	8.8	23.8
Long Beach	9.9	4.6	14.5
Monterey	6.1	4.3	10.4
Oakland Intl	9.5	4.6	14.1
Ontario Intl	12.1	3.1	15.2
Palm Springs Muni.	9.0	4.2	13.2
San Diego Lindberg	12.7	4.2	16.9
Santa Barbara	6.8	4.1	10.9
San Francisco	15.8	5.7	21.5
San Jose Intl	13.8	5.3	19.1
Sacramento Metro	10.3	3.6	13.9
Santa Ana/Orange County/John Wayne	12.3	6.1	18.4

Source: Louise E. Maillett letter (Reference 14)

$$C_j = TIM \times [MC_j + OC_j]$$

Or $$C_j = TIM \times [MC_j + (FF_j / D \times FC)]$$

Where:
C_j - total operating and maintenance cost of APU model installed on aircraft type j for one LTO cycle
TIM - APU operating time per LTO cycle (time in mode), in hours
MC_j - cost, in dollars per hour, of maintaining the APU model installed on aircraft type j
OC_j - cost, in dollars per hour, of operating the APU model installed on aircraft type j
FF_j - APU fuel flow (or fuel consumption), in pounds per hour, of APU model installed on aircraft type j
D - jet fuel density of 6.6751 pounds per gallon to convert fuel flow units from pounds per hour to gallons per hour
FC - fuel cost, in dollars per gallon
j - aircraft type

To calculate APU costs for multiple aircraft at an airport, the above equation(s) also would be used to calculate APU costs for each operating condition (e.g., aircraft type or operating time per LTO). Then, to calculate the total APU costs for multiple aircraft the following equation would be used. This second equation multiplies the APU costs per LTO for a given aircraft type and time in mode by the number of corresponding LTOs, then sums the costs over all aircraft types.

$$C_T = \sum (C_j \times LTO_j)$$

Where:
C_T - total cost of operating and maintaining APU models installed on all aircraft types in question
LTO_j - number of landing and takeoff cycles by aircraft j for the inventory time period

APU Cost - Sample Calculation

This sample calculation illustrates the procedure for determining the cost of operating and maintaining an APU on a particular aircraft. As with the example emissions calculation discussed earlier, this cost calculation is based on a Boeing B-737-300 aircraft with APU model GTCP85-129ck. The LTO is assumed to occur at Los Angeles International Airport (LAX) in California at the 1990 average APU operating time for LAX of 105.34 minutes per

LTO. Since the APU operating time includes APU operation during aircraft taxi, the average taxi time for LAX, 23.8 minutes, is subtracted to obtain the estimated APU operating time at the gate of 81.54 minutes (105.34 - 23.80 = 81.54) or 1.359 hours. An average APU maintenance cost for narrow body aircraft of $14.60/hour is assumed to be representative for the B-737-300 aircraft. Finally, an average fuel cost of $0.53/gallon[1] is used to estimate the operating cost.

Time (hr)	Maintenance Cost ($/hr)	Fuel Flow (lb/hr)	Jet Fuel Density (lb/gal)	Fuel Cost ($/gal)	Total O&M Cost ($)
1.359 x [	14.60 + (	235.28 /	6.6751 x	0.53)] =	45.23

The cost of operating and maintaining APUs installed on multiple aircraft and/or an aircraft performing multiple LTOs is determined using the same calculation as above, applying the corresponding number of LTOs, and summing over all aircraft.

APU Cost - Data Inputs

The data needed for calculating the cost of operating and maintaining an APU include APU model, APU operating time, APU maintenance cost, and APU operating cost. As discussed above, if the APU operating cost is not known it can be calculating using the APU fuel flow (or fuel consumption) and fuel cost. The APU model, APU operating time, and APU fuel flow (included under the emission factor discussion) are discussed above. Maintenance and operating cost are discussed below.

