FULL FUEL CYCLE ASSESSMENT TANK TO WHEELS EMISSIONS AND ENERGY CONSUMPTION

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ABSTRACT

Emissions associated with the production and distribution of fuels can be significant in comparison with tailpipe and exhaust emissions. Examining these fuel-cycle emissions for alternative-fueled vehicles appears relevant when assessing the overall environmental impact of these vehicles from both a global and local perspective.

This study determines oxides of nitrogen (NO_x), non-methane organic gases (NMOG), air toxics, carbon monoxide (CO), and carbon dioxide (CO_2) emissions for methanol, diesel, liquefied petroleum gas (LPG), and electric vehicle operation. Reformulated diesel, biodiesel, and synthetic diesel were also analyzed. These fuel options are of interest because they potentially result in relatively low refueling emissions. The purpose of the study was to investigate those fuels that might be categorized as having low fuel cycle emissions. Vehicles operating on 100 percent methanol, LPG, and diesel were judged by the California Air Resources Board (ARB) to result in fuel-cycle NMOG emissions that are close to 0.01 g/mi. Fuels with clearly lower fuel cycle emissions such as compressed natural gas (CNG) and hydrogen were not analyzed in this study. Gasoline was also not analyzed as the results of a 1996 fuel-cycle study indicated NMOG emissions to be about 0.03 g/mi. These results do not reflect improvements that could be achieved with advanced gasoline hybrid vehicle technologies and further investigation is warranted.

Emissions considered in this study are those associated with the operation of extraction, production, and distribution equipment. Emissions associated with the production or decommissioning of facilities or vehicles are not evaluated. Emission calculations are based on vehicle operation in California.

This report covers on road and off road vehicle emissions that are consistent with California ARB emission projections for the years 2012, 2017, 2022, and 2030

KEYWORDS

Full Fuel Cycle Analysis, Well to Tank, Criteria Pollutants, Multi-media impacts, EMFAC

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SECTION 1. INTRODUCTION

1.1 Background

The California Energy Commission's *2005 Integrated Energy Policy Report* and comments to the report from Governor Schwarzenegger make clear that the state needs to promote the efficient use of petroleum products and promote reductions in the demand for petroleum. California Assembly Bill (AB) 1007 reaffirms the ongoing need to address these critical transportation energy issues. While primarily directed to increase non-petroleum fuel use in California, AB 1007 responds to several other policy directives and state and federal legislation, including reduction of greenhouse gas emissions and improved air quality.

Chaptered in September 2005 (Chapter 371, Statutes of 2005), AB 1007 (Pavley) requires the Commission to "develop and adopt a state plan to increase the use of alternative transportation fuels" in California. It directs the Commission to work with the California Air Resources Board (ARB), State Water Resources Control Board, Department of Food and Agriculture, and "other relevant state agencies" in developing this plan. AB 1007 defines an alternative fuel as any non-petroleum fuel including electricity, ethanol, biodiesel, hydrogen, methanol, and natural gas that has demonstrated the ability to meet applicable vehicular emission standards.

AB 1007 states that the plan will "ensure there is no net material increase in air pollution, water pollution, or other dangerous substances that are known to damage human health." The determination of the impacts of increased alternative fuel use may have on petroleum consumption and on criteria air pollutants, air toxics, greenhouse gases, water pollutants, and other substances known to damage human health are to be determined on a full fuel cycle basis.

1.2 Report Scope

Full fuel cycle emissions are determined on a well-to-wheels (WTW) basis, which includes fuel production and distribution, or fuel cycle emission, and vehicle emissions.

This report focuses on the tank-to-wheels (TTW) cycle and analyzes the emissions from vehicles and other transportation fuel applications as part of the full fuel cycle assessment of California transportation fuels. A variety of vehicle types including both on-road and off-road applications were assessed with emission analysis tools that reflect the emission standards, fuels and operating conditions in California. Criteria pollutant emission from baseline gasoline and diesel vehicles, toxic air contaminants and water impacts are also analyzed in this report.

A second report, the well-to-tank (WTT) assessment, analyzes fuel production and distribution, and will complete the well-to-wheel full fuel cycle assessment.

Greenhouse gas emissions from vehicles include CO_2, nitrous oxide (N_2O), methane (CH_4), and refrigerants. Emission estimates of N_2O and CH_4 are examined in this TTW report as well as the vehicle energy consumption and carbon intensity of fuels. CO_2 emissions are also calculated from the carbon content of the fuel and shown in the WTW report. The final WTW report will include all these greenhouse gas emission estimates for vehicle use and fuel production and distribution

The WTW and WTT emissions are provided in separate volumes. Vehicle TTW emissions and energy consumption are examined in this report. Criteria pollutant emissions from baseline gasoline and diesel vehicles, toxic air contaminants, and water impacts are provided and estimates of the effect of alterative fuel operation are included. The calculation of alterative fueled vehicle emissions on a g/mi basis is included in the full WTW report.

Emissions associated with the production of materials for vehicles or facilities typically fall into the category of life cycle analysis, which is not covered in the full fuel cycle analysis. This report provides references for more information on vehicle life cycle analysis.

1.2.1 *Vehicle Life Cycle*

Vehicle cycle (TTW) emissions include vehicle evaporative emissions and vehicle tailpipe emissions. Emissions associated with producing and recycling the vehicle are not included in the full fuel cycle analysis but would be part of a life cycle analysis (Figure 1-1). The impact of vehicle production and recycling is small compared to overall vehicle-related emissions, but not insignificant. Vehicle production contributes on the order of 10 to 20 percent of overall emissions and this contribution increases as vehicles meet more stringent emissions standards (Friedrich and Bickel 2001). Energy inputs for vehicle manufacturing would be different for alternative fueled vehicles with significantly different fuel storage systems. Tanks for compressed natural gas (CNG) and hydrogen vehicles, as well as battery electric drive vehicles, weigh many times more than a gasoline tank and require more energy inputs. While these components can be recycled, the energy inputs will lead to some differences in a vehicle life cycle analysis (Weiss 2000). The impact of battery recycling will also be different that those of conventional IC engine vehicles. A study for the ARB examined the potential impacts of battery recycling (Montano1995).

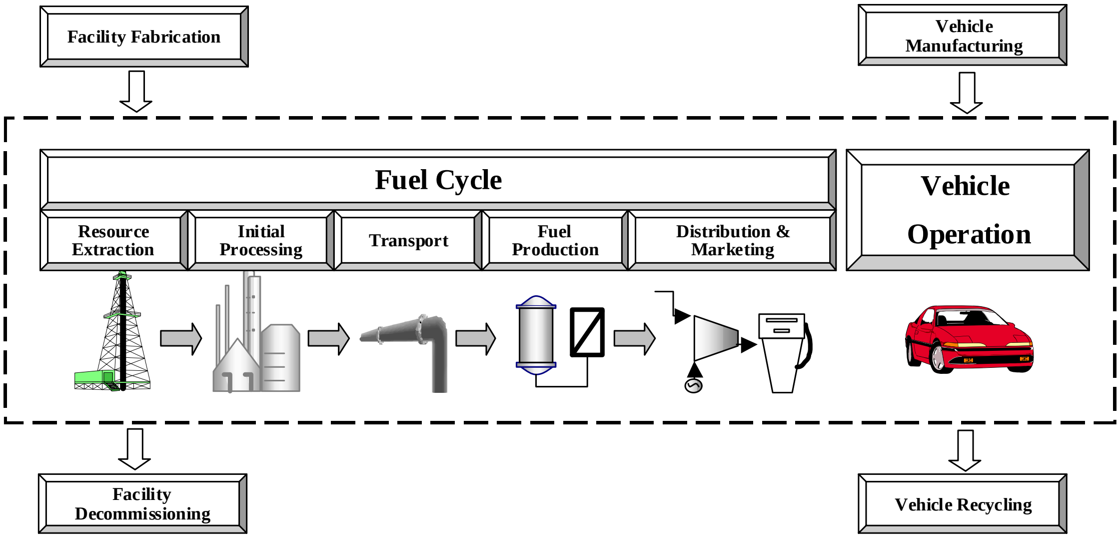


Figure 1-1. Activities Related to Fuel Production and Vehicle Operation in the Full Fuel Cycle Analysis

For emission strategies such as vehicle miles traveled (VMT) reductions, presenting vehicle manufacturing and recycling emissions impact on a per-mile basis would be misleading because such a comparison would not reflect the benefit of longer vehicle life.

1.2.2 Air Emissions

Emissions from the vehicle's tailpipe are called exhaust emissions. Incomplete combustion of the fuel is the primary cause of hydrocarbon (HC), carbon monoxide (CO), and particulate (PM) emissions (ARB 2003). Oxides of nitrogen emission (NO_x) are produced during combustion at high temperatures and pressures, but especially under lean air/fuel ratio conditions. Properly working catalysts reduce tailpipe emissions from gasoline vehicles by over 90 percent when combined with electronic systems that monitor the air/fuel ratio. Due to higher combustion temperatures, excess air, and high pressures, a diesel-fueled vehicle emits comparatively more NO_x than a comparable gasoline-fueled vehicle on a g/mi basis. In gasoline engines, NO_x emissions can be controlled using a three-way catalyst, which uses the exhaust CO and HC to reduce the NO_x. The oxidation catalyst portion of the three-way catalyst simultaneously reduces the CO and HC. However, the lean overall air/fuel ratios used by diesel engines preclude the use of conventional three-way catalysts for NO_x emission control. NO_x reduction catalysts can be used on diesel engines with the addition of a reducing agent to the exhaust. In these engines, conventional oxidation catalysts can be used for PM, CO, and HC reduction.

Criteria pollutant emissions in this report reflect ARB's emission modeling efforts for on-road and off-road vehicles. Emission factors in g/mi or g/gallon (gal) of fuel were developed for the various scenario years in this study based on ARB's EMFAC on-road model and the Off-Road Database. These composite emission factors reflect projections for emission control technology and the roll in and retirement of the vehicles in the on-road and off-road equipment fleet.

Refrigerants from vehicle air conditioning systems are also a source of GHG emissions. Refrigerant emissions are not included in the analysis since these would not change with different fuel options, unless alternative refrigeration cycles such as those considered for electric drive systems are used (Farrington 1999). Furthermore, air conditioning losses are typically not considered part of the fuel cycle.

1.2.3 Multimedia Impacts

Spills of refined fuels gasoline and diesel during transportation can impact soil, surface water, and groundwater. Spills of fuel can occur in many modes during transport to private and commercial distribution centers. Water impacts related to fuel production and delivery spills are included in the well-to-tank analysis.

Water impacts from vehicle operation include leaks of engine oil, coolant, fuel, and tire/brake wear. Wear metals from engines accumulate in engine oil. These metals can include chromium, lead, magnesium, cadmium, and copper. Components such as hydrocarbons from engine oil and metals from brake wear build up on road surfaces and then enter the run off water with seasonal rains. Engine oil and other fluids also create an environmental hazard when disposed of inappropriately.

To the extent that fuel leaks from engines are relatively rare, the water impacts from different internal combustion engine technologies might be expected to be similar. Oil consumption from internal combustion engines (ICEs) continues to decrease and the uncertainties in the impacts of oil leaks are large. Nonetheless, water impacts from fluid leaks are part of the full fuel cycle and are estimated here. Some vehicle technologies such as fuel cell and battery electric vehicles do not have water impacts from engine oil. Electric drive systems will however require recycling of battery materials or precious metals from the fuel cell membrane (Montano 1995, Carlson 2003).

Other water impacts from the vehicle include water and coolant consumption for engines as well as water consumption and waste water from vehicle washing. These impacts could be grouped into a life cycle analysis. Similar to refrigerant losses, these water impacts are not likely to be different among fuel options.

1.2.4 Objectives

This report supports the specific requirements of AB 1007 to assess the vehicle emission impacts, while also providing a comprehensive framework for the full fuel cycle analysis, especially for fuel production and vehicle operation in California. Included here are the energy consumption, vehicle exhaust and evaporative emissions, and water impacts from vehicle operation.

The analysis objectives for the TTW portion of the full fuel cycle emissions include:

- Determine vehicle emissions occurring in the years 2012, 2017, and 2022. Also support the development of emission scenarios for 2030 and 2050. The full fuel cycle analysis provides input into scenarios that assess the emission impacts in specific calendar years, which depend on vehicle introduction rates and the age of the vehicle fleet. The estimates here reflect the emissions in specific calendar years (and potential air quality impacts) rather than the emissions over the life of the vehicle.
- Determine vehicle emissions on a g/mi basis that are consistent with the state's emission inventory calculations for vehicle activity, driving conditions, temperatures, and other factors affecting on-road vehicle emission estimates.
- Estimate the impact of alternative fuel operation on vehicle energy use, criteria pollutants, toxics, and water impacts.
- Determine emissions for a range of on-road and off-road applications that are representative candidates for using alternative fuels.

1.2.5 Report Organization

The report includes the following sections:

2 Vehicle Applications – Describes vehicle applications and uses of alternative fuels that were analyzed in the full fuel cycle analysis.

3 Vehicle Energy Consumption – Determines baseline conventional vehicle energy consumption and compares alternative and conventional vehicle energy consumption

4 Criteria Pollutant Emissions – Develops g/mi and g/gal of fuel emission factors for conventional and alternative fueled on-road and off-road vehicles that are consistent with California emission inventories. The emission factors reflect the vehicle population, mileage accumulation, temperature and other environmental effects, and maintenance assumptions in the vehicle inventory.

5 Greenhouse Gas Emissions – Reviews approach for calculating vehicle CO_2 emissions (WTW report) and provides CH_4 and N_2O emission factors.

6 Water Impacts – Estimates fluid losses from vehicles affecting water impacts that could affect storm water run off.

7 Vehicle Cycle Conclusions – Examines results and limitations of TTW analysis.

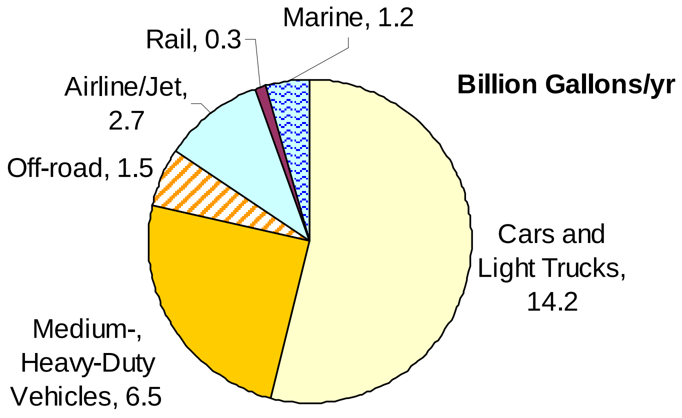
8 Bibliography – Provides references and additional information on TTW analysis.

SECTION 2. VEHICLE APPLICATIONS

This report assesses the emissions from vehicles and transportation fuels. In California, specifications for transportation fuels apply to vehicles and equipment that fall into both on-road vehicle and off-road vehicle categories. The grouping of these vehicle categories within state emission inventory models is discussed in this section. Potential uses of alternative fuels are also discussed.

2.1 Transportation Fuels

When ranked according to gasoline consumption, California is the second largest consumer in the world, after the entire United States. The state consumes over one-tenth of the nation's gasoline. When total petroleum consumption is include, about two-thirds of the state's petroleum usage is for transportation fuels in the on- and off-road categories, which are primarily fueled by gasoline and diesel fuel meeting on-road requirements. Airline and jet fuel is similar to kerosene or No. 1 diesel. Marine vessels are fueled with bunker fuel.



Fuel Consumption CA Mix.xls

Figure 2-1. Petroleum Consumption in California, 2004 (DOE EIA)

2.2 On-Road Vehicles

Vehicles that are required to be registered for driving on public roads comprise the on-road vehicle category. This category includes passenger cars and light trucks as well as medium and heavy duty vehicles and buses. The light truck category includes both pick up trucks as well as sport utility vehicles. The categories of on-road vehicles for the California Stateside emissions inventory are listed in Table 2-1. Vehicles and emissions are tabulated in the inventory by the technology groups: non-catalyst equipped (NCAT), catalyst equipped (CAT) gasoline vehicle, and diesel powered (DSL) vehicles.

Table 2-1. Vehicle Classes in EMFAC

Description	Class	Weight, lb (GVWR)	Fraction of Fuel Used as Gasoline, 2005
Passenger Cars	LDA	All	99.9%
Light-Duty Trucks	LDT1	0-3,750	98.4%
Light-Duty Trucks	LDT2	3,751-5,750	99.9%
Medium-Duty Trucks	MDV	5,751-8,500	99.9%
Light-Heavy Duty Trucks	LHDT1	8,501-10,000	88.1%
Light-Heavy Duty Trucks	LHDT2	10,001-14,000	67.1%
Medium-Heavy Duty Trucks	MHDT	14,001-33,000	10.6%
Heavy-Heavy Duty Trucks	HHDT	33,001-80,000	1.1%
Other Bus	OB	All	47%
School Buses	SBUS	All	9.8%
Urban Bus	UB	All	10.2%
Motor Homes	MH	All	79%
Motorcycles	MCY	All	100%

Source: Based on fuel usage in TTW_EMFAC_Toxics.xls

Each class is dominated either by gasoline or diesel fueled vehicles. The TTW analysis is based on the dominant fuel as the baseline for comparison with alternative fuel operation. The analysis tools can also examine diesel vehicles and alternative fuel blends in light- and medium-duty vehicles. For example, in the case of urban buses, TTW emissions are calculated for diesel (the predominant fuel) buses and alternative fueled buses that could displace diesel buses.

2.2.1 Emission Control Technologies

In order to comply with ARB regulations, vehicles are built with various levels of emission control depending of the requirements for the vehicle class. For example, light-duty vehicles can be certified in California to the following certification bins. These bins correspond closely to EPA bins.

- Low emission vehicle (LEV)
- Ultra low emission vehicle (ULEV)
- Super low emission vehicle (SULEV)
- Partial zero emission vehicle (PZEV)
- Zero emission vehicle (ZEV)

The California emission inventory is developed for a mix of emission control technologies within each vehicle class that are projected to comply with the overall emission requirements for that vehicle class. This study calculates the composite emission factor that corresponds to the vehicle mix in the inventory rather than selecting an individual certification class (such as PZEVs). The difference between the composite of emission control technologies projected on the road and an individual technology group can be significant because of the different warranty requirements and deterioration rates assumed for various emission control technologies.

In summary, the California emission inventory provides a detailed assessment of the mix of vehicle types and emission control technologies. Emission estimates correspond to the inventory and reflect the aggregate mix of vehicles and control technologies within a vehicle class on the road in a given year.

2.2.2 Introduction Rates

The analysis accommodates the introduction of new fuels as blends, and new vehicle technologies. When fuel formulations change or new blends are introduced, all of the vehicles on the road can be affected immediately. Introducing new vehicle technologies displaces new conventional vehicle technologies. Therefore blend options and new vehicle technology options are treated with different baseline vehicle emission rates.

The impact of new vehicle technologies in a given calendar year depends upon the introduction rate of a given new technology, which may vary by year. Vehicle retirement rates and annual mileage accumulation also vary for different vehicle model years operating in a given calendar year. The population of vehicles by model year in the 2017 California on-road inventory is illustrated in Figure 2-2. This distribution would serve as a baseline for new technologies if the new vehicle technology were introduced at a fixed market share starting 2010.

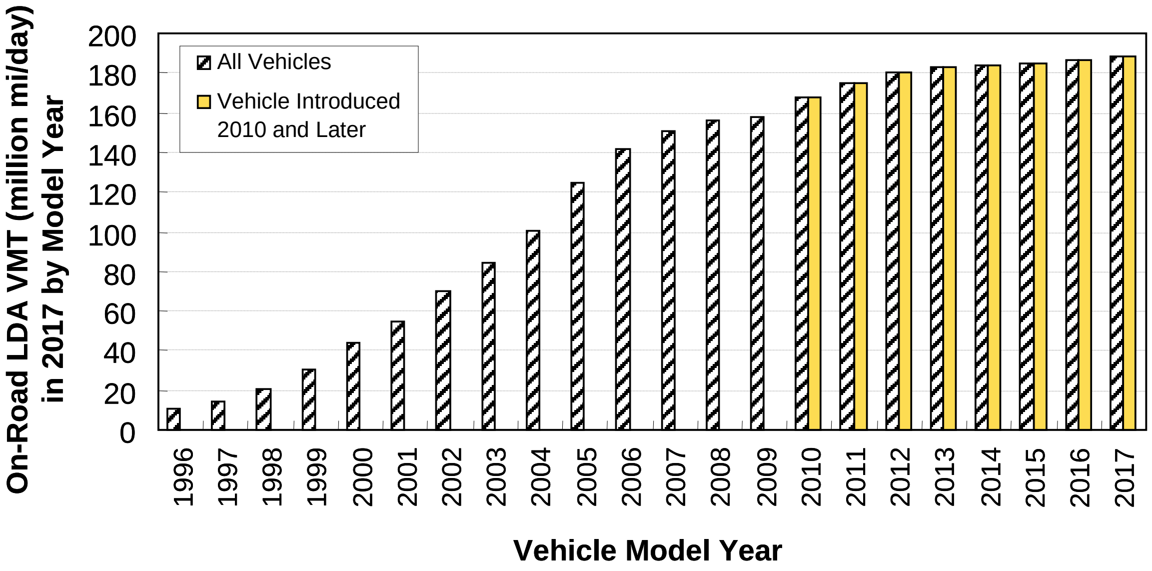


Figure 2-2. Vehicle Population for Total Inventory and New Vehicle Introduction Rates (illustrative values)

2.2.3 Alternative Fuel Technologies

The TTW analysis was performed for vehicle technology options that were deemed plausible by the Commission, ARB, the report authors, and stakeholders. The criteria for selecting vehicle fuel combinations to highlight in the report included the following:

- Existing vehicle/fuel application
- Affected by changes in fuel blend
- Likely target application for alternative fuel use
- Input from technology developers

Table 2-2 shows the vehicle fuel combinations where alternative fuels have either been tested or stakeholders provided input that these are desirable applications for alterative fuel use. All of the fuel options considered here are represented either in the light-duty passenger car or transit bus vehicle classes. The WTW report compares the full fuel cycle emissions for midsize passenger cars and urban buses in order to represent the impact of alternative fuels. The baseline data for gasoline and diesel vehicles is provided in this report and analysis tools to enable the examination of a wider range of vehicle classes.

Each vehicle application corresponds to a vehicle class in the California emissions inventory as documented in the EMFAC model. Some applications like garbage trucks, school buses, and transit buses are considered premium targets for alternative fuels because the vehicles operate in urban areas with more population exposure to emissions. A variety of alternative fuel options have been demonstrated or are under development for these vehicle applications.

Analysis tools were developed to determine the emissions for the gasoline and diesel baseline vehicles in Table 2-2, and to calculate the emissions for alternative fueled vehicles. Examining the vehicle and fuel options in Table 2-2, all of the significant alternative fuel options are represented as possibilities for light-duty automobiles and transit buses, which are the basis for discussing the results in this report and the WTW analysis.

Other fuel options lend themselves to niche applications at this time. For example, E-diesel appears to be most suited for heavy duty fleet applications that employ centralized fueling. The fleet operator can better coordinate safety requirements for the fuel by providing information and training to vehicle operators and personnel associated with a fleet. Methanol and DME also fall into this category, operating from dedicated fueling facilities with dedicated engine technologies. A review of the current status of alternative fueled vehicle including the current uses of these fuels can be found in the Alternative Fuels Market Assessment (TIAX 2006) prepared for the Commission.

Some vehicle/fuel combinations do not appear to lend themselves to commercial applications or do not appear targets for development. These combinations were not analyzed.

