

Determining relative air quality impacts of various personal vehicle options in 2050

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1. INTRODUCTION

There is considerable pressure in the state of California and throughout the world to consider, promote, and even mandate alternative vehicles and fuels to improve air quality and to reduce greenhouse gas emissions and fuel consumption. Ozone and other criteria pollutant concentrations as well as particulate formation and transport will be impacted by changes in vehicle types, miles traveled and emissions as well as atmospheric physics and chemistry. A thorough and scientifically sound analysis of both the emissions and atmospheric physics and chemistry is required to understand the environmental impacts and to make wise decisions amongst the possible alternative vehicle and fuel options. The current project develops detailed spatially- and temporally-resolved emissions inventories for personal vehicle and fuel options *and* assesses environmental impacts with a state-of-the-art air quality model.

Previous studies evaluated air quality impacts of hybrid-electric and fuel cell vehicles in the US relative to the existing conventional vehicle technology (Colella et al., 2005, Jacobson et al., 2005). These studies assumed that emissions from hybrid vehicles were lower than conventional vehicles proportionally to their respective gas mileage. Results showed moderate improvements in air quality due to hybrid-electric vehicle implementation. Recently, plug-in hybrid electric (PHEV) have received major attention as General Motors and Toyota are developing their first PHEV models to be commercialized by 2010. Based on the recent developments, PHEV technology is closer to be commercialized than fuel cell vehicles. In addition, development of PHEV vehicles is helping the development of battery technologies, which in turn, will help the development of battery-electric vehicle models in the future.

This report presents results from a rigorous study that includes development of spatially and temporally resolved emissions scenarios for various alternative vehicle options. Resulting emissions fields are included in detailed simulations of potential air quality impacts using a comprehensive atmospheric chemistry and transport model solved on a 252-node super-computer. The predicted air quality impacts are then used to evaluate the relative air quality impacts of alternative vehicle options involving battery-electric, hybrid-electric and plug-in hybrid-electric technologies in the South Coast Air Basin in 2050. Information on vehicle activity for the SoCAB is used to develop detailed performance characteristics and emissions inventories for each vehicle and fuel type option. Air quality impacts are then determined by simulation of the atmospheric chemistry and transport for each case.

2. PERSONAL VEHICLE TYPES

The present study analyzes the effect of widespread implementation of vehicle hybrid technologies on air quality, relative to the current technology mix for automobiles. The methodology consists in assuming that all light-duty automobiles (LDA) are substituted by hybrid electric vehicles, which can incorporate plug-in capabilities, or with pure electric vehicles. This section describes the vehicular options considered in the present study.

2.1 Baseline Light-Duty Automobile (LDA)

The baseline light-duty automobile (LDA) assumed in this study corresponds to the automobile mix that the EMFAC model estimates will be present in the SoCAB in the year of study, namely 2050. The EMFAC model is developed by the ARB, and uses information on vehicle activity from the Department of Motor Vehicles and the California Transportation Department. The total emissions from vehicles can then be calculated using emission factors derived from vehicle testing. These emission factors depend on the number of starts, the ambient conditions and the speed of the vehicle, among other factors. Results from the EMFAC model provide emissions from vehicle operation, as well as evaporative emissions of VOC, and particle emissions from braking and tire wear (ARB, 2007).

Figure 1 shows the relative change in vehicular activity, emissions from on-road mobile sources and fuel use for the period 2010-2040. Although the number vehicles, trips and vehicle miles traveled are estimated to increase, emissions of criteria pollutants are expected to decrease due to reduction of vehicle tailpipe emissions. This reduction is caused by the progressive market penetration of low-emitting vehicles, and the gradual retirement of higher-emitting older models.

Table 1 presents the emission factors for an average light-duty automobile for the year 2050. The emission factors are disaggregated into two factors: (1) emission factors for normal operation, i.e. emissions from driving, and (2) emission factors for start-up emissions. In addition, Table 1 presents the contribution of operation and start-up emissions to total emissions from LDA. More than 85% of emissions correspond to normal operation, whereas start-up contributes to less than 15% to total LDA emissions.