- **APU Maintenance Cost -** The hourly cost of maintaining an APU should be used in calculating the APU's total operating and maintenance cost if available. This cost likely varies by air carrier. If APU maintenance cost is not available, reasonable default values

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[1] The average fuel cost is for total (scheduled and non-scheduled) domestic service of U.S. majors, nationals, and large regionals for April 1995. Source: *Air Transport World* (Reference 16)

might be \$14.60/hour for narrow body aircraft, \$50.90/hour for wide body aircraft, and \$41.00/hour for jumbo body aircraft.[2]

- **APU Operating Cost -** The hourly cost of operating a specific APU should be used in calculating the APU's total operating and maintenance cost if available. If the APU's specific operating cost is unavailable, the APU operating cost can be calculated using the APU fuel flow and an average fuel cost. For some APU models and series, fuel flow information may not be available. For APU models in which information is not available, the operating cost can be estimated using an average fuel consumption. Fuel cost should be available for each airport. For a fuel cost default value, national jet fuel costs are published in a variety of references (e.g., Penton Publication's *Air Transport World*).

PRECONDITIONED AIR AND 400 HZ GROUND POWER

A combination of 400 Hz electric power and preconditioned air (PCA) must be supplied to the aircraft at each gate to allow normal operations in the absence of APU usage. Benefits of ground-based systems include a greater energy efficiency than APU usage, substantially reduced pollutant emissions, and lower noise levels.

This section summarizes the various ground power and PCA systems available for replacing APU use. A method for estimating pollutant emissions from ground power and PCA systems is provided as a basis for comparison with APU emissions. In addition, capital, operating, and maintenance costs for each alternative are estimated based on information from several airports where these systems have been installed or considered.

400 Hz Ground Power

The APU provides electric power for aircraft operations while docked at the gate. A ground-based power source designed to replace this APU power must be provided in order to shut off the APU during this time. Commercial aircraft use 115/200V, 400 Hz power. Equipment must be installed to provide this power to individual gates at sufficient levels to maintain normal aircraft operations while the aircraft is parked at the gate. There are several different

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[2] These average costs are taken from *A 1994 feasibility study of preconditioned air for Northwest Airlines at Logan International Airport, Boston, Massachusetts* (Reference 3).

options for providing 400 Hz power to the aircraft at the gate: mobile generator units, point-of-use converters at each gate, and centralized 400 Hz generators which serve a number of gates.

Mobile Generator Units

Both electric-powered and diesel-powered mobile generator units are available to provide aircraft with the required 400 Hz power. Diesel-powered generators suffer from the same problems that make APU use unattractive: low fuel efficiency, high pollutant emissions, and high noise levels. For these reasons, they are not considered low emissions alternatives to APU use. Electric-powered mobile generators have similar equipment, load capacity, and power requirements as the 400 Hz point-of-use equipment described below.

400 Hz Point-of-Use Converters

Solid state frequency converters may be used at each gate to convert standard 480V, 60 Hz power to 115/200V, 400 Hz power with low harmonic distortion. The only requirement is sufficient 480V, 60 Hz power at the gate to supply power to the aircraft. Advantages of using the solid-state frequency converters at each gate include low power consumption, low fixed capital cost, flexibility of use, ease of repair, and low maintenance costs.

Centralized 400 Hz Power Supply

Supply of 400 Hz electric power to a number of gates may be provided by a centralized motor-generator system. This equipment typically converts the standard 480 V, 60 Hz power to 575 V, 400 Hz power in a centrally located substation room. A transformer at each gate steps the voltage down to the required 115/200 V, 400 Hz power. Design of centralized systems usually includes a redundant motor-generator to provide backup in case of motor failure.

An alternative to the use of motor-generators is the use of static inverters to provide 400 Hz power. Inverters, unlike motor-generators, have the advantage of requiring only the amount of input power which is required for the load at any given time, plus a small amount to account for power loss within the inverter.

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The physical layout of the gates is important to the design of a centralized 400 Hz ground power system. Distribution losses require generation to occur as close as possible to the gates. As a result, a "mini-central" system with two or more 400 Hz generators may be preferable to one centrally located power supply.