Table 2-2. Potential Vehicle Options for Alternative Fuel Operation

Vehicle	Car and Light Truck	Delivery Truck	Long Haul Truck	Garbage Truck	School Bus 88 Passenger	Transit Bus 40 ft
Class	**LDA, LDT1, LDT2**	**MDV**	**HHDT**	**HHDT**	**SBUS**	**UB**
RFG — E0	x	x	—	—	—	—
RFG — E5.7[1]	x, HEV, PHEV	x, HEV, PHEV	—	—	—	HEV
RFG — E10	x	x	—	—	—	—
Diesel	x	x	x, HEV	x, HEV	x	x, HEV
LPG	x	x	—	—	—	x
CNG	x	x	—	x	x	x
LNG	—	—	x	x	—	x
Methanol	—	—	—	—	—	FC
DME	—	x	x	—	—	x
FT blends	x	x	x	x	x	x
Ethanol — E85, E100	x, PHEV	—	—	—	—	—
E-diesel	—	x	x	—	—	x
Biodiesel (blends)	x	x	x	x	x	x
Electricity	PHEV, BEV	PHEV	—	—	x	—
Hydrogen	x, FCV	x	—	—	—	x, FCV

Vehicle class abbreviations in Table 2-1.
x = IC engine vehicle fuel combination evaluated
HEV = hybrid electric vehicle, PHEV = Plug in hybrid electric vehicles, EV = Battery Electric Vehicle, FC = fuel cell vehicle
N = New vehicle strategies
A = Blended fuel options

[1] RFG with 2 percent oxygen (5.7 percent ethanol) is the baseline fuel for gasoline vehicle technologies. For vehicle classes dominated by gasoline engines, emissions are calculated for all of the gasoline vehicles in the inventory as well as new vehicle introductions (for example starting 2010).

2.3 Off-Road Applications

Off-road equipment includes engines and vehicles in agricultural, construction, lawn and garden, and off-road recreation applications. The category includes equipment from hedge trimmers to cranes. Because AB1007 was aimed at transportation fuels, some reviewers of the project expressed interested in differentiating off-road applications between transportation and vehicle applications, and other off road equipment. Note that California's on road fuel requirements also apply to off road applications; so, changes to transportation fuels that are widely distributed (for example using E10 instead of conventional RFG) would also affect off-road equipment.

Other categories of off-road equipment are also of interest to the full fuel cycle analysis. Agricultural and logging equipment can be used to harvest biomass used in fuel production. Also some categories of off-road equipment are targets for electric or hydrogen operation. Because so many different categories of off-road equipment are components of the full fuel cycle analysis, TIAX developed a tool to screen the ARB off-road equipment database to develop technology specific composite emission factors.

2.3.1 Off-Road Data Analysis Tool

ARB provided data files from the California off-road inventory of emission database for the years 2005, 2012, 2017, 2022, and 2030. Each year contained about 43,000 records that consisted of information such as class of equipment, equipment name, power rating, fuel type, county in which located, air basin, population, activity, fuel consumption, and reactive organic gases (ROG), CO, NO_x, CO_2, SO_2, PM, N_2O, and CH_4 exhaust emissions in tons/day.

The entire off road inventory was summarized into 253 specific class/equipment/fuel types (see Appendix A). TIAX examined the inventory and developed a simple spreadsheet tool with on/off flags to identify equipment that allow the inventory to be calculated for specific technology groups including the following:

- Off-road vehicles (rather than all equipment)
- Agricultural equipment
- Logging equipment
- Forklifts
- Transport refrigeration units

Sixty-five of the 253 equipment types were identified in the vehicle category used for passenger or goods transport. Fuel consumption and emissions were determined for both categories of equipment and represented as a composite emission factor. Marine vessels (large ships) and aircraft were not included in the analysis because these categories of equipment do not use conventional transportation fuels and they are not called out in AB1007.

TIAX developed a spreadsheet tool that allows the off-road inventory to be summarized by selected applications and fuels. Vehicle population, fuel use, and emissions were grouped by equipment and fuel type. The flags were turned off (omitted) for marine ships, rail, earth/ground moving equipment, chain saws, and other non vehicle applications. Tables 2-3 through 2-5 summarize the equipment and population that are considered off-road vehicles powered by gasoline, diesel, or liquefied petroleum gas (LPG) and CNG, respectively, for the year 2012. These vehicle populations are based on the ARB's Off-Road Engine Database. The database was incorporated into a separate spreadsheet for the years 2012, 2017, 2022, and 2030. The files are quite large. A summary of the 253 applications as well as the entire database files are available separately.

Table 2-3. Off-Road Gasoline Vehicles in California, 2012

Class	Equipment	Population
Agricultural Equipment	2-Wheel Tractors	2,448
	Agricultural Tractors	522
	Combines	191
Airport Ground Support Equipment	A/C Tug Narrow Body	64
	A/C Tug Wide Body	26
	Baggage Tug	946
	Belt Loader	446
	Bobtail	135
	Cargo Loader	136
	Cargo Tractor	842
	Cart	27
	Catering Truck	90
	Forklift	129
	Fuel Truck	81
	Hydrant truck	64
	Lavatory Truck	105
	Maintenance Truck	142
	Passenger Stand	107
	Service Truck	446
	Water Truck	33
Construction and Mining Equipment	Skid Steer Loaders	5,429
Industrial Equipment	Forklifts	15,188
Recreational Equipment	All Terrain Vehicles (ATVs)	377,076
	Golf Carts	8,529
	Minibikes	11,253
	Off-Road Motorcycles	397,403
	Snowmobiles	24,708
	Specialty Vehicles Carts	100,845

Table 2-4. Off-Road Diesel Vehicles in California, 2012

Class	Equipment	Population
Agricultural Equipment	Agricultural Tractors	169,353
	Combines	4,180
Airport Ground Support Equipment	A/C Tug Narrow Body	289
	A/C Tug Wide Body	72
	Baggage Tug	613
	Belt Loader	296
	Bobtail	22
	Cargo Loader	361
	Cargo Tractor	6
	Catering Truck	10
	Forklift	33
	Fuel Truck	27
	Hydrant Truck	14
	Lavatory Truck	6
	Passenger Stand	10
	Service Truck	42
Construction and Mining Equipment	Off-Highway Tractors	3,306
	Off-Highway Trucks	2,425
	Skid Steer Loaders	31,969
Industrial Equipment	Forklifts	5,367
Military Tactical Support Equip	Cart	25

Table 2-5. Off-Road LPG and CNG Vehicles in California, 2012

Class	Equipment	Population
Airport Ground Support Equipment	Baggage Tug	188
	Belt Loader	50
	Bobtail	4
	Cargo Loader	23
	Cargo Tractor	91
	Catering Truck	17
	Forklift	301
	Fuel Truck	10
	Lavatory Truck	8
	Passenger Stand	4
	Service Truck	44
Industrial Equipment	Forklifts	28,770

Table 2-6. Applications for California Off-Road Equipment

Type	Application
Agricultural Equipment	Emissions used in WTT analysis for CA biomass harvesting. Emission factors in g/gal are used in the WTT report
Logging Equipment	
Forklifts (excluding rough terrain)	Baseline TTW data for electric and hydrogen fuel cell equipment
Transport Refrigeration Units	

2.3.2 Introduction Rate

The mix of off-road equipment and introduction rate has a significant effect on criteria pollutant emissions because of the introduction of newer engines with low emissions. Scenarios of off-road equipment are more complicated than those for on-road vehicles because of the wide variety of equipment and more prevalent use of private fuel tanks. As in the case for on-road vehicles, off-road applications for alterative fuels could involve both fuel blends and new vehicle technologies. The fuel use and emissions in the off-road database are for all of the vehicles in the inventory. A separate inventory of only new equipment (introduced in 2010 and beyond), which would serve as a more accurate baseline for new technologies was not included in this report. The project team decided to focus on quantifying the effect of fuel blends because off-road equipment would be affected by a change in fuels.

Nonetheless, many off-road applications are targets for alternative fuel operation. As illustrated in Table 2-5, the California inventory includes over 28,000 units of off-road equipment operate on LPG or CNG (mostly forklifts). In addition, CNG, LNG, LPG and methanol (with ignition improver) have also been tested as fuels for port trucks (yard hostlers).

Zero emission technologies have also been applied to off road equipment. Battery electric vehicles currently represent 23,000 pieces of off-road equipment and fuel cell manufacturers are starting to manufacture stacks for forklift applications. Key targets for off-road electric applications include:

- Forklifts
- Container refrigeration units
- Marine port operations
- Truck stop electrification

As in the case of new on-road vehicle technologies, CNG, LNG, LPG as well as zero emission electric transportation and hydrogen technologies represent new fuel technologies. Therefore, the baseline vehicle emissions calculated in this analysis should be based on new vehicles, which are yet to be placed in service, rather than existing vehicles that already operate. Additional analysis of emissions from a new vehicle baseline should also be completed.

SECTION 3. ENERGY CONSUMPTION

Fuel usage from vehicles and other end use applications is an important component of full fuel cycle emission calculations. The fuel cycle component (WTT) of WTW emissions, are directly proportional to vehicle energy consumption as are the direct CO_2 emissions from vehicles (when expressed on a g/mi basis). Even the formation of criteria pollutant exhaust emissions is related to fuel consumption (Heywood 1988), however, these pollutants are regulated on a g/mi basis within light-duty vehicle classes. Therefore criteria pollutant and air toxic emissions are treated as constant values within a vehicle class, independent of fuel consumption in the following TTW analysis.

Determining actual fuel consumption among different vehicle and fuel options is complicated by many factors. On-road driving does not correspond to chassis and engine dynamometer driving cycles used to test vehicles. Certification fuel for testing gasoline vehicles also has a slightly higher energy content than that of retail reformulated gasoline. The energy content of gasoline and alternative fuels also varies within its specification limits. Therefore, certification test data for vehicles does not correspond to on-road fuel consumption. However, since the objective of full fuel cycle analysis is compare actual emission impacts, the analysis takes into account estimates of energy consumption and emissions for on road driving.

The vehicle’s weight and engine performance also affect fuel consumption. The weight of alternative fueled vehicles may be different than that of a conventionally fueled vehicle and the engine performance will vary slightly as discussed below. These factors can result in difference in fuel consumption on the order of several percent (Heavenrich 2006, EPA Fuel Economy Guide).

This section provides fuel consumption estimates for baseline gasoline and diesel vehicles and comparable alternative fueled vehicles for the purposes of the full fuel cycle analysis. Actual vehicles may differ from these hypothetical comparisons because automakers or vehicle packagers may choose to configure vehicles with slightly or substantially different performance and engine technology. Nonetheless, a desirable comparison is for hypothetical vehicles with comparable performance at attributes.

Some alternative fuel technologies may not provide the same driving range as gasoline vehicles. This shortfall in driving range has prompted some reviewers of fuel cycle studies to assert that “comparable” vehicles should be modeled with extended fuel or battery capacity and a larger vehicle platform to preserve cargo space. Hydrogen and electric vehicles do not appear to be following such a trend. In the case of electric cars, a 150 mile driving range, compared with the typical 350 miles for gasoline cars, appears to be acceptable to a segment of the market (Sexton 2006, Freund 2006). Actually, a driving range over 150 miles is not considered desirable for battery electric vehicles because the increased cost in the battery and the deleterious effect of shallow battery discharging on battery life. Therefore, the comparisons here represent similar vehicles which may provide less driving range.

3.1 Conventional Fuel Vehicles

3.1.1 On-Road Vehicles

Energy consumption for alternative fueled vehicles were projected from baseline values in each vehicle class. The energy consumption reflects actual driving, compared with EPA dynamometer test results. In the case of passenger cars, real world energy consumption estimates are about 15 percent higher than dynamometer tests. Estimated actual values reflect on road driving, adjust for speed, hill climbing, air conditioning, and other factors.

3.1.2 Baseline Vehicle Energy Consumption

The energy consumption for the baseline vehicles were examined from a variety of sources. First the fuel consumption and carbon emissions in EMFAC were used to calculate energy consumption for each vehicle class. These values provided an estimate for 2005 that was consistent with values from the CalCars model provided by the Commission. TIAX then calculated fleet average energy consumption values based on model year projections from the Commission and ARB that reflect the implementation of AB1493.

Compliance with existing air pollution requirements, such as California AB 1493 (ARB 2004) may involve reductions in energy consumption for light- and medium-duty vehicles. Such changes in energy consumption impact both the vehicle and fuel cycle CO_2 proportionately, so a comparison among most alterative fueled vehicle options (ICEVs) is little changed by a declining trend in energy consumption that affects both vehicles . However, WTT criteria pollutant emissions are also proportional to the vehicle’s energy consumption while exhaust emissions presumably remain constant per mile in response to vehicle emission standards. Therefore, factoring the implications of potential changes in energy consumption into the baseline fuel economy projections provides a more accurate estimate of full fuel cycle emissions and the relative comparison among fuel options.

Table 3-1 shows the calculated energy consumption values (MJ/mi) for the scenario years which include all model year vehicles – 2012, 2017, 2022, and 2030 as well as 2005 for reference. The changes in energy consumption over time may be attributed to factors such as vehicle technology improvements including more efficient tires and reduced drag, and engine technology improvements such as a shift to fuel injection, variable valve timing, cylinder deactivation, and others (Duleep 2005).

Energy consumption is shown on a lower heating value (LHV) basis because this representation of the energy content of fuel is considered to better reflect the potential work that can be derived from an internal combustion engine or PEM fuel cell.
Table 3-2 presents the calculated fuel consumption values for the scenario years with only California vehicles model year 2010 or newer. As mentioned previously, this breakout allows for the separate treatment of new vehicle and fuel blend strategies.

Table 3-1. Baseline On-Road Fuel Consumption for All Model Years

Vehicle Class	Fuel/ Technology[3]	Scenario Year (All Model Year Vehicles) (MJ/mi), LHV				
		2005	2012	2017	2022	2030
Midsize PC [1,2]	NCAT + CAT	5.33	5.05	4.58	4.12	3.69
LDT1 [2]	NCAT + CAT	6.63	6.29	5.70	5.12	4.59
LDT2 [2]	NCAT + CAT	8.40	8.66	9.48	10.38	11.30
MDV [2]	NCAT + CAT	12.68	13.07	14.31	15.66	17.06
LHDT1	NCAT + CAT	11.63	11.51	11.35	11.21	11.08
LHDT2	NCAT + CAT	12.0	11.8	11.7	11.5	11.4
MHDT	DSL	20.2	20.0	19.7	19.4	19.2
HHDT	DSL	25.3	25.0	24.6	24.3	24.1
OBUS	DSL	20.1	19.9	19.7	19.4	19.2
SBUS	DSL	20.8	20.6	20.3	20.1	19.9
UB	DSL	36.5	36.1	35.6	35.2	34.8
MH	CAT	9.2	9.15	9.02	8.90	8.81
MCY	NCAT + CAT	1.73	1.83	2.78	2.78	2.81

1 Energy consumption for average LDA is 5.52 MJ/mi for LDA in 2005.

2. Change in fuel consumption over time based on ARB's projection for improvement in new vehicle fuel consumption consistent with AB1493 requirements. Impact on all model year fleet mix was calculated with average vehicle roll in and retirement matrix.

3. Gasoline fueled NCAT + CAT, diesel fueled DSL

Table 3-2. Baseline On-Road Fuel Consumption for 2010 or Newer Model Years

Vehicle Class	Fuel/ Technology[2]	Scenario Year (Model Year 2010 or Newer) (MJ/mi)			
		2012	2017	2022	2030
Midsize PC [1]	CAT	4.59	4.14	3.91	3.67
LDT1 [1]	CAT	6.56	5.91	5.58	5.25
LDT2	CAT	9.56	10.36	10.80	11.33
MDV	CAT	14.44	15.64	16.31	17.11
LHDT1	CAT	11.4	11.18	11.07	10.96
LHDT2	CAT	11.7	11.5	11.4	11.3
MHDT	DSL	19.8	19.4	19.2	19.0
HHDT	DSL	24.8	24.3	24.0	23.8
OBUS	DSL	19.8	19.4	19.2	19.0
SBUS	DSL	20.4	20.0	19.8	19.6
UB	DSL	35.8	35.1	34.7	34.4
MH	CAT	9.1	8.88	8.79	8.71
MCY	CAT	2.81	2.80	2.79	2.81

1 Change in fuel consumption over time based on ARB's projection for improvement in new vehicle fuel consumption consistent with AB1493 requirements. Impact on all model year fleet mix was calculated with average vehicle roll in and retirement matrix.

2. Gasoline fueled NCAT + CAT, diesel fueled DSL

3.2 Light Duty Vehicles

According to the U.S. EPA, after a surge in average fuel economy during the late 70's and gradual increases during the 1980's, average fuel economy has been on the decline. Though per-vehicle fuel economy has remained steady or only slightly decreased, the market shift to heavier SUVs and light trucks in the 1990's has brought the overall average down about 2 mpg to 24.6 mpg (Heavenrich 2006). Figure 3-1 shows the average fuel economy trends for California vehicles for the past 30 years. Fuel economy increased rapidly in the late 70's and then improvements in passenger car and light truck classes have been zero or modest. The weighted average[1] fuel economy of passenger cars and trucks has declined because of the growth in light truck populations. As shown in Figure 3-2, most passenger cars sold in the U.S. achieve between 22 and 36 mpg, with a small percentage achieving more or less than this range.

Similarly, over 80 percent of light trucks achieve between 15 and 23 miles per gallon, with most of the rest achieving up to 32 mpg. This sales fraction data is useful in determining the possible shifts in fuel economy trends.

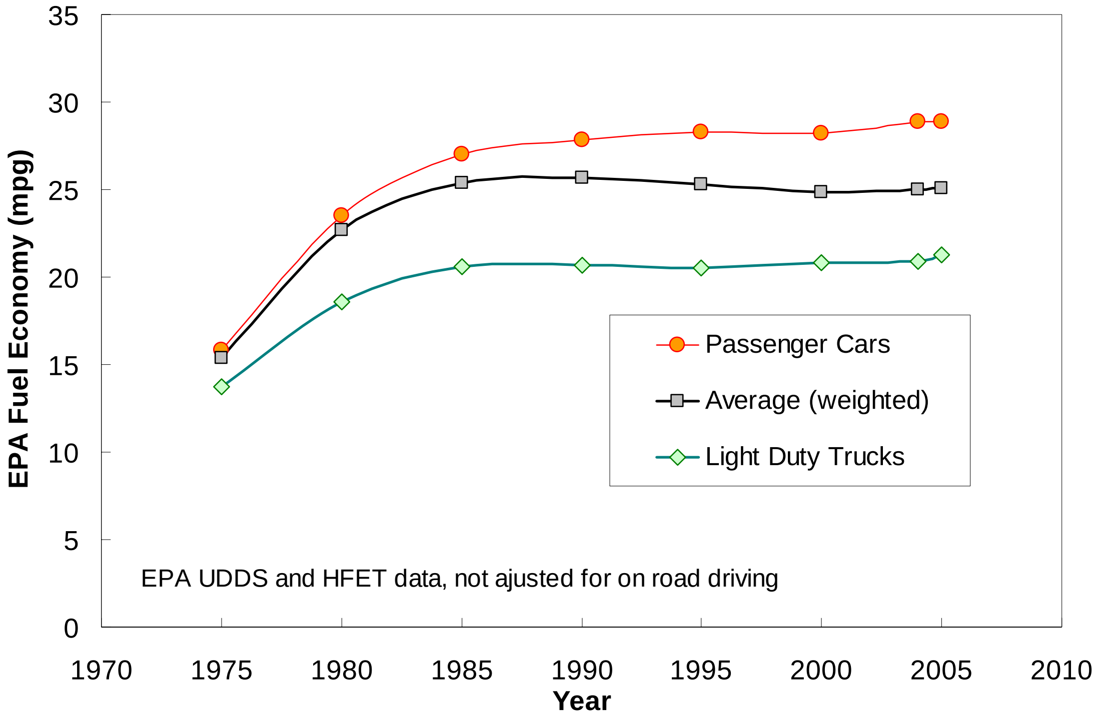


Figure 3-1. Fuel Economy of California's New Vehicles, Source California Energy Commission

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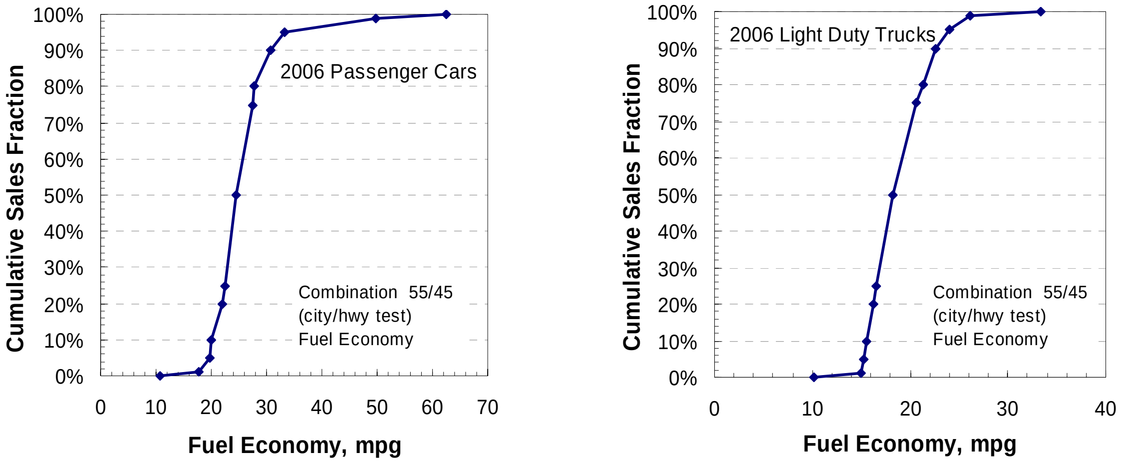
[1] Harmonically weighted average, vehicle population x gallons/mile



Source: Heavenrich 2006

Figure 3-2. Sales Fractions of 2006 U.S. Passenger Cars and Light-Duty Trucks by Fuel Economy

3.2.1 Alternative-Fueled Vehicle Energy Consumption

To compare the fuel cycle of a new alternative vehicle to the conventional vehicle it replaced, it is important to know the fuel economy of both. However, determining the fuel economy of the replaced vehicle is no small task, and it can be estimated in two ways. First, the replaced vehicle could simply be the average vehicle in the entire fleet. Alternatively, one could use the fuel economy of the *class or size* of the replaced vehicle as the baseline. The second method provides a better “apples to apples” comparison and is used in this study.

Fuel Consumption Data and Projections

The U.S. EPA reports fuel economy for all certified vehicles. The U.S. EPA Fuel Economy Guides were used to determine fuel economy for current vehicles. Limited production alternative fuel vehicles are also certified and listed in the Fuel Economy Guide. Advanced technologies, such as fuel cells are at the prototype stage, but some tests and model predictions have been made relative to their fuel economy. These sources combined with consultations with stakeholders were used to develop comparisons of fuel consumption used in a 2001 ARB study (Unnasch 2001). This analysis took into account the limited data from alternative fueled vehicles as well as carmakers assessment of the relative changes in alternative fuel and gasoline technology.

Using undiscounted fuel economies[2] the average fuel economy was compared for a variety of different alternative fuel vehicles. To account for real world conditions, this certification fuel economy should be discounted by about 15 percent[3]. Other studies use drive cycle modeling of a specific vehicle platform to compare fuel consumption of different fuel options (Brinkman 2005, Choudhury 2002, EUCAR 2003, Weiss 2003). (See Section 3.2.8.)

Comparison of Alternative Fueled and Gasoline Vehicles

Fuel economy estimates for alternative fuel technologies were derived from comparisons of existing vehicles and model estimates. These comparisons were made for vehicles that are close to identical except for fuel. A consistent set of fuel economy estimates was determined by investigating the ratio of energy economy (mi/Btu or miles per gasoline gallon equivalent (mpgge) for alternative vehicles to comparable gasoline vehicles. These energy economy ratios (EERs) were then applied to a single baseline gasoline fuel economy.

The comparison of fuel cycle emissions is intended to represent vehicles that could achieve vehicles that could be sold in the market to retail customers. These comparisons would then represent vehicles in similar classes and performance capabilities. This is not necessarily straightforward, as various vehicles have different attributes that are particular to the technology and are not be replicated in another vehicle technology. This issue will be discussed further in the following subsections.

It is anticipated that the fuel consumption values will be used as baseline estimates for the full fuel cycle analysis. Therefore the energy consumption comparisons will have a lasting impact on the perceived benefits of different transportation options. Policies that affect vehicles could take into account future certification test data for energy consumption for each vehicle type and relate any incentives to actual vehicle performance. Therefore, any projections in improved vehicle fuel consumption for alternative fueled vehicles should be conservative in order to protect the environment from increased in full fuel cycle emissions due to vehicle operation.