An advantage of the centralized ground power systems is the ability to design generators for less than the peak load at every gate. However, both centralized and mini-central systems have a high fixed capital cost and significant space requirements. If motor-generators are used to supply 400 Hz power, efficiency is less than that of point-of-use converters at each gate.

Preconditioned Air Systems

Ground-based preconditioned air systems supply the cabin with temperature-controlled fresh air while the aircraft is parked at the gate. The systems typically deliver air to the cabin while the aircraft is mated to the bridge. Two types of electrically-powered PCA systems are available: individual packaged airconditioning assemblies at each gate and centralized systems providing PCA to a number of gates. In both cases, standard 480V, 60 Hz electrical power is used. Mobile diesel-powered airconditioning units are also available, but these offer lower emissions benefits than the electric PCA systems and are not considered low-emission alternatives to APU usage.

Individual packaged assemblies at each gate

Individual packaged airconditioning assemblies may be installed on the bridge of each gate. These systems draw on the 480V, 60 Hz power supplies already in place at most gates. Power requirements are dependent upon the cooling or heating loads of the aircraft being serviced by PCA. A typical point-of-use PCA system consists of air input filters, compressors and condenser coils, blower and blower motor, evaporator coils, and a resistance heating element.

The advantages of a simple system such as this at each gate include:

- applicable for all airports, independent of gate layout
- unit breakdown affects only one gate
- low fixed capital costs

The disadvantages of point-of-use PCA systems include:

- higher maintenance costs
- lower energy efficiency than centralized PCA
- design for maximum real-time cooling load for each gate required

Centralized PCA Systems

Centralized PCA systems provide temperature-controlled fresh air to aircraft at a number of gates from a central refrigeration plant. This arrangement is suitable for airports with a high total aircraft cooling load and a physical layout that allows a central refrigeration plant to service many gates. A typical plant supplies a chilled solution of ethylene glycol and water through an insulated pipeline to the gates. An airhandling unit at each gate blows filtered outside air through coils containing the chilled solution, which is returned to the refrigeration plant. Electric resistance heating units are also available at each gate for winter conditions. The central refrigeration plant typically contains chillers and chiller pump, condenser water pump, loop pump, expansion tank, air separator, cooling tower, motor-controlled valves, motor control center, and a computer control system. Ice storage may be provided to reduce the peak demand required by real-time cooling systems.

Advantages of the centralized PCA systems include:

- energy efficiency
- low maintenance costs
- ability to design for less than the maximum demand at every gate

Disadvantages of centralized PCA are:

- high fixed capital costs
- space requirements for the central refrigeration plant
- possible breakdown affecting a large number of gates

Estimating Emissions From Ground Power and PCA Systems

This section discusses the methodology and data inputs for calculating emissions by ground power and PCA systems. No direct pollutant emissions result from the supply of 400 Hz power or preconditioned air to the aircraft. However, pollutant emissions do result from the generation of electric power at the power plant. In order to estimate those emissions, we must know how much electricity is consumed by aircraft at the gate as well as emission factors at the power plant.

Ground-based 400 Hz Emissions - Calculation Methodology

Electric power consumption by a frequency converter or generator supplying 400 Hz power to aircraft should be calculated as a monthly or yearly average per gate. This power consumption is a function of both expected aircraft loads and the overall design of the 400 Hz supply system. The following equation may be used to estimate power plant emissions resulting from 400 Hz supply to aircraft at one gate:

$$E_{ij} = PC_j \times EI_i$$

Where: E_{ij} - emission of pollutant i, in pounds, produced by the power plant as a result of 400 Hz power supply to aircraft j
PC_j - total power consumption, in kWh, by the 400 Hz power supply system for gate servicing aircraft type j
EI_i - emission index for pollutant i, in pounds of pollutant per kWh electric power produced

To calculate emissions for multiple gates at an airport, the above equation need only be applied to all gates being serviced by 400 Hz ground power. The sum of those emissions represents all emissions to the atmosphere as a result of supplying 400 Hz power to aircraft by ground equipment.

400 Hz Ground Power Emissions - Sample Calculation

This calculation illustrates the procedure for determining the pollutant emissions from a power plant resulting from 400 Hz power being supplied to an aircraft while it is docked at an airport gate. A typical power consumption rate for a wide body gate 400 Hz power supply system is 10,000 kWh per month or 120,000 kWh per year. Emission rates from power plants are a function of the regional power supply network. Assuming the example gate is in California in 2000, 1 kWh of power supplied results in 0.00004 lb of hydrocarbon emissions, 0.00044 lb of carbon monoxide emissions, and 0.00031 lb of nitrogen oxide emissions (see Table 1). Total annual pollutant emissions from the power plant would be:

Pollutant	Power Consumption (kWh/year)		Emission Rate (lb/kWh)		Emissions (lb/year)
HC	120,000	x	0.00004	=	4.8
CO	120,000	x	0.00044	=	52.8
NO_x	120,000	x	0.001031	=	37.2

400 Hz Ground Power Emissions - Data Inputs

Only two pieces of information are required to estimate emissions from 400 Hz power supply to aircraft: power consumption at the gate and pollutant emissions rates from the power plant. These are multiplied together to estimate the total emissions in a given period of time under investigation. Emissions from power plants were discussed earlier.

- **Electric Power Consumption at the Gate by 400 Hz Supply** - Power consumption (in kWh) by the 400 Hz supply system is a result of both the aircraft load and the type of system delivering 400 Hz power to the aircraft. As a result, a simple calculation based on the amount of time aircraft spend at the gate with the APU shut down is not warranted. Power is consumed by the electric motor-generator or frequency converter even in the absence of a load, although often at a very low rate, depending on the type of equipment. In many cases an estimate of the total power consumption by a gate's 400 Hz power supply is available. A summary of information from several airports is given in Table 12.

  If a per-gate power consumption figure is not available, an estimate may be derived by considering the expected mix of aircraft serviced by a gate and the average power loads corresponding to those aircraft. These loads for common commercial aircraft

TABLE 12: 400 HZ SUPPLY SYSTEM ELECTRIC POWER CONSUMPTION[1]

Airport	No. Gates	400 Hz System	Electric Consumption (kWh/y and kW demand)	
			Total	Per Gate
San Francisco	21 JB 3 WB	Centralized (split)	1.82M kWh 760 kW	75,800 kWh 32 kW
		Point-of-use	1.65M kWh 740 kW	68,600 kWh 31 kW
Washington National	23 WB 21 NB	Centralized (vertical M-G)	5.48M kWh 900 kW	124,500 kWh 20 kW
		Centralized (horiz. M-G)	5.48M kWh 900 kW	124,500 kWh 20 kW
		Centralized (inverters)	2.61M kWh 585 kW	59,300 kWh 13 kW
		Mini-central (vertical M-G)	5.15M kWh 650 kW	117,000 kWh 15 kW
		Mini-central (horiz. M-G)	5.15M kWh 650 kW	117,000 kWh 15 kW
		Mini-central (inverters)	2.61M kWh 585 kW	59,300 kWh 13 kW
		Point-of-use	2.61M kWh 585 kW	59,300 kWh 13 kW
		Electric Mobile Units	2.61M kWh 585 kW	59,300 kWh 13 kW
		Diesel Mobile Units	440,000 gallons	10,000 gallons

Note: JB=Jumbo Body, WB=Wide Body, NB=Narrow Body; M-G = motor-generator

[1] Sources:

San Francisco - *Preconditioned Air and 400 Hz Study for San Francisco International Airport New Concourses "A" and "G"* (Reference 4)

Washington National - *400 Hz Power System Study* (Reference 17) docked at a gate are given in Table 13. Loads in kVA must be converted to kilowatts (kW) and multiplied by the average time (in hours) per LTO with electric power supplied to the aircraft. The result is total power consumption per LTO, measured in kWh.