Figure 3-3 shows the EERs for passenger cars. The approach for determining EERs, and future vehicle trends, was extensively reviewed by a technical advisory committee (TAC) including state agencies, carmakers, and fuel providers in 2001. The values for hydrogen and electric cars have been reexamined an adjusted to reflect newer data and modeling results. The following discussion identifies basis for the EER values.

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[2] The EPA Fuel Economy Guide lists discounted fuel economy results to account for real world driving. Undiscounted values are published at EPA's Fuel Economy website (www.fueleconomy.gov). Undiscounted values provide a better comparison among various alternative technologies and fuels because the sticker value reported in the fuel economy guide is only reported to two significant

[3] EPA's adjustment for on-road driving is City FE x 0.9 and Highway FE x 0.82.

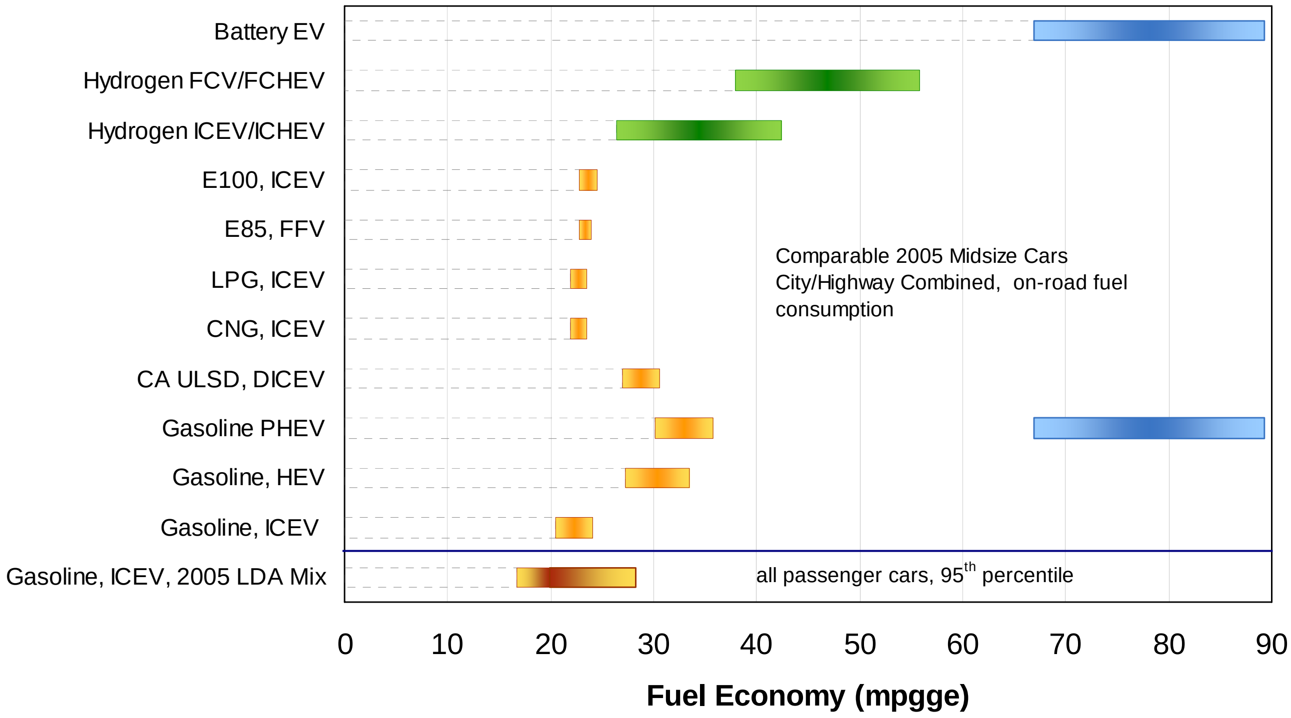

Figure 3-3. Fuel Economy Comparisons for Midsize Cars[4]

As discussed in the following sections, these EER values take into account future improvements in both IC engine and electric drive technology. The values in Figure 3-3 are generally consistent with all but the comparison of battery EVs in Section 3.2,7; The analysis is applied to midsize cars, which are larger than typical EVs[5]; therefore, the on-road mileage is lower than that of some EVs in use today.

Table 3-3 shows the EER values and corresponding energy consumption in gasoline equivalent miles per gallon and MJ/mi. Note that the equivalent gallon here contains 119 MJ, which is consistent with on-road RFG. The volumetric fuel consumption for the alternative fueled vehicles varies in proportion to the fuel's heating value (see WTT report).

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[4] On-road fuel economy values. This value is consistent with the CalCars and EMFAC estimates for in-use operation, which is about 15 percent lower in fuel economy than the EPA city/highway test data. The values here are based on EERs and applied to a single baseline vehicle. Therefore, the fuel economy for electric vehicles is lower than that typically observed by EV drivers, as many of these vehicles are not midsize cars. This study does not address the issue of an alternative fuel customer buying a vehicle in a different class than the baseline gasoline.

[5] A separate comparison of subcompact gasoline cars could be made with EVs. In this case the in-use gasoline fuel economy would be up to 30 mpg with EV equivalent fuel economy of 108 mpgge or 0.31 kWh/mi (AC power).

Table 3-3. Energy Consumption for Passenger Cars

Technology	Energy Economy Ratio (EER)			Energy Consumption	
	Baseline	Low	High	(mpgge)	(MJ/mi)
Gasoline, ICEV, 2005 LDA Mix	—	—	—	20.8	5.71
Gasoline, ICEV	1.0	0.92	1.08	22.33	5.33
Gasoline, HEV	1.35	1.22	1.5	30.14	3.95
Gasoline PHEV	1.40	1.35	1.6	31.26	3.81
ULSD, DICEV	1.25	1.21	1.37	28.80	4.13
Biodiesel - BD20, DICEV	1.25	1.21	1.37	28.80	4.13
FT Diesel – FT30, DICEV	1.25	1.21	1.37	28.80	4.13
CNG, ICEV	1.0	0.98	1.08	22.33	5.33
LPG, ICEV	1.0	0.98	1.08	22.33	5.33
E85, FFV	1.03	1.02	1.06	23.00	5.17
Ethanol, dedicated ICEV	1.07	1.03	1.1	23.89	4.98
Hydrogen ICEV/ICHEV	1.3	1.18	1.9	29.02	4.10
Hydrogen FCV/FCHEV	2.0	1.7	2.5	44.65	2.67
PHEV Grid mode	3.6	3.0	4.2	80.38	1.48
Battery EV	3.6	3.0	4.2	80.38	1.48

Sources Unnasch 2001, EPA Fuel Economy Guide, EPRI 2001, EPRI 2003, Unnasch 2005, Brinkman 2005.

The purpose of the midsize baseline in Figure 3-3 is simply to present a comparison in miles per gasoline equivalent gallon that represent vehicle technologies that might be built with all of the fuel options represented here. The relative comparison among alternative fuels is not expected to change significantly within comparable light-duty vehicles.

3.2.2 Advanced Gasoline Technologies

The comparison of alterative fueled technologies to gasoline vehicles is complicated by the steady improvement in gasoline vehicle fuel economy. Improvements in gasoline vehicle technology can include engine modifications such as:

- Variable valve timing
- Fuel injection
- Rich/lean combustion strategies
- Cylinder deactivation at low load (displacement on demand, DOD)

- Reduced throttle losses though direct injection (DI)
- Engine downsizing for hybrid strategies

Other improvements in vehicles can also reduce fuel consumption including:

- Light weight materials
- Reduced drag coefficient
- Low rolling resistance tires
- Hybrid drive train

GM analyzed a variety of alternative fuel and gasoline technologies in their well to wheels studies (Choudhury 2002, GM, Brinkman 2005). They modeled the performance of different vehicle and drive train technologies using a drive cycle analysis approach. The results are shown in Table 3-4 for the most recent study. The projections in gasoline vehicle fuel consumption in Tables 3-1 and 3-2 are consistent with the potential for fuel economy improvement shown here.

Table 3-4. Technology Options for Gasoline Vehicles

Gasoline Technology	Fuel Economy (mpg)	Change
SI ICE, No DOD	20.2	-5%
Baseline SI ICE	21.3	0%
DI SI	24.2	14%
DOD SI HEV	26.5	24%
DI SI HEV	29.2	37%

SI= spark ignited, DOD = displacement on demand (cylinder deactivation), DI = direct injection

Source: Brinkman 2005

A variety of hybrid drive strategies can improve vehicle fuel economy. The extent of hybridization is generally reflected by the electric motor size and battery storage. Mild hybrid strategies involve replacing the flywheel with an integrated starter motor (about 10 kW). More extensive hybrid strategies involve higher power motors, integrated hybrid transmissions, and 300 Volt battery systems. Improvements range from 10 to 60 percent (Greene 2004, Duleep 2005, EPRI 2001)

3.2.3 Diesel Vehicles

While diesel engine offer significant improvement over today’s gasoline engines, diesel vehicles are generally not considered an option for displacing gasoline vehicles

because of the challenges in meeting NO_x and PM emission standards. Diesel vehicles might be certified in higher emission categories than the average gasoline vehicle. More lower emission gasoline vehicles (such as PZEVs) would need to be built to arrive at a composite emission rate that complies with ARB requirements. Therefore, no change in criteria pollutant emissions should be assumed for scenarios where diesel passenger cars replace a baseline gasoline vehicle. Diesel vehicles also serve as an option for the use of alternative fuels such as biodiesel and FT diesel.
Only Volkswagen currently produces light-duty diesel vehicles in the United States. Three models of diesel vehicles were compared against their gasoline counterpart, namely the Golf, Jetta, and New Beetle. Comparisons of these vehicles with similar gasoline vehicles resulted in an EER of 1.37.

The Commission examined 176 European direct-injected diesel vehicles and compared them against 831 European gasoline vehicles of the same class. This resulted in an EER of 1.21. Thus the range of EERs for future diesel vehicles was assumed to be 1.21 to 1.37. Improvements in gasoline engine technology will close the gap between gasoline and diesel fuel consumption. A direct injected gasoline vehicle could achieve essentially the same fuel consumption (on a MJ/mi basis) as a diesel vehicle according to the modeling results from GM (Table 3-3).

3.2.4 E85 Flexible Fuel Vehicles

E85 is a relatively high-octane (rating of 105) fuel that contains 72 percent of the energy in gasoline on a volumetric basis (approx. 82,000 Btu per gallon, compared to 114,000 Btu/gal for gasoline certification fuel (indolene). The fuel economy data for E85 passenger cars is reported in the EPA Fuel Economy Guide. For E85 FFVs, the data are reported for the vehicle operating on gasoline as well as the vehicle operating on E85. Results are presented in miles per actual gallon showing the sticker value (reported with two significant figures). A comparison of the data shows that on average an FFV traveling on ethanol requires 1.34 gallons of ethanol or 1 gallon of gasoline to drive the same distance. This value is referred to as the fuel substitution ratio. This figure is based on the average fuel substitution ratio for 31 FFVs and agrees with similar calculations performed for prior model years (Unnasch 2001). When compared on an energy equivalent basis, the energy consumption on E85 is 3 percent lower than that of FFVs operating on gasoline[6] supporting an EER value of 1.03.

The improvement in performance has been attributed to a variety of factors including charge air cooling and higher octane number than gasoline. The latent heat of vaporization of ethanol is about six times as high as that of gasoline. This fuel property results in increased cooling of air entering the cylinder as well as during the compression stroke. The decrease in air temperature increases the density of the air

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[6] The energy content of gasoline is higher than E85 by a factor of 1.39 (1/0.72). The accuracy of the 3 percent improvement is about 1 percent (likely fuel efficiency improvement is 2 to 4%) due to uncertainties in the test fuel's exact composition, heating value, variations in vehicle performance, and reporting of fuel economy with only 2 significant figures of precision.

charge and results in less work required by the piston. Newer engines with knock detectors can take advantage of the higher octane number of E85. Timing can be advanced to the onset of knock, which results in more efficient engine operation. The energy consumption is also improved for FFVs operating on E85 for similar reasons.

3.2.5 CNG and LPG Vehicles

Fuel economy for LPG vehicles was estimated from existing CNG vehicle data. No EPA certification data was available for existing identical LPG and baseline gasoline vehicles. An EER range of 0.98 to 1.08 was estimated for CNG and CPG vehicles. LPG has an octane number greater than gasoline but lower than CNG and a lower weight fuel system.

EER values ranging from 0.93 to 1.01 are observed for certified CNG vehicles in the EPA Fuel Economy Guide. CNG vehicles weigh more than gasoline vehicles because of the heavier fuel tank. However, the high octane number of methane and potential for lean operator in some driving modes. allows carmakers to potentially build a more efficient engine. An EER of 1.0 was assumed for CNG and LPG vehicles based on inputs from carmakers and effecting the trend towards more advanced CNG fuel systems.

3.2.6 Hydrogen Vehicles

This section summarizes a survey of the estimated and projected mileage and range of hydrogen-fueled vehicles, all of which are in the demonstration stage of development. Since these are not production vehicles, and since in most cases, formal fuel economy testing has not been done. Published papers, press releases, and private communication with manufacturer representatives provide the basis for the information here.

Table 3-5 describes the storage, mileage, and range for a variety of hydrogen-fueled vehicles. The first three rows are vehicles powered by H_2-fueled IC engines; the Ford H2RV is a hybrid drivetrain, but the other two H_2-engine vehicles have conventional drivetrains. The rest of the vehicles are powered by H_2 fuel cells with hybrid-electric drivetrains. It is important to reemphasize that most of these vehicles are experimental prototypes developed to prove out new technologies, and in many cases, the vehicles have not been optimized for many of the functional characteristics of high volume production vehicles such as fuel economy, range, package space and other key customer attributes. Because most of these vehicles are development prototypes (some are one-of-a-kind prototypes), extreme care must be taken in drawing any conclusions regarding the capabilities of future production-intent vehicles, and in comparing one prototype in the matrix to another. In addition, few of these vehicles have been subjected to rigorous testing to confirm the characteristics shown in the matrix below. These data provide only limited insight into the relative comparison with basline gasoline vehicle because they are not tested on EPA driving cycles. A more detailed evaluation of the vehicle data is described by TIAX, Sandia National

Laboratory, as U.C. Davis as part of the California Hydrogen Highway Blueprint Plan (Unnasch 2005).

Table 3-5. Estimated Mileage and Range for a Collection of Vehicles

Vehicle	Storage Mode	H_2 (kg)[a]	Mileage[b] (mpgge)	Range (miles)	Reference
Ford P2000 – ICE [c]	3600 psi	1.5	36.8	70	Szqabowski
Ford H2RV	5000 psi	2.8	45	125	Ford
BMW 750hL – ICE	Liquid	9.9	22	218	CNN 2001
ECD/Quantum modified ICHEV [d]	MH	3.0	44.3 - 54	132	Ovonic
Ford Focus FCV	5000 psi	4.3	47	200	Fuel Cell Industry 2002
Toyota FCHV	5000 psi	3.1	57	180	Scott, Yamaguchi
Honda FCX[e]	5000 psi	3.6	67.9	210	Yamaguchi, EPA FEG 2004, 2006
DOE Validation Program—Dynamometer/Sticker	5000 psi	3-5	49.5-68	101-190	Wipke
DOE Technology Validation Program—On-road			30.5-46	80-160	
Chrysler Natrium	$NaBH_4$	10	30	300	Jost
GM HydroGen3	Liquid	4.5 4.8	55 50	250 240	Jost, Calstart
GM HydroGen3	10,000 psi	3.1	55	170	Fuels and Vehicles 2003
GM Hy-wire	5000 psi	2	40	80	Markus

[a] Hydrogen storage based on values in references. Methods for determining mass of hydrogen storage, which depend on fueling protocol and other parameters, differ among the range of information sources.

[b] Fuel consumption in miles per gasoline equivalent gallon. 1 gge ≅ 119 MJ. This value differs among the references cited. 1 kg hydrogen contains 120 MJ on and LHV basis. Basis for fuel economy including driving cycle vary among the references.

[c] City/Highway/Combined values are 31.4/46.7/36.8

[d] City/Highway/Combined values are 42.3/46.1/43.9 mi/kg. Vehicle was tested with antilock braking system disabled in order to enable testing on dynamometer. This modification also disabled the function of regenerative braking in the modified hydrogen vehicle. Developers estimate a 10 mi/kg improvement in fuel economy if regenerative braking were functioning during dynamometer test. Combined fuel economy of 49 mpg was achieved

[e] Fuel economy date from EPA Fuel Economy Guide. City/Highway/Combined values published in the Fuel Economy Guide are 62/51/57 (mi/kg). These values are adjusted (90% city, 78.8% highway) to reflect the lower fuel economy achieved during on road driving compared with dynamometer test results for the city and highway driving cycles. Fuel economy results without the adjustment factors is 67.3 mi/kg.

Today's hydrogen vehicles do not achieve the potential of modeling assessments for a variety of reasons. Most projections of hydrogen vehicle fuel consumption are based on their potential as fully developed vehicles. These estimates for future vehicles assume optimized integration of components like compressors, power electronics, and cooling systems. Ideal packaging and heat recovery from the fuel cell are also assumed. Other important factors such as the fuel cell operating voltage, pressure, and temperature capability affect the overall efficiency of the fuel cell and combined vehicle system.

Hydrogen ICE vehicles were estimated to be 1.3 times more efficient than gasoline vehicles for a comparable drive train configuration. If a hybrid gasoline vehicle and hybrid hydrogen vehicle were compared the relative benefit would be similar. The full fuel cycle analysis does not cover situations where a hydrogen ICE vehicle developer employs technology above and beyond what is considered standard for the gasoline vehicle. However, the analysis tools and results from this study can be applied to such vehicles.

Advanced Technology Hydrogen Vehicles

Hydrogen vehicles could exceed the assumed 1.3 EER with some of the following technological approaches:

- Large battery hybridization
- Plug-in hybrid operation
- Reduction in weight, size, and drag

To the extent that such improvements are not commercially available in gasoline ICEVs, an advanced hydrogen vehicle could achieve more favorable fuel economy comparisons.

A comparison issue arises when considering the hydrogen fuel cell vehicle. A variety of fuel economy improvements are projected for fuel cell vehicles depending on their technology maturity and degree of battery hybrid integration. When compared to a gasoline ICE, fuel cell vehicles could achieve a 1.8x to 2.5x improvement in energy efficiency. This relative ranking would be lower when compared to a gasoline HEV, however, not all gasoline vehicles will be HEVs. The baseline fuel efficiency improvement for hydrogen FCVs used in the analysis is 2.0 times that of the gasoline vehicle. Again, this value can be adjusted on a case-by-case basis with actual vehicle data. The energy consumption for electric drive vehicles may also need to be considered for plug-in hybrid vehicles. Again a wide range of energy consumption values are reported, depending on the vehicle technology, driving range, and other factors. An EER value of 2.0 was also agreed as an acceptable baseline value for hydrogen fuel cell vehicles in the California hydrogen Highway Blueprint plan (Unnasch 2005).

Should the hydrogen ICE vehicle employ technology above and beyond what is considered conventional technology, then the actual certified test results would reflect these improvements. Such vehicles could benefit from future policy actions that provide benefits in proportion to full fuel cycle emission benefits.

3.2.7 Electric Vehicles

The EER comparison of electric and gasoline vehicles was examined to reflect data from recent electric vehicles. Unfortunately energy consumption data for electric vehicles is not available from comparable test methods with gasoline vehicles. EPA certification data was available for vehicles built by carmakers in 1999 and 2000. Even this data is difficult to interpret because of the wide range in vehicle charging that can be accomplished within the test procedure.

The comparison of fuel cycle emissions in the 2001 ARB study was intended to represent a significant volume of vehicles that could be certified as PZEVs. In principal this assumption could require electric vehicles to have 300 mile range and the same cargo capacity as gasoline vehicles. Therefore some stakeholders argued that the EER comparison should take into account expanding the battery capacity and vehicle weight for electric vehicles.

Table 3-6 shows EER comparisons between battery EV and gasoline vehicles from a variety of sources. EPA certification data is shown for 1999 and 2000 vehicles. The EPA data is compared for the city and highway combined drive cycle results, without adjustment for on-road driving for both the gasoline and electric vehicles. Other data was provided by Southern California Edison based on vehicles that were operated in a test loop. Finally, DC power consumption was adjusted by estimates of charger efficiency to project the on-road fuel consumption for three vehicles. Five million miles of Toyota RAV data were collected in a survey by the EAA and a charger efficiency of 85 percent was assumed (Freund 2006). Similar estimates were made for and AC Propulsion and Tesla Motors vehicles. These vehicles were compared with EPA certification data adjusted for on-road driving.

A series of GM EV1 data is compared. The vehicle performance with improved battery technology is also projected. In the case of the EV1, the questions of a baseline vehicle makes an assessment of the EER difficult so a range of gasoline cars are shown here[7]. The EV1 was tested against an Acura by SCE, so the EER calculations are compared for these two different vehicles. Other suggest that the EER comparison covering a wide range of fuel consumption ranging from a GM Metro two seater to a Mazda Miyata two seater.

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[7] Mazda Miyata: 25.3 mpg, Acura: 31.9 mpg, Geo Metro: 46 mpg.