PCA System Emissions - Calculation Methodology

The methodology for calculating pollutant emissions resulting from the supply of preconditioned air to the aircraft is similar to that used for 400 Hz ground power systems. The two pieces of information required are the average consumption of electric power per gate by the PCA system and the power plant emission factors given previously.

PCA System Emissions - Sample Calculation

This calculation illustrates the procedure for determining the pollutant emissions from a power plant resulting from PCA being supplied to an aircraft while it is docked at a gate. The power consumption rate for a PCA supply system (including heated air in winter) at San Francisco Airport was estimated to be 212,000 kWh per year for a gate capable of serving jumbo aircraft. Emission rates from power plants are a function of the regional power supply network. Assuming the example gate is in California in 2000, 1 kWh of power supplied results in 0.00004 lb of hydrocarbon emissions, 0.00044 lb of carbon monoxide emissions, and 0.001031 lb of nitrogen oxide emissions. Total annual pollutant emissions from the power plant would be:

Pollutant	Power Consumption (kWh/year)		Emission Rate (lb/kWh)		Emissions (lb/year)
HC	212,000	x	0.00004	=	8.5
CO	212,000	x	0.00044	=	93.3
NO_x	212,000	x	0.00031	=	65.7

PCA System Emissions - Data Inputs

Only two pieces of information are required to estimate emissions from PCA supply to aircraft: power consumption by the PCA system and pollutant emissions rates from the power plant. These are multiplied together to estimate the total emissions in a given period of time under investigation. Power plant emissions were discussed earlier.

TABLE 13: TYPICAL 400 HZ LOAD REQUIRED BY VARIOUS AIRCRAFT[1]

Aircraft	**Peak Load (KVA)**	**Average Design Load (KVA)**
A-320	60	20
B-727-200	60	18
B-737-300	60	15
B-747-400	120[2]	50
B-757-200	60	30
B-767-300	90	45
MD-80	60	20

[1] Source: *Preconditioned Air and 400 Hz Study for San Francisco International Airport New Concourses "A" and "G"* (Reference 4)

[2] 211 kVA required for the B-747-400 if cooking with all 16 ovens is done at the gate (Reference 13)

- **Electric Power Consumption at the Gate by PCA Equipment** - Power consumption (in kWh) by the PCA system is largely a result of the cooling and heating loads of the aircraft being serviced. The PCA system must be designed to accommodate both the hottest day in summer and the coldest day in winter. These peak demand conditions, however, are much higher than the annual average power consumption. An in-depth analysis of power consumption based on aircraft mix at a gate, passenger loading, and weather conditions is beyond the scope of this section. However, analyses for PCA systems at Logan International Airport (Boston), San Francisco International Airport, and Zurich Airport have been performed. The results of these studies are summarized in Table 14. The relatively mild summertime conditions at these three airports should be taken into consideration when applying these figures to warmer climates.

Costs of 400 Hz Power Supply and PCA Systems

Per gate capital, operating, and maintenance costs for 400 Hz power supply and PCA systems are quite variable. The number and type of aircraft serviced at a gate, outside weather conditions, and the type of systems chosen to provide these services all have a great impact on costs. However, comprehensive cost studies which have been performed for other airports give a range of expected costs per gate.

400 Hz Power Supply Costs

Table 15 gives an overview of capital, maintenance, and fuel costs for two airports at which studies of 400 Hz supply were carried out. Fuel costs were based on local electric rates which take both demand (in kW) and energy consumption (in kWh) into account. A sample set of electric utility rates is given in Table 16.

PCA System Costs

Table 17 gives an overview of capital and maintenance costs for three airports at which studies of PCA were carried out. The Zurich Airport study includes costs for both 400 Hz supply and PCA.

Summary - 400 Hz and PCA System Costs and Emissions

Based on the information presented above, costs and emissions per gate for typical 400 Hz and PCA supply systems can be estimated. These are shown in Table 18.

TABLE 14: PCA SYSTEM ELECTRIC CONSUMPTION[1]

Airport	No. Gates	PCA System	Electric Consumption (kWh/y and kW demand)	
			Total	Per Gate
Boston	3 WB 6 NB	Individual PCA assemblies at gate	-	-
San Francisco	21 JB 3 WB	Individual PCA assemblies at gate	5.08M kWh 3500 kW	212,000 kWh 146 kW
		Central PCA (no ice storage)	5.15M kWh 3342 kW	215,000 kWh 139 kW
		Central PCA (with ice storage)	5.08M kWh 3213 kW	212,000 kWh 134 kW
Zurich	28	Central PCA + 400 Hz Supply	10M kWh	357,000 kWh

Note: JB=Jumbo Body, WB=Wide Body, NB=Narrow Body

[1] Sources:

Boston - *A feasibility study of preconditioned air for Northwest Airlines at Logan International Airport, Boston, Massachusetts* (Reference 3)

San Francisco - *Preconditioned Air and 400 Hz Study for San Francisco International Airport Concourses "A" and "G"* (Reference 4)

Zurich - *Airport Ground Power Concepts for Aircraft Energy and Environmental Concerns: A Holistic Approach* (Reference 12) (note: The Zurich airport study gives information for combined 400 Hz and PCA Supply)

TABLE 15: SUMMARY OF 400 HZ SYSTEM COSTS AT SAN FRANCISCO AND WASHINGTON NATIONAL[1]

Airport	**No. Gates**	**400 Hz System**	**Capital Cost ($)**		**Electric Costs (based on local rates)**		**O & M costs ($) (including electric)**	
			Total[2]	**Per Gate**	**Total**	**Per Gate**	**Total**	**Per Gate**
San Francisco	21 JB 3 WB	Centralized (split)	$1.54M	$64,100	$231,000	$9,600	$275,000	$11,500
		Point-of-use	$2.15M	$89,600	$216,000	$9,000	$275,000	$11,500
Wash. National	23 WB 21 NB	Centralized (vertical M-G)	$3.96M	$90,100	$232,000	$5,300	$232,000 (electric only)	$5,300 (electric only)
		Centralized (horiz. M-G)	$4.01M	$91,100	$232,000	$5,300	$232,000 (electric only)	$5,300 (electric only)
		Centralized (inverters)	$4.02M	$91,400	$181,000	$4,100	$181,000 (electric only)	$4,100 (electric only)
		Mini-central (vertical M-G)	$2.45M	$55,600	$190,000	$4,300	$190,000 (electric only)	$4,300 (electric only)
		Mini-central (horiz. M-G)	$2.55M	$57,900	$190,000	$4,300	$190,000 (electric only)	$4,300 (electric only)
		Mini-central (inverters)	$2.33M	$53,000	$181,000	$4,100	$181,000 (electric only)	$4,100 (electric only)
		Point-of-use	$2.31M	$52,500	$181,000	$4,100	$181,000 (electric only)	$4,100 (electric only)
		Electric Mobile Units	$2.45M	$55,700	$181,000	$4,100	$181,000 (electric only)	$4,100 (electric only)
		Diesel Mobile Units	$2.06M	$46,800	$326,000	$7,400	$377,000	$8,600

Note: JB=Jumbo Body, WB=Wide Body, NB=Narrow Body; M-G=motor-generator

[1] Sources:

San Francisco - *Preconditioned Air and 400 Hz Study for San Francisco International Airport New Concourses "A" and "G"* (Reference 4)

Washington National - *400 Hz Power System Study* (Reference 17)

[2] $M = million dollars

TABLE 16: SAMPLE UTILITY COST RATES[1]