Table 3-6. EER Calculation for Battery Electric Vehicles

Electric Vehicle	Data Source	Electric Energy Consumption		Gasoline Comparison Vehicle	Data Source	Gasoline FE (mpg)	EER
		(kWh/mi)	(mpgge)				
'06 Telsa Roadster - LiON	Tesla Motors	0.205	163.4	'06 Lotus Elise	EPA On Road	25.0	6.53
'06 ACP eBox LiON	AC Propulsion[1]	0.259	129.3	'06 Scion xB	EPA On Road	31.0	4.17
'99 Toyota RAV4 - NiMH	SCE Test Loop	0.382	87.7	'99 Toyota RAV4 - 2WD - Auto 2.0L	SCE Test Loop	27.9	3.15
'03 Toyota RAV4EV	EEA Survey [3]	0.2935	114.1	'03 Totota RAV4 - 2WD - Auto 2.0L	EPA On Road	26.0	4.39
'04 GM EV-1-LiON	EEA Projection [2]	0.205	163.4	'99 Acura Integra - Auto - 1.8L	EPA Unadjusted	31.9	5.12
'99 GM EV-1 - NiMH - without parasitic load	EEA Projection [4]	0.273	122.8		EPA Unadjusted	31.9	3.85
'99 GM EV-1 - NiMH - 102 kW	EPA Unadusted	0.321	104.4		EPA Unadjusted	31.9	3.27
'99 GM EV-1 - PbA - 102 kW	EPA Unadusted	0.280	119.6		EPA Unadjusted	31.9	3.75
'99 GM EV-1 - NiMH - 102 kW	SCE Test Loop	0.299	112.1		SCE Test Loop	31.9	3.51
'99 GM EV-1 - PbA - 102 kW	SCE Test Loop	0.283	118.3		SCE Test Loop	31.9	3.71
'00 Ford Ranger - PbA	SCE Test Loop	0.434	77.1	'00 Ford Ranger - 2WD - Auto 2.5L	SCE Test Loop	25.5	3.03
'00 Ford Ranger - NiMH	SCE Test Loop	0.428	78.2		SCE Test Loop	25.5	3.07
'00 Ford Ranger - PbA	EPA Unadusted	0.405	82.7		EPA Unadusted	25.5	3.24
'00 Ford Ranger - NiMH	EPA Unadusted	0.421	79.5		EPA Unadusted	25.5	3.12
Midsize PHEV60	ADVISOR model, EPRI 2003	0.285	117.2	Midsize V6 127 kW	ADVISOR model, EPRI 2003	28.9	4.06
SUV PHEV60		0.433	77.1	SUV, V8 212 kW		18.3	4.22

1) Data provided by AC Propulsion 11/9/2006

2) Data extrapolated from using Tesla pack in EV1

3) EAA survey of 132 vehicles (over 5 million miles traveled) yielded 0.245 kWh/mi DC, AC factored = 0.289

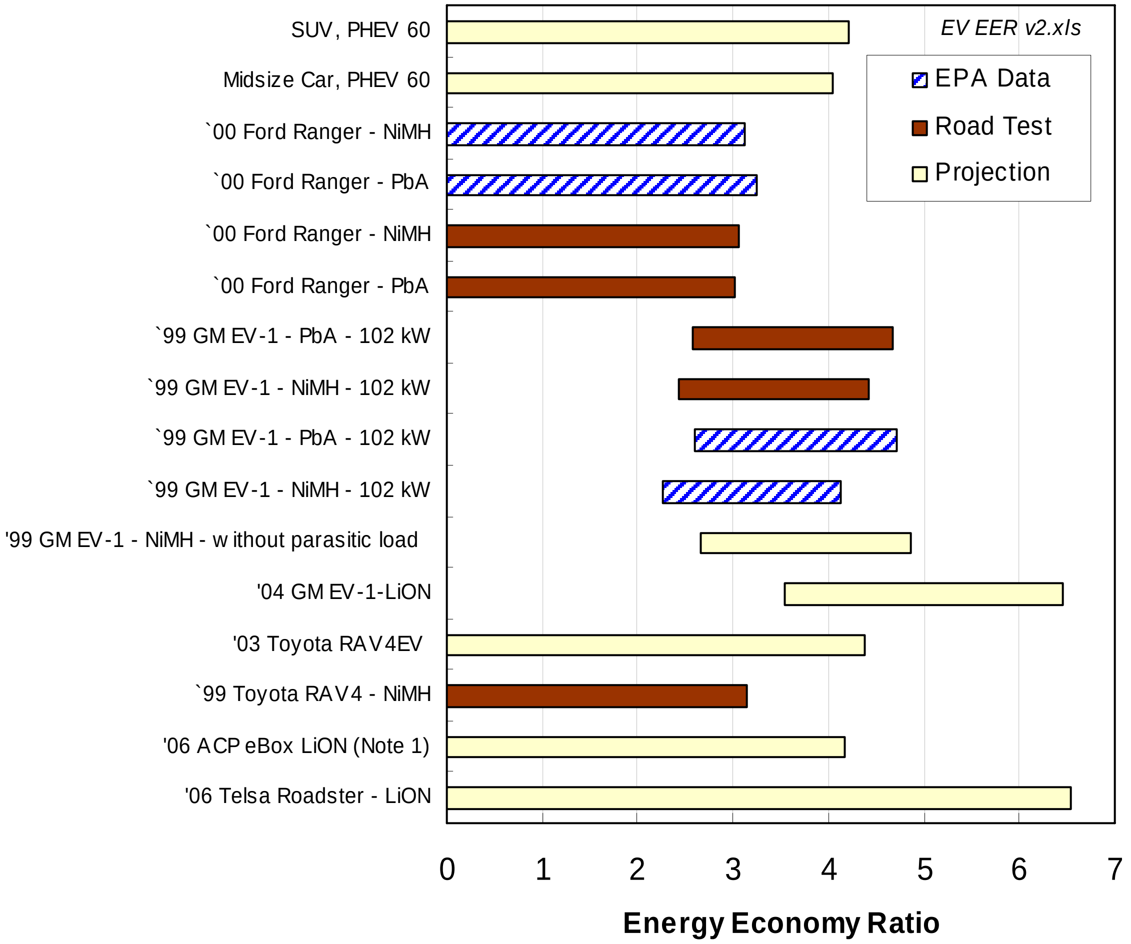

Figure 3-4. Comparison of EER Values for Electric Vehicles

Plug in hybrids are also an option for electric transportation. These vehicles have been extensively examined by stakeholder groups led by EPRI (EPRI 2001, 2002, 2003). These efforts included collaborations with researchers and automakers to analyze the configuration and energy consumption of plug in hybrids. These studies considered PHEVs with an all electric operation mode where the vehicle is capable of operating at speeds up to 65 mpg on the battery charge. Examples of the modeling analysis from the EPRI report are shown in Table 3-6 for a midsize car and SUV. Since these analyses were performed for vehicles with all electric driving capability, the energy consumption would be similar for an battery EV. The weight of the batteries would increase but the vehicle would not include a gasoline engine.

More recently, PHEVs have been built to operate with smaller electric motors that do not offer full all electric drive capability. These are conversions of gasoline HEVs such as the Prius. The vehicles operate in a blended mode where electric power and gasoline contribute to driving most of the time. The Sacramento Municipal Utility District is performing a series of tests on these vehicles against comparable gasoline hybrid vehicles. EPRI is also analyzing them. The data from this effort will be available in 2007. As the data from PHEVs in blended mode is not published, Figure 3-5 illustrates how the energy consumption could be provided as an input to the full fuel cycle analysis.

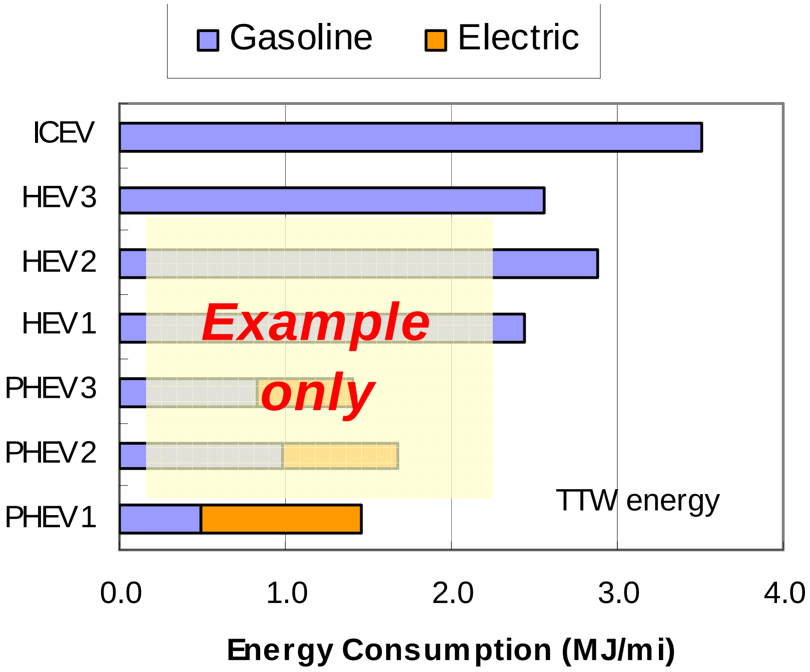

Figure 3-5. Example of Method for Comparing PHEV Energy Consumption with Blended use of electricity and Gasoline

3.2.8 Comparison with Other Studies – Light-Duty Vehicle Energy Consumption

Several fuel cycle studies have estimated the fuel consumption for alterative fueled vehicles as shown in Table 3-7. The GM WTW studies have included drive cycle modeling for both European and U.S. vehicles and driving cycles based on engine maps and vehicle configurations using GM's in-house model. The EUCAR study also included drive cycle modeling based on engine maps. The gasoline energy consumption divided by the energy consumption of the alterative fueled vehicle provides the EER comparisons from these studies. The EER inputs for GREET are also shown. The EER values that are used in the TTW analysis draw on both the comparable vehicle comparisons described previously, automaker inputs, and comparison with modeling studies. The values shown for the vehicle modeling depend on the assumptions for engine maps and vehicle weight, which accounts for discrepancies between the modeling results and actual vehicle data. The most notable disparity between modeling results and vehicle data occurs with hydrogen vehicle where many of the vehicles are assembled with prototype parts that are quickly evolving and not fully integrated with auxiliary components such as air compressors. For the modeling studies, the EER comparisons are similar among the studies cited even though the vehicle platforms differ. The most important factors that affect the relative differences are:

- Baseline gasoline engine technology
- Hybridization of FCV system
- Ideal weight for components (assumed in all the studies)
- High temperature membranes, which reduce balance of system weight and improve FC efficiency

Table 3-7. Comparison of EER Values with Other Studies

Technology	This Study Baseline	GREET 1.7 NT & LT	GM2003			EUCAR EER
			Baseline	Low	High	
Gasoline, ICEV	1.0	1.0	1.0	0.95	1.052	1.0
Gasoline, HEV	1.35	1.35	1.24	1.15	1.56	1.3
Gasoline, PHEV	1.40	1.52/1.82	—	—	—	—
Diesel, DICEV	1.25	1.49/1.68	1.21	1.18	1.27	1.25
CNG, ICEV	1.0	1.03/1.05	0.986	0.93	1.038	1.0
LPG, ICEV	1.0	1.05	—	—	—	1.0
E85, FFV	1.03	1.05	1.0	0.95	1.052	1.03
Ethanol, dedicated ICEV	1.07	1.07	—	—	—	—
Hydrogen, ICEV	1.3	1.2/1.3	1.20	1.14	1.26	1.3
Hydrogen, FCV	2.0	2.32/2.64	2.36	2.24	2.56	2.4
PHEV, Grid Mode	3.6	3.0	2.46	2.63	2.81	—
Battery EV	3.6	3.5	—	—	—	—

A significant variation in the EER values is also observed among conventional ICEVs. For example E85 vehicles in some modeling studies show no improvement in fuel economy. The engine map that is an input to the analysis has the same efficiency parameters as that of the gasoline vehicle, so the result is not surprising. Major WTW studies have not placed the same emphasis on modeling the energy consumption of electric vehicles. The most significant modeling study is the series of EPRI reports on PHEVS. The results for the vehicles with the largest battery (PHEV60) result in EERs in of about 4.1.

3.3 Heavy-Duty Vehicles

The comparison of energy consumption for heavy-duty vehicles is shown in Table 3-8. These values are based on more limited modeling studies and a review of data from natural gas vehicle operation (Jackson). EER values of 0.85 to 0.9 have been observed for gaseous fueled vehicles from demonstration tests and dynamometer testing. The trend for CNG and other gaseous fuels is towards higher pressure fuel injection systems and improvements in efficiency compared with baseline diesel vehicles (Eaves 2006). Meanwhile, the fuel economy of diesel vehicles is expected to decline by up to 5 percent as technologies such as particulate traps are incorporated to meet new emission standards. The EER values in Table 3-8 reflect a comparison of future gaseous fueled vehicles compared with diesel vehicles with exhaust after treatment. Some developers argue that the EER should be closer to 0.95 for CNG vehicles with high pressure injection technologies. However, there is no guarantee that all vehicles will be equipped with these technologies and data on fuel consumption is still being compiled. Therefore, the WTW analysis is based on the EER values in Table 3-8. As in the case of hydrogen ICEVs and all other technologies, policies could be developed to measure WTW impacts based on actual vehicle performance.

Limited data is available on methanol and hydrogen fuel cell buses. The values in Table 3-8 are based on limited modeling studies.

Table 3-8. EER Estimates for Heavy-Duty Vehicles

Technology	EER
Diesel, DICEV	1
Diesel, DHEV	1.25
Gasoline, HEV	1.1
LPG, ICEV	0.94
CNG, ICEV	0.94
LNG, ICEV	0.93
FT30, ICEV	1
BD20	1
Methanol, FCV	1.3
Hydrogen ICEV	1.1
Hydrogen FCV	1.5
Battery EV	2.7

Other studies have estimated the energy consumption of heavy-duty alternative fueled vehicles. These include both fuel cycle analyses (HD option in GREET (Wang 2005, Unnasch 1998), as well as cost studies for heavy-duty vehicle operations. The data and analysis on a wide range of heavy-duty vehicle options is limited. With the wide range of engine configurations and packaging options available to heavy-duty vehicles and relatively limited test data, the uncertainty in fuel economy comparisons is larger than that of light duty vehicles. Based on the published data and analysis, the authors estimate the uncertainty associated with energy consumption to be 1 to 5 percent (expressed on an EER basis), with the lower range of uncertainties applying to diesel fuel blends.

3.4 Off-Road Applications – Energy Consumption

The California off-road inventory of engines was obtained from ARB for the years 2005, 2012, 2017, 2022, and 2030. The activity and fuel consumption of the total inventory of engines in California for the year 2012 is summarized in Table 3-9. Of this inventory, the identified vehicle population's (see Section 2.2) activity and fuel usage is presented in Table 3-9. California's off-road vehicle population is approximately 6 percent of the total off-road engine inventory, but it consumes about 32 percent of the fuel. A contributing factor is due to the high usage of engines. Approximately 56 percent of all activity is from the vehicle population.

Table 3-9. Off-Road Equipment Fuel Consumption in California, 2012

Fuel	Population	Activity (hr/day)	Fuel Consumption (gal/day)
Total Off-Road Engines			
CNG 4-stroke	31,053	147,569	356,291
Diesel	626,990	1,291,281	4,304,145
Gasoline 2-stroke	9,104,554	1,853,755	455,430
Gasoline 4-stroke	9,314,537	2,901,473	1,163,787
TOTAL	19,077,134	6,194,077	6,279,653
Off-Road Vehicles			
CNG 4-stroke	29,510	143,286	321,383
Diesel	218,429	355,394	1,264,556
Gasoline 2-stroke	387,517	1,117,320	182,011
Gasoline 4-stroke	559,896	1,841,132	255,328
TOTAL	1,195,352	3,457,132	2,023,277
Agricultural Equipment			
Diesel	187,441	234,604	795,228
Gasoline 4-stroke	172,504	38,031	29,537
TOTAL	359,945	272,635	824,765
Logging Equipment			
Diesel	2,786	10,135	67,186
Gasoline 2-stroke	4,656	2,628	2,414
Gasoline 4-stroke	7,305	4,843	3,162
TOTAL	14,747	17,606	72,762
Forklifts (excluding rough terrain forklifts)			
CNG 4-stroke	29,071	142,467	316,803
Diesel	5,400	26,535	65,654
Gasoline 4-stroke	15,317	75,109	154,077
TOTAL	49,788	244,111	536,534
Transport Refrigeration Units			
Diesel	69,430	266,420	293,775
Gasoline 4-stroke	5,568	11,452	6,708
TOTAL	74,998	277,873	300,483

Off road EXHAUST 2012_export tables.xls

Source: ARB Off-Road Database, selected from TTW Off_Road 2012.xls

SECTION 4. CRITERIA POLLUTANT EMISSIONS

Considerable amounts of test data and analysis have been incorporated into the estimates of vehicle emissions, particularly for California and other regional emission models. Many factors affect on-road vehicle emissions including emission certification levels, vehicle life, maintenance, and other parameters related to the operation of the vehicle. The approach for estimating emissions from vehicles differs among light- and heavy-duty vehicle and off-road applications as well as fuel types, which are all incorporated into the full fuel cycle analysis.

The scope and approach for determining TTW impacts is described in this section. First the emission sources associated with vehicle and other fuel use applications are discussed. The vehicle and other fuel use applications examined in this study are then identified. Finally the approach for determining baseline vehicle exhaust emissions, alterative fueled vehicle emissions, and water impacts are described. The list of vehicle fuel types in the evaluation are shown in Table 4-1.

Table 4-1. Vehicle Fuel Type

Abbreviation	Vehicle Fuel Types
NCAT	Baseline non-catalytic gasoline
CAT	Baseline catalytic gasoline
DSL	Baseline diesel
G0	0% Ethanol
G5.7	5.7% Ethanol
GHEV	5.7% Ethanol hybrid electric vehicle
E10	10% Ethanol
E85	85% Ethanol FFV
ULSD	Ultra low sulfur diesel
ULSD HEV	Ultra low sulfur diesel hybrid electric vehicle
CNG	Compressed natural gas
LPG	Liquefied petroleum gas
LNG	Liquefied natural gas
Methanol	Methanol
DME	Dimethyl ether
FTD 30	30% Fischer-Tropsch diesel
BD20	20% Bio-diesel
E-Diesel	Diesel with 7% ethanol
H2ICE	Hydrogen internal combustion engine
H2FCV	Hydrogen fuel cell vehicle
PHEV	Plug-in hybrid electric vehicle
BEV	Electric vehicle

4.1 On-Road Vehicles

The California on-road vehicle fleet population and its related emissions were modeled by California Air Resources Board's Motor Vehicle Emission Inventory modeling program, EMFAC 2007 production version 2.24.6. The annual average for all of California’s vehicle population was performed for the years 2005, 2012, 2017, 2022, and 2030. The main function of ARB’s EMFAC model is to generate emission factor information for the numerous vehicle classes, such as heavy-duty trucks and passenger cars

Most of the light- and medium-duty vehicle exhaust data used for modeling are collected in ARB Surveillance programs. Most vehicles are tested on a dynamometer, which simulates on-road driving. Because HDT engines may be sold independent of the chassis, HDT engines are tested on engine dynamometers, which simulate the load experienced by the engine. Individual vehicle parameters such as axle ratio, aerodynamics and gross vehicle weight are represented rather crudely by the engine dynamometer test.

Primary inputs to the model are:

- Driving activity
- Population
- Vehicle Miles Traveled (VMT)
- Vehicle starts
- Ambient temperature
- VMT by speed distribution

EMFAC produces a number of seasonal inventories for different purposes. Seasonal adjustments in the model include

- Ambient temperature,
- Humidity and the
- Reid Vapor Pressure (RVP) of dispensed fuel

Episodic inventories are needed to assess worst case conditions for ozone, high ambient temperature and low relative humidity and carbon monoxide, and low ambient temperature and high relative humidity, in order to estimate how effective adopted or proposed emission reductions strategies will be in reducing peak concentrations of pollutants. While EMFAC produces both episodic and month specific inventories, ARB considers an annual average inventory is best suited for assessing emission trends over time. (ARB 2003). Only average emissions are included in this report; however the impact among fuel options may vary by season.

The annual average calculations for California vehicles model year 2010 or newer were performed for years 2012, 2017, 2022, and 2030. The emission results (tons/day) were calculated for various weight classes for non-catalytic gasoline (NCAT), catalytic gasoline (CAT), and diesel fueled (DSL) vehicles.

4.1.1 Baseline Vehicle Emissions

The on-road emission inventory data has two parts: emissions-related and activity-related. The emissions-related data reflects new vehicle testing information and the latest vehicle registration data from the California Department of Motor Vehicles. The activity-related data are updated by the regional transportation agencies which estimate of the daily vehicle miles of travel, the distribution of travel by speed, and the number of starts per vehicle per day by year.

Evaporative emissions occur when fuels leak or evaporate from the fuel storage and delivery system. These emissions occur both during vehicle operation and when the vehicle is not being driven.

Diurnal emissions result from evaporation in the fuel system and breakthrough of vapors from the carbon canister, hoses, and connectors when the vehicle is not being operated and the ambient temperature is rising. Hot soak emissions result when vapors escape within one hour after the engine is turned off. These emissions are caused by high under-hood and fuel temperatures.

Resting loss emissions are defined as losses due to permeation of fuel through rubber and plastic components when the vehicle has not been operated for at least an hour and the ambient temperature is either constant or decreasing.

Running losses occur when hot fuel vapors escape from the fuel system or overwhelm the carbon canister while a vehicle is being operated. Evaporative emissions are measured using a Sealed Housing Evaporative Determination (SHED) Test. This test is performed by placing a vehicle in an airtight enclosure, also referred to as a shed, to capture the evaporating gases

The exhaust, evaporative, and tire and brake wear emissions used here correspond to values from ARB’s EMFAC model. The model estimates emissions on a tons/year basis taking into accounts factors such as driving patterns, trips per day, and vehicle emissions control system. The model output is typically used to determine the emissions “inventory” for a year with a mix of vehicle types and vehicle ages or model years (MY). Emission rates in g/mi were determined for a set of inventory runs by dividing total annual emissions by miles driven. The following groupings of emission rates were determined:

- New Vehicles — Introduction starting 2010 – to enable the comparison of new alternative fuel vehicles with new baseline vehicles
- All vehicles – All of the model year vehicles in the inventory to enable the — assessment of changing fuel blends

4.1.2 Gasoline and Diesel Vehicles

The EMFAC model provides the results for criteria pollutants grouped by technology (NCAT, CAT, DSL). The emissions from EMFAC 2007 used in this study are volatile organic compounds (VOC) evaporative, VOC exhaust, CO, NO_x, PM exhaust, PM due to tires and brakes, and SO_x. The results are provided in tons per day and per 1000 of miles travel for the vehicle classes in the model. TIAX developed a spreadsheet tool to store EMFAC runs and to calculate emissions on a g/mi basis for the scenario years in this study. The function of the spreadsheet is described in Table 4-2.

Table 4-2. TTW Analysis Tool for EMFAC

Worksheet Name	Function	Data Source and Inputs
TTW Input	User inputs and results. Calculates g/mi emissions for a specific vehicle class and year.	User selects vehicle class from list that corresponds to Table 2-1. Then select EMFAC Scenario Year. Choice is for all vehicles or introduction starting 2010. Multi-media impacts from Section 6 are entered here.
TTW Toxics	Calculates toxics for each vehicle option	ARB speciation database for toxic emissions (ARB 2005)
TTW Veh	Multiplies alternative fuel adjustment factors by baseline vehicle emission rates in g/mi	Select base data for each vehicle class and technology type. Also input adjustment factor for alternative fueled vehicles from Section 4.1.3
Active GPMi	Calculates emissions from the selected EMFAC scenario year on a g/mi basis	From ActiveE
ActiveE	Selects data from selected scenario year	Displays standard EMFAC output for the selected scenario year. The EMFAC outputs for each scenario year are in the worksheets to the right.

Table 4-3 shows the composite g/mi emission factors for catalyst equipped light-duty automobiles for both the entire vehicle inventory with all model years, and for vehicles introduced after 2010. The all model year grouping serves as a baseline for E85 FFVs, which are all catalyst equipped and already represent over 200,000 vehicles on the road in California.

Baseline emissions for new vehicle technologies are represented by EMFAC runs with vehicle introduction starting 2010.

Table 4-3. EMFAC Composite Emission Factors (g/mi) Gasoline LDA-CAT

Emissions, g/mi	YEAR with All Vehicle Model Years					Year with MY Starting in 2010			
	2005	2012	2017	2022	2030	2012	2017	2022	2030
VOC Evaporative	0.202	0.140	0.113	0.092	0.067	0.013	0.019	0.028	0.037
VOC Exhaust	0.286	0.142	0.088	0.059	0.035	0.013	0.015	0.017	0.021
CO	4.632	2.629	1.750	1.213	0.805	0.362	0.443	0.502	0.558
NO_x	0.431	0.223	0.140	0.093	0.059	0.026	0.031	0.035	0.039
PM Exhaust	0.011	0.013	0.013	0.013	0.013	0.004	0.007	0.010	0.012
PM Tire/Brake	0.021	0.021	0.021	0.021	0.021	0.020	0.021	0.021	0.021
Lead	0	0	0	0	0	0	0	0	0
Benzene	0.0088	0.0046	0.0031	0.0022	0.0014	0.0004	0.0006	0.0007	0.0008
1-3 Butadiene	0.0018	0.0009	0.0006	0.0004	0.0002	0.0001	0.0001	0.0001	0.0001
Formaldehyde	0.0043	0.0021	0.0013	0.0009	0.0005	0.0002	0.0002	0.0003	0.0003
Acetaldehyde	0.0009	0.0005	0.0003	0.0002	0.0001	0.0000	0.0000	0.0001	0.0001
Diesel PM	0	0	0	0	0	0	0	0	0
Lead	0	0	0	0	0	0	0	0	0

Changing the gasoline blend affects all of the vehicles. The composite emissions for all gasoline (CAT + NCAT) vehicles are shown in Table 4-4. This grouping provides an appropriate baseline for low level ethanol blends, which would affect all of the gasoline vehicles on the road.

Table 4-5 shows the emission factors for the fleet of diesel vehicles in the state. EMFAC input assumptions do not project a growth in light-duty diesel vehicles, so calculating the 2010 introduction scenario as a baseline for diesel and HEVs is not possible. However, ARB regulations place an overall cap on the emissions from light-duty automobiles, so when new diesel vehicles, presumably with higher NO_x levels than the average gasoline vehicle, are introduced to the mix of gasoline vehicles would need to be adjusted to accommodate these emission levels. Therefore, the introduction of new diesel technologies is best examined by simply comparing the fuel cycle emissions on a g/mi basis with gasoline and noting the challenges in complying with vehicle exhaust standards.

Tables 4-6 and 4-7 show the emission factors for heavy-duty trucks and urban buses. The heavy duty truck emissions are shown here because diesel trucks haul liquid fuels and the average emissions are an input to the analysis in the WTT report. The emissions from urban buses are examined in detail in the WTW report. Similar tables can readily be generated for other vehicle classes from the TTW EMFAC tool.

Table 4-4. EMFAC Composite Emission Factors (g/mi) Gasoline LDA-CAT+NCAT

Emissions, g/mi	YEAR with All Vehicle Model Years				
	2005	2012	2017	2022	2030
VOC Evaporative	0.289	0.157	0.115	0.092	0.067
VOC Exhaust	0.400	0.167	0.092	0.059	0.035
CO	5.851	2.882	1.784	1.214	0.805
NO_x	0.498	0.238	0.142	0.093	0.059
PM Exhaust	0.012	0.013	0.013	0.013	0.013
PM Tire/Brake	0.021	0.021	0.021	0.021	0.021
Lead	0	0	0	0	0
Benzene	0.318	0.319	0.308	0.162	0.0014
1-3 Butadiene	0.067	0.068	0.067	0.034	0.0002
Formaldehyde	0.227	0.231	0.230	0.116	0.0005
Acetaldehyde	0.054	0.056	0.055	0.028	0.0001
Diesel PM	0	0	0	0	0
Lead	0	0	0	0	0

Table 4-5. EMFAC Composite Emission Factors (g/mi) LDA-DSL

Emissions, g/mi	YEAR with All Vehicle Model Years				
	2005	2012	2017	2022	2030
VOC Evaporative	0	0	0	0	0
VOC Exhaust	0.209	0.176	0.148	0.104	0.000
CO	0.808	0.756	0.717	0.674	0.465
NO_x	1.482	1.462	1.458	1.452	1.628
PM Exhaust	0.150	0.113	0.099	0.104	0.104[1]
PM Tire/Brake	0.016	0.025	0.025	0.025[1]	0.025[1]
Lead	0	0	0	0	0
Benzene	0.0042	0.0035	0.0030	0.0021	0.0000
1-3 Butadiene	0.0004	0.0003	0.0003	0.0002	0.0000
Formaldehyde	0.0307	0.0260	0.0218	0.0153	0.0000
Acetaldehyde	0.0153	0.0130	0.0109	0.0076	0.0000
Diesel PM	0.1498	0.1134	0.0989	0.1037	0.0000
Lead	0	0	0	0	0

[1] EMFAC data modified for consistency with other years

Table 4-6. HHDT-DSL

Emissions, g/mi	YEAR with All Vehicle Model Years					Year with MY Starting in 2010			
	2005	2012	2017	2022	2030	2012	2017	2022	2030
VOC Evap	0	0	0	0	0	0	0	0	0
VOC Exh	1.82	1.17	0.71	0.48	0.37	0.25	0.29	0.33	0.35
CO	6.34	4.16	2.70	1.97	1.62	1.09	1.28	1.41	1.52
NO_x	21.50	13.23	7.41	4.78	3.63	2.16	2.65	3.05	3.36
PM Exh	0.982	0.531	0.283	0.167	0.114	0.067	0.084	0.095	0.104
PM Tire/Brake	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064
Lead	0	0	0	0	0	0	0	0	0
Benzene	0.0364	0.0235	0.0142	0.0096	0.0074	0.0050	0.0059	0.0065	0.0069
1-3 Butadiene	0.0035	0.0022	0.0013	0.0009	0.0007	0.0005	0.0006	0.0006	0.0007
Formaldehyde	0.2680	0.1727	0.1044	0.0709	0.0544	0.0366	0.0431	0.0478	0.0508
Acetaldehyde	0.1339	0.0863	0.0522	0.0354	0.0272	0.0183	0.0215	0.0239	0.0254
Diesel PM	0.9816	0.5305	0.2827	0.1665	0.1141	0.0668	0.0844	0.0952	0.1039
Lead	0	0	0	0	0	0	0	0	0

Table 4-7. UB-DSL

Emissions, g/mi	YEAR with All Vehicle Model Years					Year with MY Starting in 2010			
	2005	2012	2017	2022	2030	2012	2017	2022	2030
VOC Evap	0	0	0	0	0	0	0	0	0
VOC Exh	0.869	0.807	0.759	0.705	0.604	0.042[1]	0.042[1]	0.042	0.023
CO	3.988	3.656	3.277	3.005	2.376	0.885	0.967	0.975	1.003
NO_x	20.60	18.89	17.01	15.50	12.36	0.664	0.595	0.551	0.560
PM Exh	0.359	0.322	0.293	0.272	0.231	0.042[1]	0.042[1]	0.042	0.047
PM Tire/Brake	0.021	0.020	0.019	0.019	0.018	0.023[1]	0.023[1]	0.023[1]	0.023
Lead	0	0	0	0	0	0	0	0	0
Benzene	0.0174	0.0162	0.0152	0.0141	0.0121	0.0008[1]	0.0008[1]	0.0008	0.0005
1-3 Butadiene	0.0017	0.0015	0.0014	0.0013	0.0011	0.0001[1]	0.0001[1]	0.0001	0.0000
Formaldehyde	0.1279	0.1188	0.1116	0.1037	0.0889	0.0062[1]	0.0062[1]	0.0062	0.0034
Acetaldehyde	0.0639	0.0594	0.0558	0.0518	0.0444	0.0031[1]	0.0031[1]	0.0031	0.0017
Diesel PM	0.3587	0.3217	0.2933	0.2721	0.2311	0.0424[1]	0.0424[1]	0.0424	0.0466
Lead	0	0	0	0	0	0	0	0	0

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[1] EMFAC data modified for consistency with other years

The baseline vehicle emission estimates are based on EMFAC runs for the analysis years in this study. EMFAC runs were made for the entire vehicle inventory (all of the vehicles), as well as for new vehicles with an introduction date of 2010. In the case of the introduction of new vehicle technologies, where the current population of vehicles is relatively low, appropriate baseline vehicle emissions would reflect when the new vehicle technologies are first introduced. The analysis here is based on the year 2010 introduction. This analysis can also be performed for other introduction rates, but the results here reflect the trend in lower emissions from new vehicles. The analysis matrix completed incorporates the evaluation cases given in Table 4-8.

Table 4-8. Baseline Vehicles for Estimating Alternative Fueled Vehicle Emissions

Fuels	Light-Duty Vehicles			Medium- and Heavy-Duty Vehicles	
	New	Blend Displacing Gasoline	Blend Displacing Diesel	New	Blend Displacing Diesel
RFG — E0	—	A	—	—	—
RFG — E5.7	**N (CAT)**	**A (CAT+NCAT)**	—	—	—
RFG — E5.7, HEV	N	—	—	N	—
RFG — E10	N	A	—	—	—
Diesel	—	—	**A (DSL)**	**N (DSL)**	**A (DSL)**
LPG	N	—	—	—	—
CNG	N	—	—	N	—
LNG	—	—	—	N	—
Methanol	—	—	—	N	—
DME	—	—	—	N	—
FT blends (30%)	—	—	A	—	A
Ethanol — E85	—	A	—	—	—
E-diesel	—	—	—	—	A
Biodiesel, BD20	—	—	A	—	A
Electricity	N	—	—	—	—
Hydrogen ICEV	N	—	—	N	—
Hydrogen FCV	N	—	—	N	—

Baseline vehicles shown in bold
A = Average Fleet, all vehicles on-road
N = New technology

The EMFAC results were calculated for the mix of vehicle over the VMT that is predicted by EMFAC, with emissions expressed on a g/mi basis. The emission rates reflect the change in emission standards for different model years, deterioration rates, as well as the change in VMT as vehicles age. The effect of vehicle age on VMT for passenger cars is illustrated in Figure 4-1. Figure 4-2 illustrates the difference in emission rates when calculated for all of the gasoline cars and vehicles introduced in 2010 and beyond. The differences in emissions among the different light-duty vehicle classes (passenger cars and light trucks) is illustrated in Figure 4-3[8].

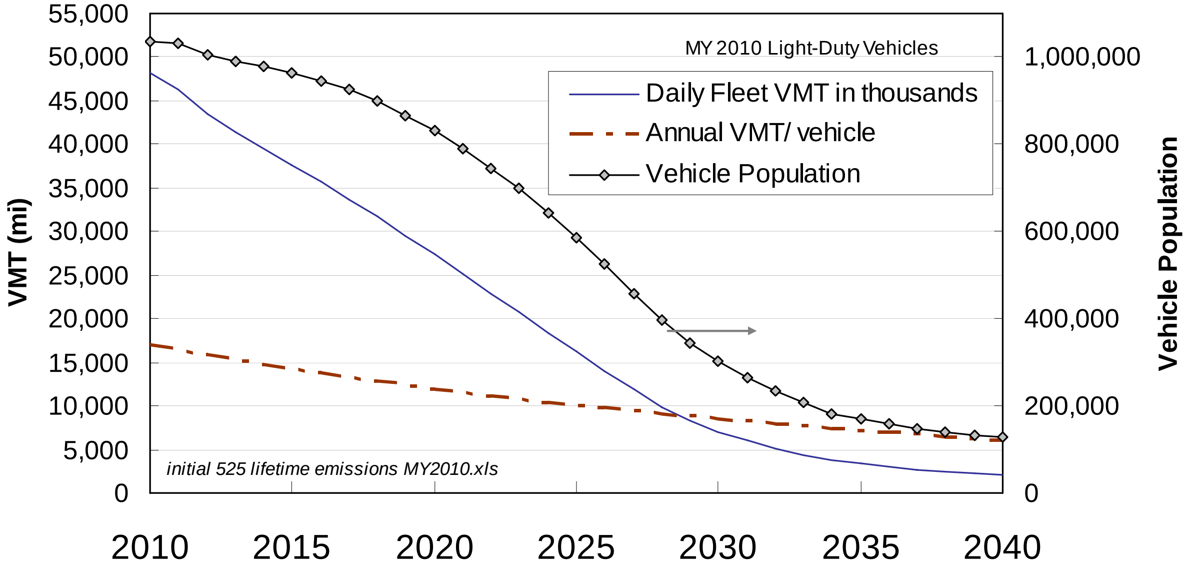

Figure 4-1. Total Mileage Accumulation of Light-Duty Automobiles by Model Year

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[8] Data Illustrated in Figure 4-2 and 4-3 are taken from EMFAC version 2.23.7.60606. All other data used to support the discussion in this report were taken from EMFAC version 2.24.6. Using data from the newer EMFAC version has no effect on the charts given in Figures 4-2 and 4-3.

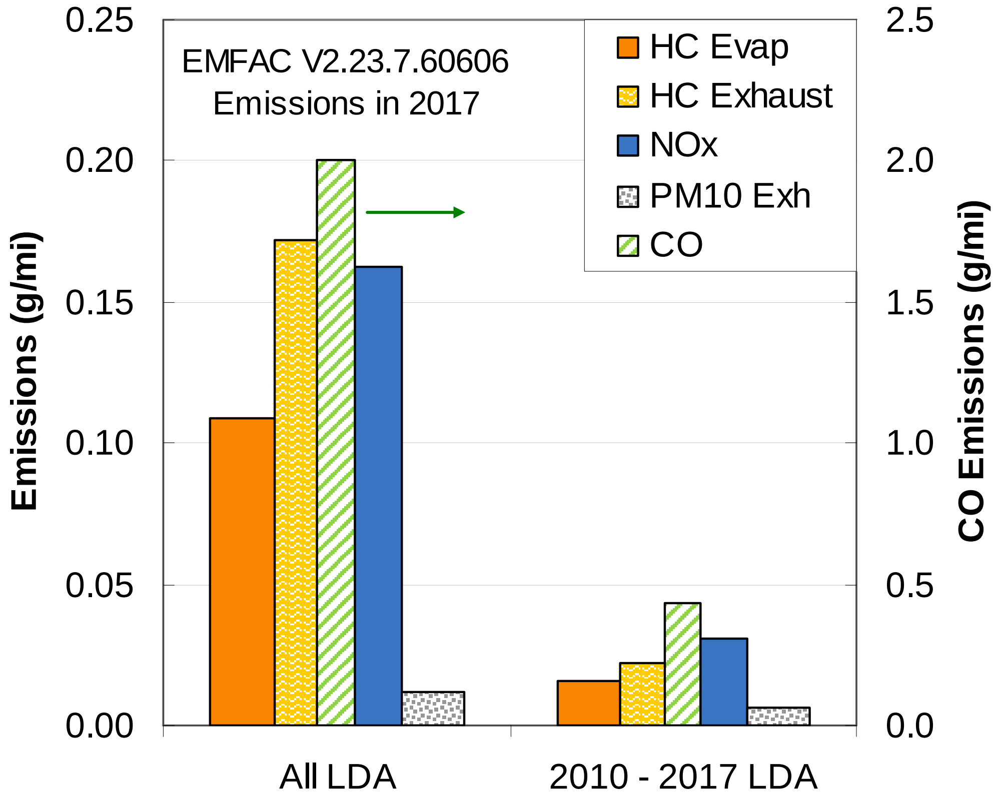


Figure 4-2. Average Light-Duty Automobile Emissions in 2017, All Vehicles and Starting 2010

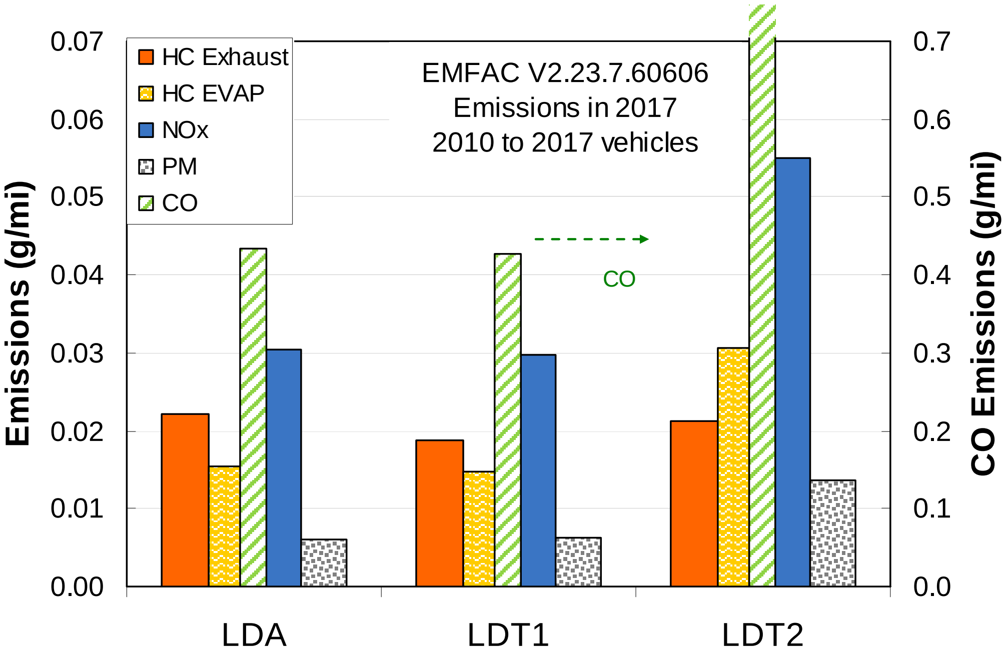


Figure 4-3. Average Light-Duty Vehicle Emissions, 2017 (gasoline vehicles newer than 2010)

4.1.3 Alternative Fuel Vehicles

Emissions from alternative fueled vehicles were estimated for a range of vehicle and off road equipment applications. The approach used here, and in other fuel cycle studies, was to adjust a baseline petroleum fueled vehicle emissions by a factor that reflects the alternative fuel or vehicle technology. This method results in emission estimates that are consistent with the baseline vehicle data set.

Table 4-9 shows the baseline emission adjustment factors for each fuel/vehicle technology considered in the analysis of light- and medium-duty vehicle criteria pollutant emissions. Table 4-10 shows the corresponding adjustment factors for criteria pollutant emissions from heavy-duty vehicles. Adjustment factors are given in the tables for each criteria and other pollutants considered in the analysis. The emissions factor (g/mi) for any pollutant /fuel /vehicle technology from the respective vehicle category (light-/ medium- or heavy- duty) is given by the product of the emission adjustment factor from Tables 4-9 or 4-10 with the corresponding baseline composite emission factor (g/mi) from Tables 4-3 through 4-7 for the same pollutant/ fuel /vehicle technology. Recall that the baseline case corresponds to the use of the baseline CaRFG3 gasoline or California on-road (though invariably used in off-road applications as well) diesel fuel (CaULSD). Thus, all adjustment factors for these baseline fuels are 1. Adjustment factors for most other fuel/ vehicle technology combinations are either 1 or 0. Values of 1 reflect that, in the absence of data to the contrary, there is no reason to believe the specific pollutant emissions from respective fuel /vehicle technology to be any different than for the baseline fuel. Values of 0 occur for fuels/ vehicle technology combinations that have no emissions of the respective pollutant. Occasional non- 1, 0, adjustment factors are noted; these are for cases for which data supporting the value noted exist.

The adjustment factors shown in Tables 4-19 and 4-10 are based upon the baseline values in the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model version 1.7. Adjustments to these values are indicated here.

A considerable quantity of emissions data is available for alternative fueled vehicles. However, there is significant scatter in the data, and the data do not reflect new vehicles and do not always show like comparison. Thus, the project team agreed to use existing assessments of emission adjustment factors from the GREET model unless significant data was provided to indicate that other emission rates were appropriate.

Table 4-9. Criteria Pollutant Adjustment Factors Applied to the Light- and Medium-Duty Baseline Vehicles

Vehicle/ Fuel Type	Technology	Base Data	Vehicle Type	Start Year	HC Exh	HC Evap	CO	NO_x	PM Exh	CH_4	N_2O
RFG0	ICEV	CAT + NCAT	Blend	All	1		1	1	1	1	1
RFG	ICEV	CAT + NCAT	Blend Baseline	All	1		1	1	1	1	1
E10	ICEV	CAT + NCAT	Blend	All	1		1	1	1	1	1
RFG	FFV	CAT	E85 Baseline	All	1		1	1	1	1	1
E85	FFV	CAT	E85 Blend	All	1		1	1	1	1	1
RFG	ICEV	CAT	New	2010	1	1	1	1	1	1	1
RFG	HEV	CAT	New	2010	1	1	1	1	1	1	1
RFG	PHEV	CAT	New	2010	1	1	1	1	1	1	1
LPG	ICEV	CAT	New	2010	1	0	1	1	1	1	1
CNG	ICEV	CAT	New	2010	1	0	1	1	1	2	1
H2ICE	ICEV	CAT	New	2010	0.2	0	0.2	1	0.1	0	0.2
H2FCV	FCV	CAT	New	2010	0	0	0	0	0	0	0
Electric	PHEV	CAT	New	2010	0	0	0	0	0	0	0
Electric	BEV	CAT	New	2010	0	0	0	0	0	0	0
CA ULSD	DICEV	DSL	Blend Baseline	All	1	0	1	1	1	1	1
ULSD HEV	DICEV	DSL	Blend	All	1	0	1	1	1	1	1
FTD 30	DICEV	DSL	Blend	All	0.75	0	0.84	0.95	0.92	1	1
BD20	DICEV	DSL	Blend	All	0.79	0	0.89	1.02	0.90	1	1

Table 4-10. Criteria Pollutant Adjustment Factors Applied to the Heavy-Duty Baseline Vehicles

Vehicle/ Fuel Type	Technology	Base Data	Vehicle Type	Start Year	HC Exh	HC Evap	CO	NO_x	PM Exh	CH_4	N_2O
RFG	Gasoline	DSL	New	2010	1	a	1	1	1	1	1
LPG	HEV	DSL	New	2010	1	0	1	1	1	1	1
CNG	ICEV	DSL	New	2010	1	0	1	1	1	1	1
CA ULSD	DICEV	DSL	New Baseline	All	1	0	1	1	1	1	1
CA ULSD	DHEV	DSL	New	All	1	0	1	1	1	1	1
LNG	ICEV	DSL	New	2010	1	0.5[b]	1	1	1	2	1
Methanol	FCV	DSL	New	2010	1	0.5[b]	1	1	1	1	1
DME	DICEV	DSL	New	2010	1	0	1	1	1	1	1
CA ULSD	DICEV	DSL	Blend Baseline	All	1	0	1	1	1	1	1
FTD30	DICEV	DSL	Blend	All	0.75	0	0.84	0.95	0.92	1	1
BD20	DICEV	DSL	Blend	All	0.79	0	0.89	1.02	0.90	1	1
E-Diesel	DICEV	DSL	Blend	All	1	0	1	1	1	1	1
H2	ICEV	DSL	New	2010	1	0	0.2	1	0.1	0	0.2
H2	FCV	DSL	New	2010	0	0	0	0	0	0	0
Electric	BEV	DSL	New	2010	0	0	0	0	0	10	0

[a] Evaporative emissions estimated from gasoline MDV emission factors.
[b] Estimated as fraction of gasoline evaporative emissions.

Ethanol Blends

The ethanol blend fuels evaluated in this study are those containing no ethanol (E0), 5.7 percent ethanol (RFG5.7), 10 percent ethanol (E10), and 85 percent ethanol (E85). RFG5.7 is the baseline fuel which meets all current ARB specifications for phase 3 reformulated gasoline (CaRFG3) fuel sold for use in LDVs. Pragmatically, this means that all gasoline sold in the state meets CaRFG3 specifications. Refiners can produce gasoline that deviates from these specifications provided it can be shown that the predicted emissions associated with the use of the alternative gasoline are equivalent to the emissions from the use of a gasoline that meets all CaRFG3 specifications. The California Predictive Model (PM), developed by the ARB, is used to establish this emissions equivalency. E0 formulations can be easily produced, and shown by the PM to cause no increase in criteria or toxic pollutants. E10 formulations that pass the emissions equivalency requirement can be produced, but parameters other than fuel oxygen content (2 percent oxygen for RFG5.7 compared to 3.5 percent oxygen for E10), such as sulfur content, aromatics content, and 90 percent component vaporization temperature (T90), need to be varied as well. The biggest challenge in producing PM compliant E0 is the increase in the HC exhaust emissions component of the ozone-forming potential (OFP, the regulated emission parameter in the CaRFG3 regulations that is affected by HC emissions) associated with the vehicle emissions. This increase is partially offset by a decrease in the traditionally measured evaporative HC. Any additional predicted exhaust OFP increases can be easily offset by varying other regulated parameters in the E0 formulation. The RVP increase arising from the increased RVP of ethanol causes increased evaporative (traditionally measured evaporative HC) emissions for E10 fuel compared to RFG5.7. However, these increases can be relatively easily offset by varying other fuel formulation parameters. The predicted increase in NO_x emissions in going from RFG5.7 to a compliant E10 is more difficult to offset by varying other fuel composition parameters, but NO_x compliant E10 formulations can be produced at some (relative high) expense. E85 formulations are designed to comply with the CaRFG3 regulations when used in an FFV that was specifically designed to meet emissions requirements for gasoline fuels containing any concentration of ethanol from E0 to E10.

A more recently discovered evaporative HC component that is affected by fuel ethanol content is that associated with HC permeation through fuel system components. Permeation HC emissions increase through certain (though not all) vehicle fuel system component materials with any ethanol-containing gasoline. Permeation emissions are decreased for E0 fuel compared to RFG5.7 fuel, though it is not clear that permeation emissions are increased for E10 fuel compared to RFG5.7. Nevertheless, the most recent (draft, not yet adopted) PM takes into consideration the permeation effects of fuels with varying ethanol. Thus, PM compliant E10 (no emissions increases) formulations can be produced.

The toxics emissions effects for fuels of varying ethanol content more or less follow the HC emissions changes. The organic speciation of the toxic emissions is altered with differing ethanol content. For example aldehyde (formaldehyde and acetaldehyde) emissions increase as ethanol content increases, such as for E10 compared to RFG5.7. However, any gasoline fuel sold in California for use in LDVs must comply with restrictions from the PM, so differing ethanol content compliant fuels must show no increase in toxicity-weighted toxics emissions when compared to the baseline RFG5.7 fuel.

Biodiesel Blends

Emission factors for a biodiesel blend of 20 percent biodiesel (BD20) with California ULSD (compliant California diesel fuel of nominally 20 percent aromatics, 8 ppm sulfur) is estimated to have the emission reductions shown in Table 4-11 for medium- and heavy-duty diesel vehicle applications.