Charge	Rate
Basic Charge	$69 / Month
Demand Charge (30 min.)	$10.258 / kW
Distribution Demand Charge	
1. First 700 Kw	$1.406 / kW
2. Next 4300 Kw	$1.123 / kW
3. Additional Kw	$0.967 / kW
Energy Charge	
1. First 24,000 kWh	$0.01345 / kWh
2. Next 186,000 kWh[2]	$0.00701 / kWh
3. Additional kWh[2]	$0.00290 / kWh
Fuel Charge	$0.01641 / kWh
RKVA Demand Charge	$0.15 / RKVA

[1] Source: Rates from Virginia Electric Power Co. and *400 Hz Power System Study* (Reference 17)

[2] Add 210 kWh for each kW in excess of 1000 kW demand

TABLE 17: SUMMARY OF PCA SYSTEM COSTS AT VARIOUS AIRPORTS[1]

Airport	No. Gates	PCA System	Capital Cost ($)		Electric Costs (based on local rates)		O & M costs ($) (including electric)	
			Total	**Per Gate**	**Total**	**Per Gate**	**Total**	**Per Gate**
Boston	3 WB 6 NB	Individual PCA assemblies at gate	$610,000	$68,000	N/A	N/A	$83,000	$9,200
San Francisco	21 JB 3 WB	Individual PCA assemblies at gate	$4.44M	$185,000	$489,000	$20,400	$629,000	$26,200
		Central PCA (no ice storage)	$4.93M	$205,000	$484,000	$20,200	$571,000	$23,800
		Central PCA (with ice storage)	$4.63M	$193,000	$464,000	$19,300	$550,000	$22,900
Zurich	28	Central PCA + 400 Hz Supply	$19.9M	$711,000	N/A	N/A	$1.66M	$59,000

Note: JB=Jumbo Body, WB=Wide Body, NB=Narrow Body, N/A = Not Available

[1] Sources:

Boston - *A feasibility study of preconditioned air for Northwest Airlines at Logan International Airport, Boston, Massachusetts* (Reference 3)

San Francisco - *Preconditioned Air and 400 Hz Study for San Francisco International Airport New Concourses "A" and "G"* (Reference 4)

Zurich - *Airport Ground Power Concepts for Aircraft Energy and Environmental Concerns: A Holistic Approach* (Reference 12)

TABLE 18: ESTIMATED COSTS AND EMISSIONS PER GATE FOR 400 HZ AND PCA SUPPLY[1]

Gate Type	Annual Electric Consumption (kWh)	Capital Costs ($)	Annual O & M Costs (including electric) ($/yr)	2000 Emissions (lb/y)		
				HC	**CO**	**NO$_x$**
Jumbo	286,000	$271,000	$35,800	8.9	95	935
Wide/Narrow Body	159,000	$123,000	$13,400	4.9	53	520

[1] This table was derived by averaging costs and emissions from some of the low cost alternatives presented in the following studies:

- *Preconditioned Air and 400 Hz Study for San Francisco International Airport Concourses "A" and "G"* (Reference 4),
- *400 Hz Power System Study* (Reference 17),
- *A feasibility study of preconditioned air for Northwest Airlines at Logan International Airport, Boston, Massachusetts* (Reference 3), and
- *Airport Ground Power Concepts for Aircraft Energy and Environmental Concerns: A Holistic Approach* (Reference 12).

Total Costs and Benefits of Converting to Ground Power and PCA

Advantages of converting from APU usage to ground-based 400 Hz and PCA occur both in the form of reduced emissions and reduced operating and maintenance costs. Over a period of time these reduced costs are likely to make up for the capital cost of installing the equipment. In order to quantify these costs and benefits, the results of the previous sections must be compared.

Calculation Methodology - Overall Costs and Benefits - To quantify the costs and benefits of converting from APU usage to ground power and PCA, total costs and emissions for both cases must be compared. The previous sections gave a methodology for producing these estimates, but in order to compare "apples to apples" we must ensure that the time frames considered are the same for both cases. Table 18 shows costs and emissions on a per gate, per year basis, whereas the APU costs and emissions are derived per aircraft landing/takeoff (LTO) cycle. These must be converted to a per gate, per year total.