ARB is currently working with industry and EPA to develop an emission testing program to determine the effect of BD20 on toxic emissions using a California ULSD. This would include emissions of formaldehyde, acetaldehyde, PAHs, and others. It is expected that potency weighted toxics for BD20 will be less than for USLD alone. This is based primarily on the particulate manner (PM) reductions associated with BD20. So for purposes of the current analysis for the full fuel cycle analysis required by AB1007, it should be assumed that there is no change in toxic emissions for BD20 compared to California ULSD.

Table 4-11. Emission Impacts of BD20 and FTD30 diesel fuel blends

Pollutant	Change in Emissions	
	BD20[1]	FTD30
NO_x	+2%	-5%
PM	-10.1%	-8%
HC	-21.1%	-25%
CO	-11%	-16%

[1] Results for soybean based diesel added to average diesel fuel

Sources: EPA October 2002, TIAX private study on Fischer-Tropsch fuels, Norton, Schaberg

Baseline diesel evaporative emissions are estimated to be zero in EMFAC. Evaporative emissions (g/mi) are assumed the same as that of gasoline vehicle technologies for RFG and methanol. LNG vehicles experience boil off emissions

4.1.4 Toxic Emissions from Exhaust and Evaporative Emissions

Fractional percentages for the air toxics are applied to the hydrocarbon emission components. The hydrocarbon emission components are for vehicle running exhaust, idle exhaust, starting exhaust, diurnal evaporative, hot soak evaporative, running evaporative, and resting evaporative emissions. The fractional percentages of toxics come from ARB's organic gas speciation profiles (ARB 2005). Each profile has fractional percentages for each of the organic gas components. The organic gas species focused on in this effort were benzene, 1-3 butadiene, formaldehyde, and acetaldehyde. The ARB profile numbers used in the analysis are shown in Table 4-12. Table 4-13 shows the fractional portion (in percentage) of the base data hydrocarbon emissions that are toxics emissions.

Table 4-12. ARB Organic Gas Speciation Profile Identification Numbers

	NCAT	CAT	Diesel
Running Exhaust & Idle	401	441	818
Start Exhaust	402	877	818
Diurnal & Resting	906	906	—
Hot Soak & Running	422	422	—

Table 4-13. Percentage of Base Data Hydrocarbon Emissions for the Toxics

	NCAT	CAT	DSL
Benzene			
Run Exh	3.44%	2.64%	2.00%
Idle Exh	3.44%	2.64%	2.00%
Start Exh	2.75%	2.47%	2.00%
Diurnal	0.36%	0.36%	0.00%
Hot Soak	0.84%	0.84%	0.00%
Running	0.84%	0.84%	0.00%
Resting	0.36%	0.36%	0.00%
1,3 Butadiene			
Run Exh	0.83%	0.55%	0.19%
Idle Exh	0.83%	0.55%	0.19%
Start Exh	0.78%	0.70%	0.19%
Diurnal	0.00%	0.00%	0.00%
Hot Soak	0.01%	0.01%	0.00%
Running	0.01%	0.01%	0.00%
Resting	0.00%	0.00%	0.00%
Formaldehyde			
Run Exh	3.12%	1.70%	14.71%
Idle Exh	3.12%	1.70%	14.71%
Start Exh	1.46%	1.31%	14.71%
Diurnal	0.00%	0.00%	0.00%
Hot Soak	0.00%	0.00%	0.00%
Running	0.00%	0.00%	0.00%
Resting	0.00%	0.00%	0.00%
Acetaldehyde			
Run Exh	0.75%	0.24%	7.35%
Idle Exh	0.75%	0.24%	7.35%
Start Exh	0.35%	0.40%	7.35%
Diurnal	0.00%	0.00%	0.00%
Hot Soak	0.00%	0.00%	0.00%
Running	0.00%	0.00%	0.00%
Resting	0.00%	0.00%	0.00%

The tanks to wheel (TTW) emission factors in g/mi were calculated from the above information for each of the different combination of pollutants, vehicle classes, vehicle fuel types, and scenario years. This produces a database of around 1700 rows of data with 20 columns of alternative fuels. Table 4-14 gives the adjustment factors used for each of the toxics included in the evaluation for each combination of vehicle class and vehicle fuel type considered.

Table 4-14. Toxic Pollutant Adjustment Factors for All Vehicles

Vehicle/ Fuel Type	Technology	Vehicle Type	Start Year	Benzene	1-3 Butadiene	Formaldehyde	Acetaldehyde	PAH
RFG0	ICEV	Blend	All	Weighted toxics are required to result in no net increase over baseline RFG. Generally the mix in toxics changes with alcohol blends but the overall weighted effect must be less than or equal to RFG. An adjustment factor is assumed to be 1.0.				0
RFG	ICEV	Blend Baseline	All					0
E10	ICEV	Blend	All					0
RFG	FFV	E85 Baseline	All					0
E85	FFV	E85 Blend	All					0
RFG	ICEV	New	2010	1	1	1	1	0
RFG	HEV	New	2010	1	1	1	1	0
RFG	PHEV	New	2010	1	1	1	1	0
LPG	ICEV	New	2010	0	0	1	1	0
CNG	ICEV	New	2010	0	0	1	1	0
H2ICE	ICEV	New	2010	0	0	0	0	0
H2FCV	FCV	New	2010	0	0	0	0	0
Electric	PHEV	New	2010	0	0	0	0	0
Electric	BEV	New	2010	0	0	0	0	0
CA ULSD	DICEV	Blend Baseline	All	1	1	1	1	1
ULSD HEV	DICEV	Blend	All	1	1	1	1	1
FTD30	DICEV	Blend	All	1	1	1	1	0.8
BD20	DICEV	Blend	All	1	1	1	1	0.8

4.2 Off-Road Vehicles

ARB's off-road inventories of engines were obtained for the years 2005, 2012, 2017, 2022, and 2030. The criteria pollutant emissions from the total inventory of off-road engines in California in ton/day for the year 2012 is summarized in Table 4-15. Table 4-16 shows the corresponding off-road vehicle exhaust emissions for the year 2012 in g/gal of fuel.

Table 4-15. California Off-Road Equipment Exhaust Emissions in 2012 (tons/day)

Fuel	ROG	CO	NO_x	CO_2	SO_2	PM	N_2O	CH_4
Total Off-Road Engines								
CNG 4-stroke	3	95	12	2,352	0.00	0.21	0.00	2.39
Diesel	51	221	387	47,239	0.53	21.51	0.00	4.59
Gasoline 2-stroke	301	776	15	2,028	0.35	16.87	0.93	16.61
Gasoline 4-stroke	60	1,884	54	8,043	0.44	4.78	3.66	3.35
TOTAL	415	2,975	469	59,661	1.31	43.37	4.59	26.93
Off-Road Vehicles								
CNG 4-stroke	3	86	12	2,121	0.00	0.19	0.00	2.20
Diesel	16	63	121	13,877	0.15	6.46	0.00	1.45
Gasoline 2-stroke	162	450	3	432	0.32	3.66	0.19	8.84
Gasoline 4-stroke	7	264	11	2,023	0.34	0.48	1.15	0.38
TOTAL	187	863	148	18,453	0.81	10.78	1.34	12.87
Agricultural Equipment								
Diesel	12	45	83	8,709	0.10	4.88	0.00	1.09
Gasoline 4-stroke	2	60	2	183	0.00	0.15	0.10	0.11
TOTAL	14	106	84	8,892	0.10	5.04	0.10	1.21
Logging Equipment								
Diesel	0.6	3.2	5.1	739	0.01	0.28	0.00	0.05
Gasoline 2-stroke	2.0	4.2	0.0	9	0.00	0.01	0.00	0.10
Gasoline 4-stroke	0.2	9.5	0.2	15	0.00	0.12	0.01	0.01
TOTAL	2.8	16.9	5.4	762	0.01	0.41	0.02	0.17
Forklifts (excluding rough terrain forklifts)								
CNG 4-stroke	2.6	85	11.3	2,091	0.00	0.19	0.00	2.16
Diesel	0.8	3	5.7	721	0.01	0.30	0.00	0.07
Gasoline 4-stroke	2.1	136	6.6	1,265	0.01	0.10	0.35	0.12
TOTAL	5.4	224	23.6	4,077	0.02	0.59	0.35	2.34
Transport Refrigeration Units								
Diesel	4.9	26.9	29.3	3,200	0.04	1.81	0.00	0.44
Gasoline 4-stroke	0.4	19.6	0.3	33	0.00	0.02	0.03	0.02
TOTAL	5.3	46.5	29.5	3,232	0.04	1.83	0.03	0.46

off road EXHAUST2012_export tables.xls

Source: TTW_Offroad

Table 4-16. California Off-Road Equipment Exhaust Emissions in 2012 (g/gal)

Fuel	ROG	CO	NO_x	CO_2	SO_2	PM	N_2O	CH_4
Total Off-Road Engines								
CNG 4-stroke	7	242	31	5,988	0.00	0.54	0.00	6.08
Diesel	11	47	82	9,956	0.11	4.53	0.00	0.97
Gasoline 2-stroke	600	1,546	30	4,039	0.70	33.60	1.84	33.09
Gasoline 4-stroke	47	1,468	42	6,270	0.34	3.73	2.85	2.61
TOTAL	60	430	68	8,619	0.19	6.27	0.66	3.89
Off-Road Vehicles								
CNG 4-stroke	7	242	33	5,987	0.00	0.53	0.00	6.22
Diesel	12	45	87	9,955	0.11	4.63	0.00	1.04
Gasoline 2-stroke	807	2,244	17	2,155	1.58	18.23	0.95	44.08
Gasoline 4-stroke	24	938	41	7,189	1.21	1.69	4.07	1.34
TOTAL	84	387	66	8,274	0.36	4.83	0.60	5.77
Agricultural Equipment								
Diesel	14	52	94	9,935	0.11	5.57	0.00	1.25
Gasoline 4-stroke	61	1,856	54	5,607	0.10	4.67	3.19	3.41
TOTAL	16	116	93	9,780	0.11	5.54	0.11	1.33
Logging Equipment								
Diesel	8	43	70	9,972	0.11	3.78	0.00	0.74
Gasoline 2-stroke	745	1,576	12	3,441	0.14	2.00	1.65	39.28
Gasoline 4-stroke	68	2,727	50	4,210	0.12	35.29	4.07	3.60
TOTAL	35	211	67	9,505	0.11	5.09	0.23	2.14
Forklifts (excluding rough terrain forklifts)								
CNG 4-stroke	7	242	32	5,987	0.00	0.53	0.00	6.17
Diesel	11	41	79	9,965	0.11	4.21	0.00	0.96
Gasoline 4-stroke	12	802	39	7,448	0.07	0.58	2.06	0.68
TOTAL	9	378	40	6,893	0.03	1.00	0.59	3.96
Transport Refrigeration Units								
Diesel	15	83	90	9,881	0.13	5.60	0.00	1.36
Gasoline 4-stroke	51	2,647	36	4,399	0.13	2.46	3.72	2.87
TOTAL	16	140	89	9,758	0.13	5.53	0.08	1.40

off road EXHAUST2012_export tables.xls

Source: TTW_Offroad

Figures 4-4 through 4-7 shows the vehicle fraction and the fuel breakout of the vehicles for pollutants ROG, CO, NO_x, and PM respectively. Non vehicle engines in the off-road inventory produce the majority of the emissions. Gasoline fueled vehicles are the major contributor to ROG and CO emissions from off-road vehicles. The diesel fueled vehicle class is the major contributor to NO_x and PM emissions from vehicles.

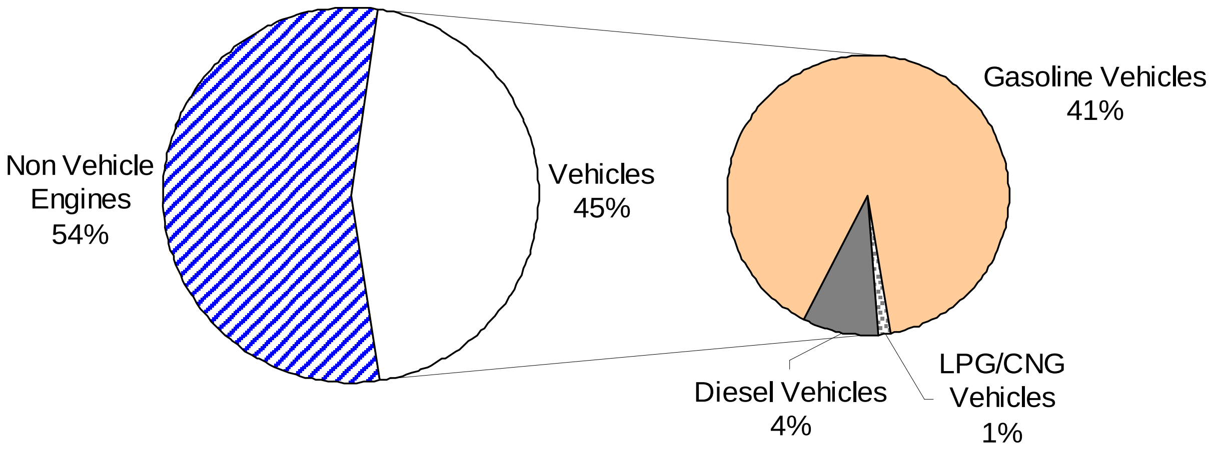


Figure 4-4. Vehicle and Fuel Fractions for ROG Emissions

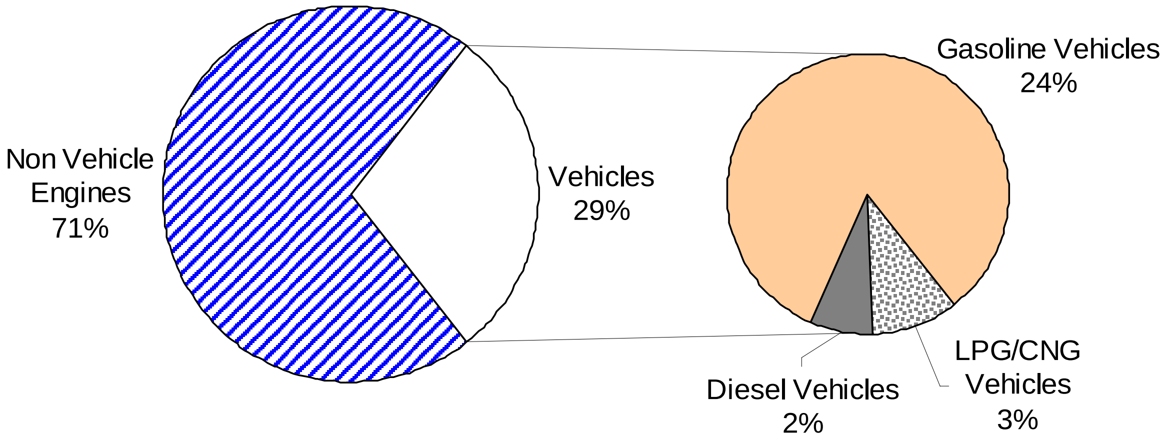


Figure 4-5. Vehicle and Fuel Fractions for CO Emissions

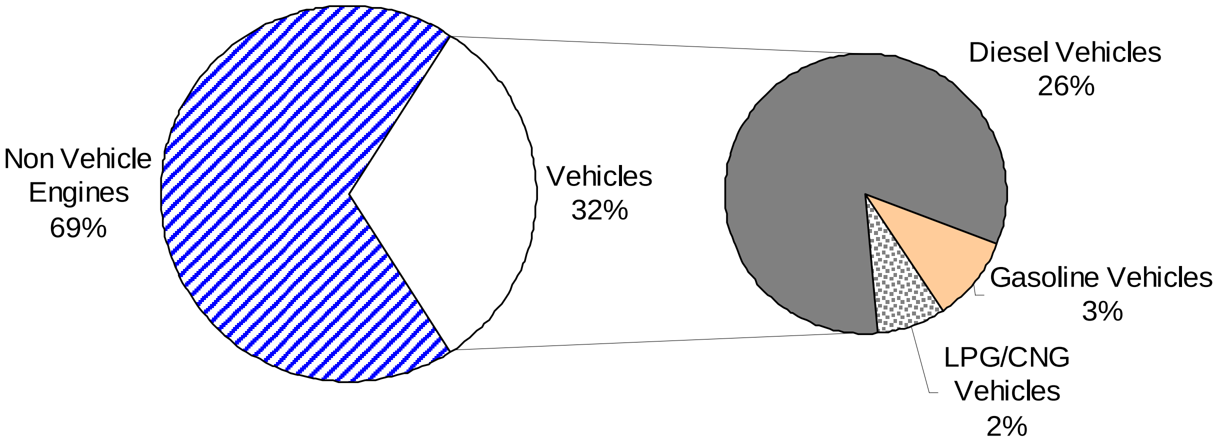


Figure 4-6. Vehicle and Fuel Fractions for NO_x Emissions

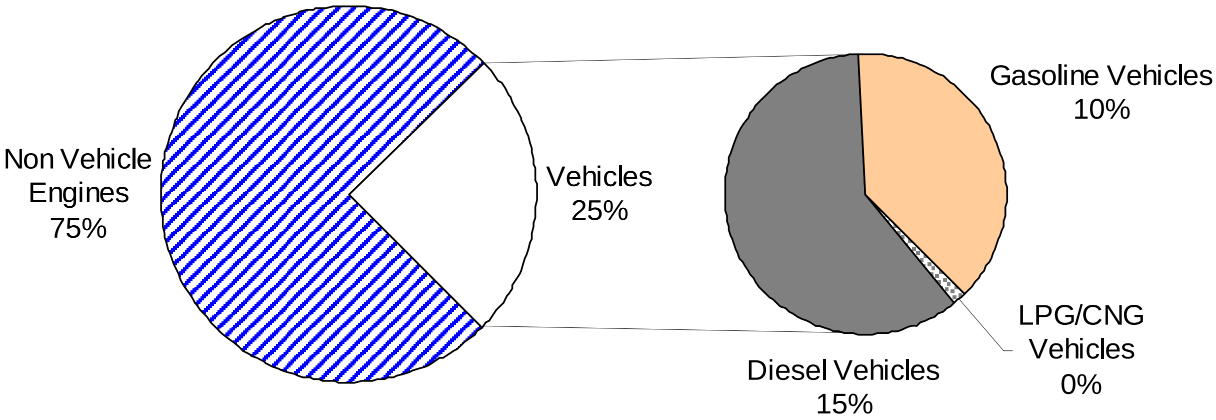


Figure 4-7. Vehicle and Fuel Fractions for PM Emissions

SECTION 5. GREENHOUSE GAS EMISSIONS

GHG emissions in the TTW analysis include exhaust emissions of CO_2 as well as CH_4 and N_2O. CO_2 emissions were calculated directly from the carbon content of the fuel after accounting for fuel that is converted to CH_4 CO, and evaporative emissions. The approach for calculating CO_2 emissions from vehicles is shown in Table 5-1. The approach to dealing with CO and HC emissions as well as the weighted contribution of their lifetime global warming potential is discussed in the WTW report.

Fuel properties have an important impact on fuel cycle and vehicle emissions. The composition of fuels determines their combustion properties including heating value. The elemental composition of carbon and sulfur translate directly to CO_2 and SO_2 emissions. Almost all of the carbon in fuel is converted to CO_2, and similarly almost all sulfur in fuel is converted to SO_2. The hydrogen content of fuels relates directly to the amount of water vapor produced during combustion. The fuel cycle GHG results for blended fuels are equivalent to the weighted average of the individual fuel components. Figure 5-1 shows the carbon content of the primary blending components of fuels. The carbon content is expressed as CO_2 on a g/MJ, lower heating value basis. The carbon factors are expressed in lower heating values because vehicle energy consumption is compared on a lower heating value basis (see Section 3). An examination of the carbon content and heating values of fuels is included in the WTT report.

As is the case with criteria pollutant emissions, CH_4 and N_2O emissions are often considered to be independent of vehicle energy consumption. Table 5-2 shows the N_2O and CH_4 emission factors in the California Climate Action Registry reporting protocols (CCAR). The emission factors are reported on a g/mi basis. The CO_2 emissions reported in the protocols enable the calculation of the CH_4 and N_2O on a g/MJ basis. These values are also shown in Table 5-2. This analysis shows that these reported emission factors seem to be derived from a limited set of emission factors on a g/MJ basis, and then applied to the energy consumption for different vehicle classes. The presentation of the emission factors on a fixed g/mi basis provides the potentially inaccurate suggestion that they are derived from data supporting a fixed value per mile driven.

Figure 5-2 shows the N_2O and CH_4 emissions data for a variety of gasoline fueled vehicles. The limited data suggest that an emission factor proportional to energy consumption might be as appropriate as a fixed g/mile emission factor.

The TTW emissions in this study are based on the fixed g/mi values in Table 5-2 because these values are used by the California Climate Action Registry and the study team could not perform an extensive evaluation for N_2O and CH_4 emissions. However, the fixed g/MJ source of the N_2O data warrants further examination to determine the relationship between N_2O and energy consumption. The effect of this assumption is that identical N_2O emissions will be assumed for vehicles with energy consumption the same as that of the baseline vehicle (a 3 and 35 percent effect for E85 FFV and gasoline HEVs, respectively).

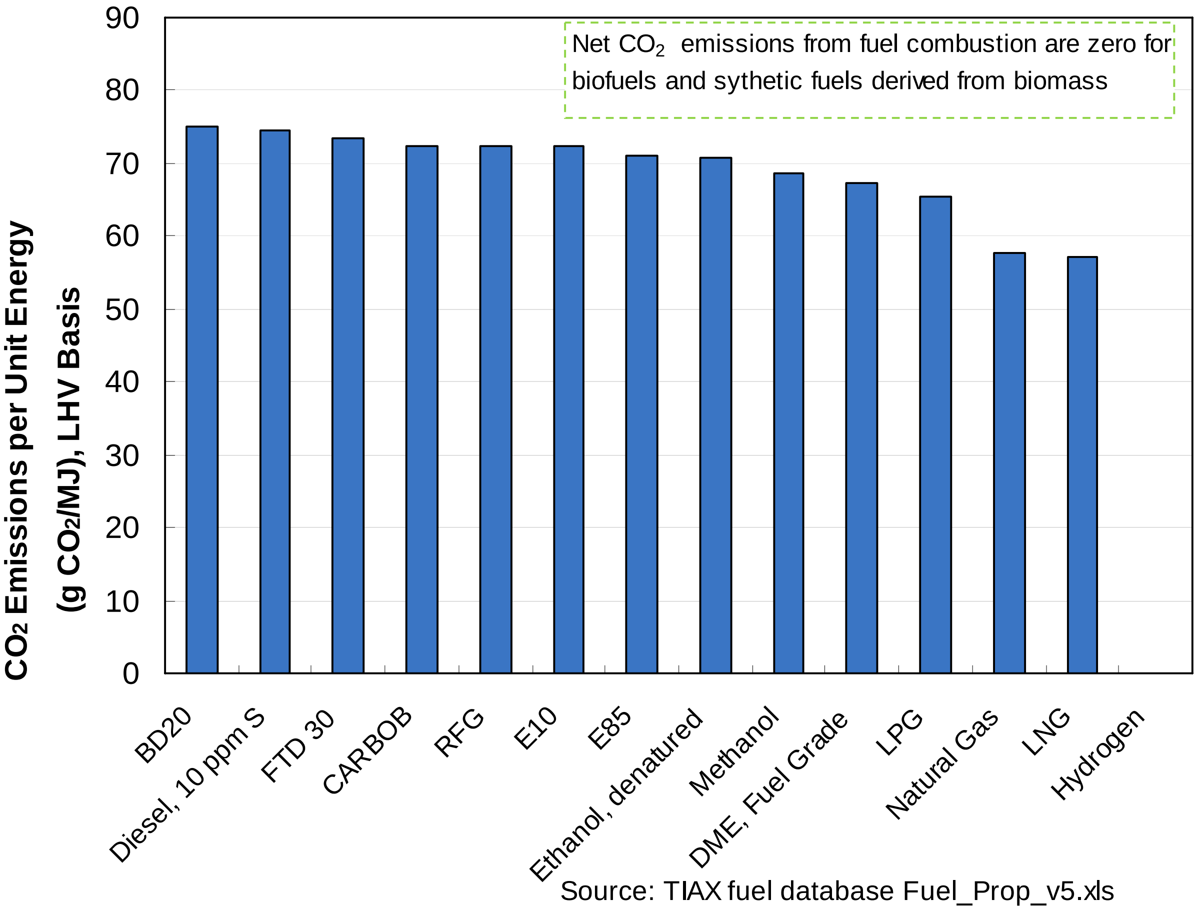
Table 5-1. Vehicle GHG Calculations

Determine vehicle energy consumption, MJ/mi

Calculate carbon factor for fuel blend, g CO_2/MJ

Determine CH_4 and N_2O per mile

CO_2 g/mi = carbon factor x MJ/mi – CH_4 x 44/16



Net CO_2 emissions from fuel combustion are zero for biofuels and sythetic fuels derived from biomass

Source: TIAX fuel database Fuel_Prop_v5.xls

Figure 5-1. Carbon Content of Fuels (CO_2 equivalent)

Table 5-2. GHG Emission Factors from California Climate Action Registry (CCAR)

Vehicle Type/Control Technology	N_2O	CH_4	N_2O	N_2O	CH_4
	(g/mi)	(g/mi)	g CO_2/ mi	g CO_2/MJ	g CO_2/MJ
Gasoline Passenger Cars					
Low Emission Vehicles	0.0283	0.0402	8.78	1.40	0.14
Tier 1	0.0463	0.0483	14.37	2.26	0.16
Tier 0	0.0816	0.0644	25.29	3.80	0.20
Oxidation Catalyst	0.0518	0.1126	16.06	1.88	0.28
Non-Catalyst	0.0166	0.1931	5.14	0.43	0.34
Uncontrolled	0.0166	0.2173	5.14	0.45	0.40
Gasoline Light Duty Truck (<8,500 GVWR)					
Low Emission Vehicles	0.0401	0.0483	12.42	1.40	0.11
Tier 1	0.0644	0.0563	19.95	2.26	0.13
Tier 0	0.1361	0.1126	42.20	3.80	0.21
Oxidation Catalyst	0.0673	0.1448	20.85	1.88	0.27
Non-Catalyst	0.0188	0.2253	5.84	0.43	0.35
Uncontrolled	0.0190	0.2173	5.89	0.46	0.35
Gasoline Heavy-Duty Vehicle (>8500 GVWR))					
Tier 0	0.2782	0.1207	86.26	3.80	0.11
Oxidation Catalyst	0.1400	0.1448	43.40	1.88	0.13
Non-Catalyst	0.0412	0.2012	12.77	0.43	0.14
Uncontrolled	0.0433	0.4345	13.42	0.46	0.31
Diesel Passenger Cars					
Model Year 1996-1999	0.0161	0.0161	4.99	0.97	0.07
Model Year 1983-1995	0.0161	0.0161	4.99	0.93	0.06
Model Year 1966-1982	0.0161	0.0161	4.99	0.72	0.05
Diesel Light Duty Trucks					
Model Year 1996-1999	0.0322	0.0161	9.98	1.40	0.05
Model Year 1983-1995	0.0322	0.0161	9.98	1.39	0.05
Model Year 1966-1982	0.0322	0.0161	9.98	1.11	0.04
Diesel Heavy Duty Trucks					
Model Year 1996-1999	0.0483	0.0644	14.97	0.70	0.06
Model Year 1983-1995	0.0483	0.0805	14.97	0.68	0.08
Model Year 1966-1982	0.0483	0.0966	14.97	0.63	0.09
Motorcycles					
Model Year 1996-1999	0.0068	0.2092	2.10	0.43	0.90
Model Year 1966-1995	0.0087	0.4184	2.69	0.45	1.48

Source: CCAR 2006

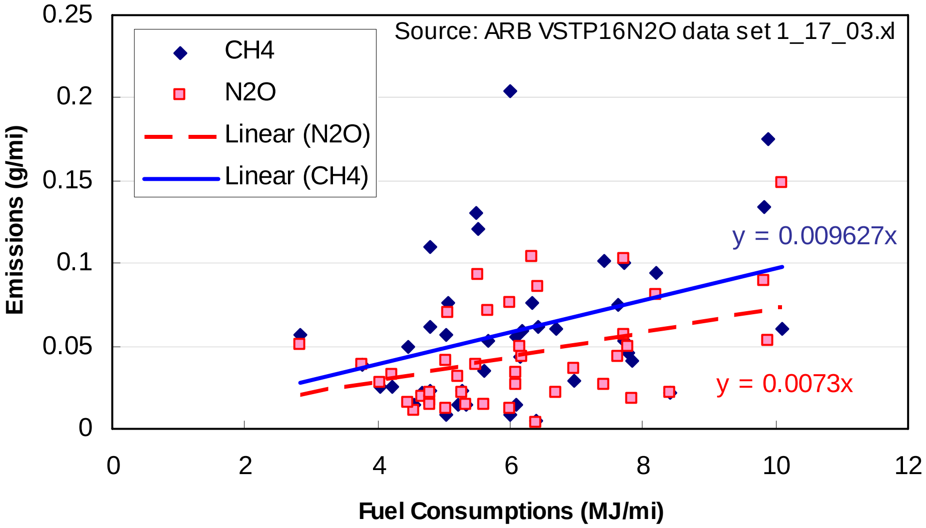


Figure 5-2. Methane and Nitrous Oxide Emissions from Light- and Medium-Duty Gasoline Vehicles

SECTION 6. WATER IMPACTS

Operating vehicles contribute a number of different types of multi-media impacts, primarily in the form of pollutants on urban water runoff. Pollutants are derived from automotive fluids, deterioration of parts, and vehicle exhaust. Once these pollutants are deposited onto road and parking surfaces, they are available for mixing with rainwater and entering storm drains. A study by the National Resources Defense Council estimated that cars and other vehicles contributed 75 percent of the total copper load to the lower San Francisco Bay through runoff (Lehner 1999). Brake pad wear contributed 50 percent of the total load, and 25 percent came from atmospheric deposition of exhaust particulate emissions. The stormwater discharge from one square mile of roads and parking lots can yield approximately 20,000 gallons of residual oil per year. Runoff from residential car washing also contributes oil, grease, grit, and detergents to the stormwater system.

Heavy metals and other contaminants are also released into California’s waters at the point of energy use. Transportation fuels such as gasoline and diesel contain trace levels of heavy metals as either impurities or additives, while other automobile components such as brake linings and motor oil contain trace amounts of heavy metals likewise emitted into waterways during vehicle operation. Tire wear is a source of cadmium and zinc; concentrations and discharge levels to storm drains can exceed allowable levels (Lehner 1999). Engine coolants and antifreeze containing ethylene glycol and propylene glycol can be toxic and contribute high biological oxidation demand (BOD) to California rivers, bays, and the Pacific Ocean.

Motor vehicle emissions, that eventually becomes urban runoff into watersheds, significantly impact U.S. water quality. EPA’s *National Water Quality Inventory* estimates that urban runoff, which is dominated by motor vehicle pollution, was responsible for 32 percent of estuaries, 18 percent of lakes, and 13 percent of river impaired by water pollution in 2000, measured on a surface area or length basis. This makes urban runoff the second, third, and fourth most important source of water pollution for estuaries, lakes, and rivers, respectively. EPA likewise estimates that one-sixth of hydrocarbons and one-half of suspended solids in streams are associated with freeway runoff (Nixon 2002).

Table 6-1 provides a qualitative summary of the metal water pollution associated with the consumption of transportation fuels, both directly and from wear on vehicle components. As the figure suggests, transportation fuel acts as a “gateway” to a variety of other water quality impacts associated with vehicle operation, from cobalt and iron in used motor oil to manganese emitted from engine wear. A straightforward analysis of water quality impacts associated with transportation fuels, whether petroleum-based or otherwise, must therefore factor in these downstream impacts.

Table 6-1. Sources of Heavy Metal Pollution in Water from Automobile Use

Source	Cd	Co	Cu	Fe	Mn	Ni	Pb	Zn
Gasoline	💧		💧				💧	💧
Exhaust						💧	💧	
Motor Oil/Grease		💧		💧		💧	💧	💧
Antifreeze				💧				💧
Undercoating							💧	💧
Brake Linings			💧	💧		💧	💧	💧
Rubber	💧		💧				💧	💧
Diesel Oil	💧							
Engine Wear				💧	💧	💧	💧	💧

Source: Nixon 2002

Vehicle exhaust contributes the nutrient nitrogen to our nation’s waters. Studies estimate that deposition of nitrogen from power plant and vehicle exhaust contributes 17 pounds per year of nitrogen and 0.7 pounds per year of phosphorus to a typical acre of land in the metropolitan Washington, DC, area (Lehner 1999).

6.1 TTW Multi-Media Analysis

Estimates of the leaks and discharges of oil and coolant from vehicles do not appear to be available. Most studies on surface water contamination appear to focus on the impact of the discharge and identifying measures to prevent releases. Attributing surface contamination to individual vehicles on a per mile basis is challenging given the difficulty in assessing emissions and the broad range of vehicle types contributing to surface discharges. Therefore, TIAX performed a rough estimate of the potential leak rate of engine oil from passenger cars. Even though leak rates can be expected to be similar among IC engine technologies, electric or hydrogen vehicles will eliminate many sources of engine oil losses.

Table 6-2 shows and estimates a number of parameters associated with the oil consumption from an IC engine vehicle. The estimates are based on a review of brochures on engine oil practices (Irwin 1997, EPA 1999, Bobistheoilguy 2007) and agree with practical experience as well as results from demonstration data testing (Lonyai 1994). While engine oil consumption rates are well understood, the fraction of the oil leaking versus burned by the engine and the fraction that is washed or drips onto the road are not readily available. TIAX assumed that 5 percent of the oil losses were leaks and of that 5 percent, 10 percent resulted in a drip on the road. The calculated emission level is 0.004 g/mi of oil. This figure is 40 percent of the vehicle particulate level[9]. While these values are simply input assumptions, they allow for the comparison of vehicle impacts with those in the fuel cycle.

The metals content of engine oil ranges significantly. The lead values in Table 6-2 is an assumed concentration with actual lead levels ranging from 0 to over 100 ppm. Lead levels in engines with low wear can be below 1 ppm.

Table 6-2. Estimate of Water Impacts from Engine Oil

Leak Parameter	Units	Older Vehicles	New Vehicles
Oil Consumption	Miles per quart	4,000[1]	400
Leak Fraction	%	5%	5%
Drip Fraction	%	10%	10%
Oil Discharge Rate	mL/mi	0.005	0.0005
Oil density	g/mL	0.750	0.750
Metals content			
Lead	ppm	2	1
Chromium	ppm	0.2	0.1
Leak Rate			
Hydrocarbons (oil)	g/mi	0.004	0.0004
Lead	g/mi	7.10E-09	3×10^{-10}
Chromium	g/mi	7.10E-10	3×10^{-11}

[1] Worst case assumptions for older vehicles

Source: Scoping analysis by TIAX to examine the relative impact of vehicle and fuel cycle impacts.

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[9] The fate of engine oil must be either removal from oil changes, losses through combustion as CO_2, HC, or PM, or leaks, which can either accumulate on the engine or wash or drip off of the vehicle.

SECTION 7. VEHICLE CYCLE CONCLUSIONS

This report provides the data and inputs for the TTW analysis. Energy consumption, criteria pollutant, air toxics, and multi-media impacts were estimated for baseline gasoline and diesel vehicles. Adjustment factors for alternative fuel vehicles were also estimated.

Criteria pollutant estimates are consistent with ARB's EMFAC emission model for on-road vehicles and Off-Road Database for off-road vehicles. Groupings of the emission estimates for vehicles into all the vehicles on the road and new vehicles allows for the assessment of blend fuel and new vehicle strategies.

Prior vehicle analysis studies, as well as vehicle test data, provide the basis for comparisons of alternative fuel vehicle energy consumption. These values are very important because WTT emissions and vehicle CO_2 are proportional to energy consumption. However, there will continue to be a broad range of estimates in the relative comparison on energy consumption. The actual performance of vehicles will ultimately need to be compared with the projections in this study and used as the basis for assigning full fuel cycle impacts.

While this report draws on a wide range of models and data sources, several limitations are noteworthy:

- Baseline vehicle criteria pollutant emissions are based on the average day. Ambient temperatures and driving patterns can significantly affect both evaporative emissions and exhaust emissions. The effect was not examined here.

- Vehicle energy consumption comparisons are based on the notion of comparable vehicles. Vehicles that are actually built invariably are configured differently. The actual energy consumption of different vehicles will need to be taken into account if policies based on the full fuel cycle impact are associated with actual vehicles.

- Emissions for new vehicle technologies are based on an introduction in 2010. If the market share of new vehicle technologies grows over time, the weighting of the baseline vehicle emissions should be more heavily weighted towards later years. However, the emission results for the 2010 vehicle mix (in 2017 for example) are significantly lower than that of all of the vehicles on the road in 2017. Therefore, the analysis of vehicle introductions starting 2010 provides a reasonable estimate of the impact of new vehicle strategies.

- Data on both criteria pollutants and air toxics from alternative fueled vehicles are limited and do not exist for future low emission technologies. An extensive examination of these emission rates was not performed because the trends toward declining emission levels from new vehicles reduce the potential impact of alternative fuels.

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APPENDIX A. ARB OFF-ROAD INVENTORY

This appendix provides more detailed information from the ARB off-road database. The following are included in the tables below:

- A-1: Complete off-road inventory equipment categories
- A-2 and A-3: Emissions in tons/day and g/gal for 2017
- A-4 and A-5: Emissions in tons/day and g/gal for 2022
- A-6 and A-7: Emissions in tons/day and g/gal for 2030
- Average daily emissions for 2012 are included in Section 4.

Table A-1. ARB Off-Road Inventory – Data Base Categories and 2012 Population

Class	Fuel	Equipment	Population
Agricultural Equipment	Diesel	Agricultural Mowers	63
Agricultural Equipment	Diesel	Agricultural Tractors	169,353
Agricultural Equipment	Diesel	Balers	1,349
Agricultural Equipment	Diesel	Combines	4,180
Agricultural Equipment	Diesel	Hydro Power Units	428
Agricultural Equipment	Diesel	Other Agricultural Equipment	3,238
Agricultural Equipment	Diesel	Sprayers	1,471
Agricultural Equipment	Diesel	Swathers	7,348
Agricultural Equipment	Diesel	Tillers	11
Agricultural Equipment	Gas 4-stroke	2-Wheel Tractors	2,448
Agricultural Equipment	Gas 4-stroke	Agricultural Mowers	2,106
Agricultural Equipment	Gas 4-stroke	Agricultural Tractors	522
Agricultural Equipment	Gas 4-stroke	Balers	2,535
Agricultural Equipment	Gas 4-stroke	Combines	191
Agricultural Equipment	Gas 4-stroke	Hydro Power Units	1,013
Agricultural Equipment	Gas 4-stroke	Other Agricultural Equipment	789
Agricultural Equipment	Gas 4-stroke	Sprayers	10,269
Agricultural Equipment	Gas 4-stroke	Swathers	3,038
Agricultural Equipment	Gas 4-stroke	Tillers	149,592
Airport Ground Support Equipment	CNG 4-stroke	Air Conditioner	8
Airport Ground Support Equipment	CNG 4-stroke	Baggage Tug	188
Airport Ground Support Equipment	CNG 4-stroke	Belt Loader	50
Airport Ground Support Equipment	CNG 4-stroke	Bobtail	4
Airport Ground Support Equipment	CNG 4-stroke	Cargo Loader	23
Airport Ground Support Equipment	CNG 4-stroke	Cargo Tractor	91
Airport Ground Support Equipment	CNG 4-stroke	Catering Truck	17
Airport Ground Support Equipment	CNG 4-stroke	Forklift	301
Airport Ground Support Equipment	CNG 4-stroke	Fuel Truck	10
Airport Ground Support Equipment	CNG 4-stroke	Lav Truck	8
Airport Ground Support Equipment	CNG 4-stroke	Lift	8
Airport Ground Support Equipment	CNG 4-stroke	Other	44
Airport Ground Support Equipment	CNG 4-stroke	Passenger Stand	4
Airport Ground Support Equipment	CNG 4-stroke	Service Truck	44
Airport Ground Support Equipment	CNG 4-stroke	Sweeper	4
Airport Ground Support Equipment	Diesel	A/C Tug Narrow Body	289
Airport Ground Support Equipment	Diesel	A/C Tug Wide Body	72
Airport Ground Support Equipment	Diesel	Air Conditioner	55
Airport Ground Support Equipment	Diesel	Air Start Unit	178
Airport Ground Support Equipment	Diesel	Baggage Tug	613
Airport Ground Support Equipment	Diesel	Belt Loader	296

Table A-1. ARB Off-Road Inventory – Data Base Categories and 2012 Population (continued)

Class	Fuel	Equipment	Population
Airport Ground Support Equipment	Diesel	Bobtail	22
Airport Ground Support Equipment	Diesel	Cargo Loader	361
Airport Ground Support Equipment	Diesel	Cargo Tractor	6
Airport Ground Support Equipment	Diesel	Catering Truck	10
Airport Ground Support Equipment	Diesel	Compressor (GSE)	29
Airport Ground Support Equipment	Diesel	Forklift	33
Airport Ground Support Equipment	Diesel	Fuel Truck	27
Airport Ground Support Equipment	Diesel	Generator	260
Airport Ground Support Equipment	Diesel	Ground Power Unit	401
Airport Ground Support Equipment	Diesel	Hydrant Truck	14
Airport Ground Support Equipment	Diesel	Lav Truck	6
Airport Ground Support Equipment	Diesel	Lift	24
Airport Ground Support Equipment	Diesel	Other GSE	61
Airport Ground Support Equipment	Diesel	Passenger Stand	10
Airport Ground Support Equipment	Diesel	Service Truck	42
Airport Ground Support Equipment	Diesel	Sweeper	4
Airport Ground Support Equipment	Gas 4-stroke	A/C Tug Narrow Body	64
Airport Ground Support Equipment	Gas 4-stroke	A/C Tug Wide Body	26
Airport Ground Support Equipment	Gas 4-stroke	Air Conditioner	1
Airport Ground Support Equipment	Gas 4-stroke	Air Start Unit	29
Airport Ground Support Equipment	Gas 4-stroke	Baggage Tug	946
Airport Ground Support Equipment	Gas 4-stroke	Belt Loader	446
Airport Ground Support Equipment	Gas 4-stroke	Bobtail	135
Airport Ground Support Equipment	Gas 4-stroke	Cargo Loader	136
Airport Ground Support Equipment	Gas 4-stroke	Cargo Tractor	842
Airport Ground Support Equipment	Gas 4-stroke	Cart	27
Airport Ground Support Equipment	Gas 4-stroke	Catering Truck	90
Airport Ground Support Equipment	Gas 4-stroke	Deicer	42
Airport Ground Support Equipment	Gas 4-stroke	Forklift	129
Airport Ground Support Equipment	Gas 4-stroke	Fuel Truck	81
Airport Ground Support Equipment	Gas 4-stroke	Generator	6
Airport Ground Support Equipment	Gas 4-stroke	Ground Power Unit	106
Airport Ground Support Equipment	Gas 4-stroke	Hydrant truck	64
Airport Ground Support Equipment	Gas 4-stroke	Lav Cart	6
Airport Ground Support Equipment	Gas 4-stroke	Lav Truck	105
Airport Ground Support Equipment	Gas 4-stroke	Lift	205
Airport Ground Support Equipment	Gas 4-stroke	Maint. Truck	142
Airport Ground Support Equipment	Gas 4-stroke	Other GSE	231
Airport Ground Support Equipment	Gas 4-stroke	Passenger Stand	107
Airport Ground Support Equipment	Gas 4-stroke	Service Truck	446
Airport Ground Support Equipment	Gas 4-stroke	Sweeper	10

Table A-1. ARB Off-Road Inventory – Data Base Categories and 2012 Population (continued)

Class	Fuel	Equipment	Population
Airport Ground Support Equipment	Gas 4-stroke	Water Truck	33
Construction and Mining Equipment	Diesel	Bore/Drill Rigs	1,322
Construction and Mining Equipment	Diesel	Cement and Mortar Mixers	626
Construction and Mining Equipment	Diesel	Concrete/Industrial Saws	115
Construction and Mining Equipment	Diesel	Cranes	2,488
Construction and Mining Equipment	Diesel	Crawler Tractors	16,513
Construction and Mining Equipment	Diesel	Crushing/Proc. Equipment	1,054
Construction and Mining Equipment	Diesel	Dumpers/Tenders	27
Construction and Mining Equipment	Diesel	Excavators	19,846
Construction and Mining Equipment	Diesel	Graders	7,313
Construction and Mining Equipment	Diesel	Off-Highway Tractors	3,306
Construction and Mining Equipment	Diesel	Off-Highway Trucks	2,425
Construction and Mining Equipment	Diesel	Other Construction Equipment	1,422
Construction and Mining Equipment	Diesel	Pavers	3,044
Construction and Mining Equipment	Diesel	Paving Equipment	625
Construction and Mining Equipment	Diesel	Plate Compactors	362
Construction and Mining Equipment	Diesel	Rollers	8,963
Construction and Mining Equipment	Diesel	Rough Terrain Forklifts	6,932
Construction and Mining Equipment	Diesel	Rubber Tired Dozers	872
Construction and Mining Equipment	Diesel	Rubber Tired Loaders	20,056
Construction and Mining Equipment	Diesel	Scrapers	2,091
Construction and Mining Equipment	Diesel	Signal Boards	3,628
Construction and Mining Equipment	Diesel	Skid Steer Loaders	31,969
Construction and Mining Equipment	Diesel	Surfacing Equipment	127
Construction and Mining Equipment	Diesel	Tractors/Loaders/Backhoes	31,703
Construction and Mining Equipment	Diesel	Trenchers	8,738
Construction and Mining Equipment	Gas 2-stroke	Plate Compactors	292
Construction and Mining Equipment	Gas 2-stroke	Tampers/Rammers	3,403
Construction and Mining Equipment	Gas 4-stroke	Asphalt Pavers	320
Construction and Mining Equipment	Gas 4-stroke	Bore/Drill Rigs	362
Construction and Mining Equipment	Gas 4-stroke	Cement and Mortar Mixers	32,330
Construction and Mining Equipment	Gas 4-stroke	Concrete/Industrial Saws	4,679
Construction and Mining Equipment	Gas 4-stroke	Cranes	77
Construction and Mining Equipment	Gas 4-stroke	Crushing/Proc. Equipment	83
Construction and Mining Equipment	Gas 4-stroke	Dumpers/Tenders	2,173
Construction and Mining Equipment	Gas 4-stroke	Other Construction Equipment	70
Construction and Mining Equipment	Gas 4-stroke	Paving Equipment	23,229
Construction and Mining Equipment	Gas 4-stroke	Plate Compactors	12,401
Construction and Mining Equipment	Gas 4-stroke	Rollers	2,630
Construction and Mining Equipment	Gas 4-stroke	Rough Terrain Forklifts	156

Table A-1. ARB Off-Road Inventory – Data Base Categories and 2012 Population (continued)