Sample Calculation - Overall Costs and Benefits - This calculation is based on a B-737-300 with APU model GTCP85-129ck at Los Angeles International Airport. For the first case, it is assumed that no ground power or PCA equipment is available at the gate. As calculated previously, the aircraft has an average gate time of 81.54 minutes. Costs and emissions were calculated for one LTO, as summarized in Table 19. If we assume that a gate serves nine aircraft LTO's per day, annual costs as shown in Table 19 may also be derived by multiplying the LTO figures by 9 (LTO's per day) and 365 (days per year).

For the second case, it is assumed that 400 Hz power and PCA are supplied by ground equipment. In addition to the cost and emissions information shown in Table 18, there are some costs and emissions associated with the small amount of time an APU must operate while the aircraft is docked. As mentioned earlier, the APU can be shut off approximately 30 seconds after mating with the bridge. In addition, the APU must be turned on about 5 minutes before the aircraft leaves the gate so that it may be properly warmed up for starting the main engines. If we assume 5.5 minutes of APU operation

TABLE 19: COSTS AND EMISSIONS FROM B737-300 APU USAGE AT ONE GATE

No. of LTOs	**Fuel Consumption**	**O & M Costs (including fuel)**	**Emissions (lb)**		
			HC	**CO**	**NO_x**
One LTO	319.6 lbs jet fuel	$45.23	0.329	5.750	1.518
One Year @ 9 LTO's / day	1,049,900 lbs jet fuel	$148,580	1,080	18,890	4,990

time per LTO, then the total cost and emissions for this case would be as shown in Table 20.

Summary - Overall Costs and Benefits

Table 21 shows that the use of ground 400 Hz power and PCA systems can significantly reduce both fuel costs and emission. For the example shown, based on the CRF calculated previously, the annualized cost would be:

APU Only (t1)
= (0.187 x $0) + $148,580/yr
= ($0) + $148,580/yr
= $148,580/yr

400 Hz and PCA (t2)
= (0.187 x $123,000) + $23,420/yr
= ($23,001/yr) + $23,420/yr
= $46,421/yr

For this example, addition of 400 Hz power and PCA systems to mitigate emissions from APU use saves $102,159/yr.

$C_{t1,t2}$ = $46,421/yr - $148,580/yr
= $102,159/yr

This results in a very favorable cost/benefit ration for NO_x of $49,460/ton.

= $102,159/yr ÷ [(4,990 lbs - 859 lbs) ÷ 2,000 lbs/ton)
= $49,460/ton

TABLE 20: COSTS AND EMISSIONS FOR EXAMPLE CASE - 400 HZ AND PCA SUPPLY AVAILABLE[1] -

Source	Fuel Consumption	O & M Costs (including fuel)	Emissions (lb)		
			HC	CO	NO_x
APU Usage: 1 LTO (5.5 min)	21.56 lb jet fuel	$3.05	0.0222	0.3879	0.1024
APU usage: 1 year	70,820 lbs jet fuel	$10,020	72.9	1,274	336
Ground Power / PCA: 1 year	159,000 kWh electric	$13,400	4.9	53	520
Total: 1 year	-	$23,420	77.8	1,327	856

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[1] Includes 5.5 minutes of APU operation per LTO

TABLE 21: COMPARISON OF APU USAGE TO GROUND 400 HZ POWER AND PCA SYSTEM USAGE FOR A B737-300 at LAX

Source	Annual Fuel Consumption	Capital Costs	Annual O & M Costs (including fuel)	Emissions (lb/yr)		
				HC	CO	NO_x
APU usage only	1,049,900 lbs jet fuel	$0	$148,580	1,080	18,890	4,990
PCA / Ground Power Available	159,000 kWh electric 70,820 lbs jet fuel	$123,000	$23,420	77.8	1,327	856

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