Class	Fuel	Equipment	Population
Construction and Mining Equipment	Gas 4-stroke	Rubber Tired Loaders	190
Construction and Mining Equipment	Gas 4-stroke	Signal Boards	155
Construction and Mining Equipment	Gas 4-stroke	Skid Steer Loaders	5,429
Construction and Mining Equipment	Gas 4-stroke	Surfacing Equipment	6,203
Construction and Mining Equipment	Gas 4-stroke	Tampers/Rammers	164
Construction and Mining Equipment	Gas 4-stroke	Tractors/Loaders/Backhoes	88
Construction and Mining Equipment	Gas 4-stroke	Trenchers	2,834
Dredging	Diesel	Compressor (Dredging)	32
Dredging	Diesel	Crane (Dredging)	2
Dredging	Diesel	Deck/door engine	4
Dredging	Diesel	Dredger	35
Dredging	Diesel	Generator (Dredging)	89
Dredging	Diesel	Hoist/swing/winch	90
Dredging	Diesel	Other (Dredging)	10
Dredging	Diesel	Pump (Dredging)	53
Entertainment Equipment	Diesel	Compressor (Entertainment)	1
Entertainment Equipment	Diesel	Generator (Entertainment)	602
Industrial Equipment	CNG 4-stroke	Aerial Lifts	954
Industrial Equipment	CNG 4-stroke	Forklifts	28,770
Industrial Equipment	Diesel	Aerial Lifts	6,800
Industrial Equipment	Diesel	Forklifts	5,367
Industrial Equipment	Diesel	Other General Industrial Equipmen	5,383
Industrial Equipment	Diesel	Other Material Handling Equipment	250
Industrial Equipment	Diesel	Sweepers/Scrubbers	4,379
Industrial Equipment	Gas 2-stroke	Other General Industrial Equipmen	97
Industrial Equipment	Gas 4-stroke	Aerial Lifts	2,783
Industrial Equipment	Gas 4-stroke	Forklifts	15,188
Industrial Equipment	Gas 4-stroke	Other General Industrial Equipmen	1,862
Industrial Equipment	Gas 4-stroke	Other Material Handling Equipment	200
Industrial Equipment	Gas 4-stroke	Sweepers/Scrubbers	2,756
Lawn and Garden Equipment	Diesel	Chippers/Stump Grinders	511
Lawn and Garden Equipment	Diesel	Commercial Turf Equipment	11,247
Lawn and Garden Equipment	Diesel	Lawn & Garden Tractors	40,226
Lawn and Garden Equipment	Diesel	Leaf Blowers/Vacuums	20
Lawn and Garden Equipment	Diesel	Other Lawn & Garden Equipment	9
Lawn and Garden Equipment	Diesel	Snowblowers	82
Lawn and Garden Equipment	Gas 2-stroke	Chainsaws	1,736,335
Lawn and Garden Equipment	Gas 2-stroke	Chainsaws Preempt	893,200
Lawn and Garden Equipment	Gas 2-stroke	Commercial Turf Equipment	1,624
Lawn and Garden Equipment	Gas 2-stroke	Lawn Mowers	388,179

Table A-1. ARB Off-Road Inventory – Data Base Categories and 2012 Population (continued)

Class	Fuel	Equipment	Population
Lawn and Garden Equipment	Gas 2-stroke	Leaf Blowers/Vacuums	1,162,055
Lawn and Garden Equipment	Gas 2-stroke	Other Lawn & Garden Equipment	45,932
Lawn and Garden Equipment	Gas 2-stroke	Shredders	115,899
Lawn and Garden Equipment	Gas 2-stroke	Snowblowers	4,344
Lawn and Garden Equipment	Gas 2-stroke	Trimmers/Edgers/Brush Cutters	3,364,381
Lawn and Garden Equipment	Gas 4-stroke	Chippers/Stump Grinders	2,431
Lawn and Garden Equipment	Gas 4-stroke	Commercial Turf Equipment	16,569
Lawn and Garden Equipment	Gas 4-stroke	Front Mowers	410,941
Lawn and Garden Equipment	Gas 4-stroke	Lawn & Garden Tractors	258,375
Lawn and Garden Equipment	Gas 4-stroke	Lawn Mowers	4,596,635
Lawn and Garden Equipment	Gas 4-stroke	Leaf Blowers/Vacuums	14,682
Lawn and Garden Equipment	Gas 4-stroke	Other Lawn & Garden Equipment	870,444
Lawn and Garden Equipment	Gas 4-stroke	Rear Engine Riding Mowers	136,982
Lawn and Garden Equipment	Gas 4-stroke	Shredders	315,453
Lawn and Garden Equipment	Gas 4-stroke	Snowblowers	82,455
Lawn and Garden Equipment	Gas 4-stroke	Tillers	163,291
Lawn and Garden Equipment	Gas 4-stroke	Trimmers/Edgers/Brush Cutters	296,551
Lawn and Garden Equipment	Gas 4-stroke	Wood Splitters	362,724
Light Commercial Equipment	CNG 4-stroke	Gas Compressors	131
Light Commercial Equipment	CNG 4-stroke	Generator Sets	395
Light Commercial Equipment	Diesel	Air Compressors	9,447
Light Commercial Equipment	Diesel	Generator Sets	24,242
Light Commercial Equipment	Diesel	Pressure Washers	495
Light Commercial Equipment	Diesel	Pumps	46,283
Light Commercial Equipment	Diesel	Welders	12,893
Light Commercial Equipment	Gas 2-stroke	Generator Sets	4,198
Light Commercial Equipment	Gas 2-stroke	Pumps	21,026
Light Commercial Equipment	Gas 4-stroke	Air Compressors	13,044
Light Commercial Equipment	Gas 4-stroke	Generator Sets	303,150
Light Commercial Equipment	Gas 4-stroke	Pressure Washers	30,321
Light Commercial Equipment	Gas 4-stroke	Pumps	48,465
Light Commercial Equipment	Gas 4-stroke	Welders	40,320
Logging Equipment	Diesel	Fellers/Bunchers	1,909
Logging Equipment	Diesel	Shredders	1
Logging Equipment	Diesel	Skidders	876
Logging Equipment	Gas 2-stroke	Chainsaws	4,656
Logging Equipment	Gas 4-stroke	Shredders	7,305
Military Tactical Support Equip	Diesel	A/C unit	163
Military Tactical Support Equip	Diesel	Aircraft Support	68
Military Tactical Support Equip	Diesel	Cart	25

Table A-1. ARB Off-Road Inventory – Data Base Categories and 2012 Population (continued)

Class	Fuel	Equipment	Population
Military Tactical Support Equip	Diesel	Communications	10
Military Tactical Support Equip	Diesel	Compressor (Military)	195
Military Tactical Support Equip	Diesel	Crane	21
Military Tactical Support Equip	Diesel	Deicer	4
Military Tactical Support Equip	Diesel	Generator (Military)	1,443
Military Tactical Support Equip	Diesel	Hydraulic unit	67
Military Tactical Support Equip	Diesel	Lift (Military)	2
Military Tactical Support Equip	Diesel	Light	5
Military Tactical Support Equip	Diesel	Other tactical support equipment	42
Military Tactical Support Equip	Diesel	Pressure Washers	3
Military Tactical Support Equip	Diesel	Pump (Military)	103
Military Tactical Support Equip	Diesel	Start Cart	2
Military Tactical Support Equip	Diesel	Test Stand	78
Military Tactical Support Equip	Diesel	Welder	79
Oil Drilling	Diesel	Compressors (Workover)	99
Oil Drilling	Diesel	Drill Rig	1,306
Oil Drilling	Diesel	Generator (Drilling)	86
Oil Drilling	Diesel	Generator (Workover)	132
Oil Drilling	Diesel	Lift (Drilling)	86
Oil Drilling	Diesel	Other Workover Equipment	271
Oil Drilling	Diesel	Pressure Washers	1
Oil Drilling	Diesel	Pump (Drilling)	436
Oil Drilling	Diesel	Pump (Workover)	460
Oil Drilling	Diesel	Snubbing	3
Oil Drilling	Diesel	Swivel	84
Other Portable Equipment	Diesel	Misc Portable Equipment	92
Pleasure Craft	Diesel	Sailboat Auxiliary Inboard Engine	5,404
Pleasure Craft	Diesel	Vessels w/Inboard Engines	9,620
Pleasure Craft	Gas 2-stroke	Personal Water Craft	531,912
Pleasure Craft	Gas 2-stroke	Sailboat Auxiliary Outboard Engine	4,380
Pleasure Craft	Gas 2-stroke	Vessels w/Outboard Engines	435,125
Pleasure Craft	Gas 4-stroke	Sailboat Auxiliary Inboard Engine	3,481
Pleasure Craft	Gas 4-stroke	Vessels w/Inboard Engines	117,753
Pleasure Craft	Gas 4-stroke	Vessels w/Inboard Jet Engines	32,811
Pleasure Craft	Gas 4-stroke	Vessels w/Outboard Engines	22,084
Pleasure Craft	Gas 4-stroke	Vessels w/Sterndrive Engines	337,081
Railyard Operations	Diesel	Compressor (Railyard)	2
Railyard Operations	Diesel	Crane (Rail-CHE)	4
Railyard Operations	Diesel	Generator (Railyard)	2
Railyard Operations	Diesel	Materials Handling (Rail-CHE)	1

Table A-1. ARB Off-Road Inventory – Data Base Categories and 2012 Population (continued)

Class	Fuel	Equipment	Population
Recreational Equipment	Gas 2-stroke	All Terrain Vehicles (ATVs)	62,258
Recreational Equipment	Gas 2-stroke	Golf Carts	4,785
Recreational Equipment	Gas 2-stroke	Off-Road Motorcycles	235,783
Recreational Equipment	Gas 2-stroke	Snowmobiles	24,708
Recreational Equipment	Gas 2-stroke	Specialty Vehicles Carts	59,983
Recreational Equipment	Gas 4-stroke	All Terrain Vehicles (ATVs)	314,819
Recreational Equipment	Gas 4-stroke	Golf Carts	3,744
Recreational Equipment	Gas 4-stroke	Minibikes	11,253
Recreational Equipment	Gas 4-stroke	Off-Road Motorcycles	161,620
Recreational Equipment	Gas 4-stroke	Specialty Vehicles Carts	40,861
Transport Refrigeration Units	Diesel	Transport Refrigeration Units	69,430
Transport Refrigeration Units	Gas 4-stroke	Transport Refrigeration Units	5,568

Table A-2. California Off-Road Equipment Exhaust Emissions in 2017 (tons/day)

Fuel	ROG	CO	NO_x	CO_2	SO_2	PM	N_2O	CH_4
Total Off-Road Engines								
CNG 4-stroke	2	99	11	2,457	0.00	0.22	0.00	1.97
Diesel	35	217	257	48,614	0.54	11.73	0.00	3.15
Gasoline 2-stroke	267	725	15	1,992	0.40	15.33	0.94	14.72
Gasoline 4-stroke	55	1,930	51	8,540	0.50	4.96	3.76	3.10
TOTAL	359	2,971	333	61,604	1.45	32.24	4.70	22.94
Off-Road Vehicles								
CNG 4-stroke	2	90	10	2,223	0.00	0.20	0.00	1.78
Diesel	11	59	79	13,876	0.15	3.74	0.00	0.97
Gasoline 2-stroke	145	428	6	500	0.37	3.21	0.24	7.93
Gasoline 4-stroke	7	282	10	2,108	0.40	0.51	1.24	0.36
TOTAL	164	859	105	18,707	0.92	7.66	1.48	11.04
Agricultural Equipment								
Diesel	8	41	56	8,598	0.10	3.00	0.00	0.70
Gasoline 4-stroke	1	57	1	183	0.00	0.16	0.10	0.08
TOTAL	9	98	58	8,781	0.10	3.16	0.10	0.78
Logging Equipment								
Diesel	0.4	3.2	2.7	739	0.01	0.14	0.00	0.04
Gasoline 2-stroke	2.0	4.2	0.0	9	0.00	0.01	0.00	0.10
Gasoline 4-stroke	0.2	9.5	0.2	15	0.00	0.12	0.01	0.01
TOTAL	2.6	16.9	2.9	762	0.01	0.26	0.02	0.15
Forklifts (excluding rough terrain forklifts)								
CNG 4-stroke	2.1	89	9.8	2,191	0.00	0.19	0.00	1.75
Diesel	0.5	3	3.3	732	0.01	0.16	0.00	0.05
Gasoline 4-stroke	1.5	139	5.7	1,285	0.01	0.10	0.34	0.08
TOTAL	4.2	230	18.9	4,209	0.02	0.46	0.34	1.88
Transport Refrigeration Units								
Diesel	3.3	32.1	28.1	4,113	0.05	0.76	0.00	0.30
Gasoline 4-stroke	0.4	19.6	0.3	33	0.00	0.02	0.03	0.02
TOTAL	3.7	51.7	28.3	4,145	0.05	0.77	0.03	0.32

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Source: ARB Off-Road Database, selected from TTW Off_Road 2017.xls

Table A-3. California Off-Road Equipment Exhaust Emissions in 2017 (g/gal)

Fuel	ROG	CO	NO_x	CO_2	SO_2	PM	N_2O	CH_4
Total Off-Road Engines								
CNG 4-stroke	6	243	26	5,992	0.00	0.54	0.00	4.80
Diesel	7	45	53	9,974	0.11	2.41	0.00	0.65
Gasoline 2-stroke	563	1,530	32	4,206	0.85	32.36	1.99	31.08
Gasoline 4-stroke	41	1,434	38	6,345	0.37	3.69	2.79	2.30
TOTAL	51	418	47	8,672	0.20	4.54	0.66	3.23
Off-Road Vehicles								
CNG 4-stroke	6	243	27	5,992	0.00	0.53	0.00	4.81
Diesel	8	42	57	9,976	0.11	2.69	0.00	0.70
Gasoline 2-stroke	735	2,174	28	2,538	1.89	16.32	1.23	40.27
Gasoline 4-stroke	22	958	34	7,166	1.35	1.73	4.21	1.23
TOTAL	73	381	47	8,303	0.41	3.40	0.66	4.90
Agricultural Equipment								
Diesel	9	48	65	9,961	0.11	3.48	0.00	0.81
Gasoline 4-stroke	44	1,783	41	5,785	0.11	4.90	3.03	2.46
TOTAL	10	110	64	9,813	0.11	3.53	0.11	0.87
Logging Equipment								
Diesel	6	43	37	9,983	0.11	1.84	0.00	0.51
Gasoline 2-stroke	745	1,576	12	3,441	0.14	2.00	1.65	39.28
Gasoline 4-stroke	68	2,727	50	4,210	0.12	35.29	4.07	3.60
TOTAL	33	211	37	9,515	0.11	3.30	0.23	1.93
Forklifts (excluding rough terrain forklifts)								
CNG 4-stroke	6	243	27	5,992	0.00	0.53	0.00	4.78
Diesel	7	40	45	9,981	0.11	2.19	0.00	0.66
Gasoline 4-stroke	9	804	33	7,457	0.07	0.58	1.95	0.49
TOTAL	7	377	31	6,884	0.03	0.75	0.55	3.08
Transport Refrigeration Units								
Diesel	8	77	68	9,920	0.13	1.82	0.00	0.72
Gasoline 4-stroke	51	2,648	36	4,398	0.13	2.46	3.72	2.87
TOTAL	9	123	67	9,823	0.13	1.83	0.07	0.75

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Source: ARB Off-Road Database, selected from TTW Off_Road 2017.xls

Table A-4. California Off-Road Equipment Exhaust Emissions in 2022 (tons/day)

Fuel	ROG	CO	NO_x	CO_2	SO_2	PM	N_2O	CH_4
Total Off-Road Engines								
CNG 4-stroke	2	102	11	2,517	0.00	0.23	0.00	1.99
Diesel	26	220	171	49,397	0.55	5.87	0.00	2.38
Gasoline 2-stroke	248	704	17	2,049	0.44	15.09	0.99	13.70
Gasoline 4-stroke	54	1,964	49	8,842	0.54	5.07	3.83	3.01
TOTAL	331	2,990	248	62,805	1.53	26.25	4.82	21.08
Off-Road Vehicles								
CNG 4-stroke	2	93	10	2,281	0.00	0.20	0.00	1.81
Diesel	7	57	51	13,853	0.15	1.97	0.00	0.66
Gasoline 2-stroke	138	427	7	540	0.40	2.91	0.28	7.55
Gasoline 4-stroke	7	293	10	2,152	0.43	0.53	1.31	0.38
TOTAL	154	870	78	18,826	0.99	5.61	1.58	10.40
Agricultural Equipment								
Diesel	5	40	36	8,532	0.10	1.64	0.00	0.45
Gasoline 4-stroke	1	56	1	184	0.00	0.16	0.09	0.07
TOTAL	6	95	37	8,715	0.10	1.80	0.09	0.52
Logging Equipment								
Diesel	0.3	3.2	1.3	739	0.01	0.04	0.00	0.03
Gasoline 2-stroke	2.0	4.2	0.0	9	0.00	0.01	0.00	0.10
Gasoline 4-stroke	0.2	9.5	0.2	15	0.00	0.12	0.01	0.01
TOTAL	2.5	16.9	1.5	762	0.01	0.17	0.02	0.14
Forklifts (excluding rough terrain forklifts)								
CNG 4-stroke	2.1	92	9.9	2,249	0.00	0.20	0.00	1.78
Diesel	0.4	3	1.7	737	0.01	0.06	0.00	0.03
Gasoline 4-stroke	1.5	140	5.7	1,294	0.01	0.10	0.34	0.08
TOTAL	4.0	235	17.4	4,280	0.02	0.36	0.34	1.89
Transport Refrigeration Units								
Diesel	3.8	38.2	27.6	4,781	0.06	0.26	0.00	0.35
Gasoline 4-stroke	0.4	19.6	0.3	32	0.00	0.02	0.03	0.02
TOTAL	4.2	57.7	27.9	4,814	0.06	0.28	0.03	0.37

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Source: ARB Off-Road Database, selected from TTW Off_Road 2022.xls

Table A-5. California Off-Road Equipment Exhaust Emissions in 2022 (g/gal)

Fuel	ROG	CO	NO$_x$	CO$_2$	SO$_2$	PM	N$_2$O	CH$_4$
Total Off-Road Engines								
CNG 4-stroke	6	243	26	5,991	0.00	0.54	0.00	4.73
Diesel	5	44	35	9,982	0.11	1.19	0.00	0.48
Gasoline 2-stroke	529	1,503	35	4,376	0.93	32.22	2.11	29.25
Gasoline 4-stroke	39	1,417	35	6,380	0.39	3.66	2.77	2.17
TOTAL	46	414	34	8,695	0.21	3.63	0.67	2.92
Off-Road Vehicles								
CNG 4-stroke	6	244	26	5,991	0.00	0.53	0.00	4.74
Diesel	5	41	36	9,988	0.11	1.42	0.00	0.48
Gasoline 2-stroke	695	2,155	35	2,722	2.04	14.69	1.39	38.09
Gasoline 4-stroke	23	973	33	7,140	1.43	1.74	4.34	1.25
TOTAL	68	384	34	8,303	0.44	2.48	0.70	4.59
Agricultural Equipment								
Diesel	6	46	42	9,977	0.11	1.92	0.00	0.53
Gasoline 4-stroke	38	1,766	32	5,834	0.11	5.01	2.88	2.14
TOTAL	7	107	42	9,830	0.11	2.02	0.10	0.59
Logging Equipment								
Diesel	4	43	17	9,990	0.11	0.55	0.00	0.35
Gasoline 2-stroke	745	1,576	12	3,441	0.14	2.00	1.65	39.28
Gasoline 4-stroke	68	2,727	50	4,210	0.12	35.29	4.07	3.60
TOTAL	31	211	18	9,521	0.11	2.11	0.23	1.79
Forklifts (excluding rough terrain forklifts)								
CNG 4-stroke	6	244	26	5,991	0.00	0.53	0.00	4.73
Diesel	5	40	23	9,991	0.11	0.84	0.00	0.46
Gasoline 4-stroke	9	807	33	7,453	0.07	0.58	1.94	0.48
TOTAL	6	377	28	6,872	0.03	0.58	0.54	3.04
Transport Refrigeration Units								
Diesel	8	79	57	9,917	0.13	0.54	0.00	0.72
Gasoline 4-stroke	51	2,649	36	4,397	0.13	2.46	3.72	2.87
TOTAL	9	118	57	9,833	0.13	0.57	0.06	0.75

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Source: ARB Off-Road Database, selected from TTW Off_Road 2022.xls

Table A-6. California Off-Road Equipment Exhaust Emissions in 2030 (tons/day)

Fuel	ROG	CO	NO_x	CO_2	SO_2	PM	N_2O	CH_4
Total Off-Road Engines								
CNG 4-stroke	2	102	11	2,517	0.00	0.23	0.00	1.99
Diesel	21	218	117	49,397	0.55	2.31	0.00	1.86
Gasoline 2-stroke	224	660	17	2,148	0.44	15.85	1.01	12.37
Gasoline 4-stroke	52	1,951	47	8,842	0.54	5.07	3.80	2.89
TOTAL	299	2,932	193	62,904	1.53	23.45	4.81	19.11
Off-Road Vehicles								
CNG 4-stroke	2	93	10	2,281	0.00	0.20	0.00	1.80
Diesel	5	56	30	13,853	0.15	0.69	0.00	0.46
Gasoline 2-stroke	134	421	7	540	0.40	2.77	0.28	7.34
Gasoline 4-stroke	7	294	10	2,152	0.43	0.53	1.31	0.38
TOTAL	148	863	57	18,826	0.99	4.20	1.58	9.98
Agricultural Equipment								
Diesel	3	39	20	8,532	0.10	0.54	0.00	0.29
Gasoline 4-stroke	1	55	1	184	0.00	0.16	0.09	0.06
TOTAL	4	94	21	8,715	0.10	0.70	0.09	0.35
Logging Equipment								
Diesel	0.2	3.2	0.7	739	0.01	0.02	0.00	0.02
Gasoline 2-stroke	2.0	4.2	0.0	9	0.00	0.01	0.00	0.10
Gasoline 4-stroke	0.2	9.5	0.2	15	0.00	0.12	0.01	0.01
TOTAL	2.5	16.9	0.9	762	0.01	0.14	0.02	0.14
Forklifts (excluding rough terrain forklifts)								
CNG 4-stroke	2.1	92	9.9	2,249	0.00	0.20	0.00	1.78
Diesel	0.3	3	0.8	737	0.01	0.02	0.00	0.03
Gasoline 4-stroke	1.5	140	5.7	1,294	0.01	0.10	0.34	0.08
TOTAL	3.9	235	16.5	4,280	0.02	0.32	0.34	1.89
Transport Refrigeration Units								
Diesel	3.8	38.2	26.8	4,781	0.06	0.18	0.00	0.35
Gasoline 4-stroke	0.4	19.6	0.3	32	0.00	0.02	0.03	0.02
TOTAL	4.2	57.8	27.1	4,814	0.06	0.20	0.03	0.37

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Source: ARB Off-Road Database, selected from TTW Off_Road 2030.xls

Table A-7. California Off-Road Equipment Exhaust Emissions in 2030 (g/gal)

Fuel	ROG	CO	NO_x	CO_2	SO_2	PM	N_2O	CH_4
Total Off-Road Engines								
CNG 4-stroke	6	244	26	5,991	0.00	0.54	0.00	4.73
Diesel	4	44	24	9,988	0.11	0.47	0.00	0.38
Gasoline 2-stroke	486	1,431	37	4,655	0.95	34.35	2.19	26.82
Gasoline 4-stroke	37	1,411	34	6,395	0.39	3.66	2.75	2.09
TOTAL	41	407	27	8,725	0.21	3.25	0.67	2.65
Off-Road Vehicles								
CNG 4-stroke	6	244	26	5,990	0.00	0.53	0.00	4.74
Diesel	4	41	22	9,995	0.11	0.50	0.00	0.33
Gasoline 2-stroke	685	2,153	37	2,763	2.07	14.20	1.43	37.56
Gasoline 4-stroke	22	974	32	7,139	1.43	1.74	4.33	1.25
TOTAL	65	381	25	8,317	0.44	1.85	0.70	4.41
Agricultural Equipment								
Diesel	4	45	23	9,987	0.11	0.63	0.00	0.34
Gasoline 4-stroke	34	1,757	28	5,862	0.11	5.02	2.80	1.93
TOTAL	5	106	24	9,841	0.11	0.78	0.10	0.39
Logging Equipment								
Diesel	3	43	9	9,994	0.11	0.21	0.00	0.29
Gasoline 2-stroke	745	1,576	12	3,441	0.14	2.00	1.65	39.28
Gasoline 4-stroke	68	2,727	50	4,210	0.12	35.29	4.07	3.60
TOTAL	31	211	11	9,524	0.11	1.80	0.23	1.73
Forklifts (excluding rough terrain forklifts)								
CNG 4-stroke	6	244	26	5,990	0.00	0.53	0.00	4.75
Diesel	4	40	12	9,996	0.11	0.27	0.00	0.36
Gasoline 4-stroke	9	807	33	7,453	0.07	0.58	1.94	0.48
TOTAL	6	377	26	6,872	0.03	0.51	0.54	3.04
Transport Refrigeration Units								
Diesel	8	79	56	9,916	0.13	0.37	0.00	0.72
Gasoline 4-stroke	51	2,649	36	4,397	0.13	2.46	3.72	2.87
TOTAL	9	118	55	9,833	0.13	0.40	0.06	0.75

off road EXHAUST2012_export tables.xls

Source: ARB Off-Road Database, selected from TTW Off_Road 2030.xls