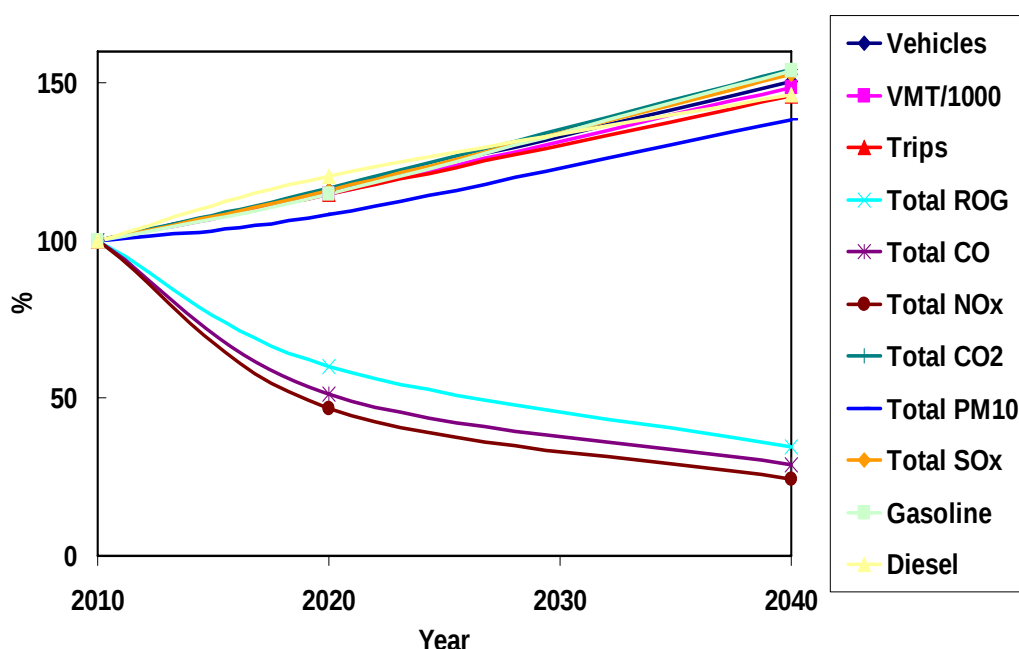


Figure 1. Trends in on-road mobile emissions, fuel usage and vehicular activity estimated by EMFAC version 2.2 (April 2003) for the period 2010 to 2040.

Table 1. Emission factors for vehicle operation and start-up, for an average light-duty vehicle estimated for the year 2050, and the contribution of normal operation and start-up emissions to total emissions from light-duty vehicles

	Emission Factors		Total contribution	
	LDA operation (g/mile)	LDA start-up (g/start)	LDA operation (%)	LDA start-up (%)
VOC	0.063	0.027	92.60	7.40
NO _x	0.032	0.026	86.76	13.24
CO	0.545	0.518	84.87	15.13
SO _x	0.004	--	100.00	--
PM _{2.5}	0.014	0.007	91.76	8.24

2.2 Hybrid Electric Vehicle (HEV)

The hybrid electric vehicle considered in this study is based on the 2000 Toyota Prius. The specifications for this model are presented in Table 2. This model has been upgraded with more powerful engine and electric motor in subsequent versions. However, emissions from newer versions are not readily available. Hence, emissions from the 2000 Toyota Prius are used in this report to estimate the emissions from hybrid vehicles. These estimates could represent an upper bound for emissions as newer

versions of hybrid vehicles will eventually emit at a lower rate. The emission factors for the 2000 Prius are presented in Table 3. As there is little information on start-up emissions from HEV, this study assumes the same start-up emission factors as in the case of LDA. Furthermore, as current models of Prius are certified as AT-PZEV, which implies that these vehicle guarantee zero evaporative emissions for the first 150,000 miles, evaporative emissions from HEV are neglected. Further studies on vehicle emissions will help develop a better understanding of emissions from HEV, both from normal operation and start-up emissions.

Table 2. Technical specifications for the 2000 Toyota Prius

Specifications	Value
Curb Weight:	1254 kg
Engine Specifications:	1.5 L inline 4 cylinder 52 kW at 4500 rpm 111 Nm at 4200 rpm
Electric Motor:	33 kW at 1040-5600 rpm 350 Nm at 0-400 rpm
Batteries:	NiMH, 228 cells at 1.2 V each
Mileage (city/hwy):	4.5/4.6 L/100 km
Emissions control:	three-way catalyst

Table 3. Emission factors for the 2000 Toyota Prius (from Graham, 2006)

	Prius 2000 (g km⁻¹)^a
CO	0.070
NO _x	0.008
NMHC	0.004
NMOG	0.004
HCHO	0.0001
PM	0.004
TC	0.0002

2.3 Plug-in Hybrid Electric Vehicle (PHEV)

Future plug-in electric vehicles have the potential to allow for all-electric range driving cycles for daily average trip mileage. Some automakers are developing architectures that would allow an all-electric range of 40 miles, which would meet the daily range for an average passenger vehicle. Such range would imply that PHEV would be a truly flex-fuel vehicle, since the vehicle could achieve the daily mileage with electric propulsion only, as well as with the internal combustion only, or a combination of both.

However, there remain some challenges that have to be overcome until a 40-mile range is achieved. Recently, Toyota announced that a first commercial PHEV version of the Prius will be available by 2010, with all-electric autonomy of 8 miles. General Motors is developing the GM Volt with the expectation of meeting the 40-mile all-electric range, although it is still facing challenges with the battery.

This report analyzes the emissions from PHEV with different all-electric ranges. In general, control strategies for PHEV are designed in a way that there is an all-electric range, in which the state of charge (SOC) of the battery is depleted down to a lower limit. This driving cycle is generally termed as charge-depleting mode. Once this lower limit is achieved, the engine is turned on so that the SOC is sustained. Such condition is termed as charge-sustaining mode. Hybrid vehicles operate in charge-sustaining mode exclusively. The all-electric range of the PHEV is determined by the size of the battery, the lower limit for the SOC before the vehicle goes into charge-sustaining mode and the power and energy demand during the driving cycle. Recent studies suggest that PHEV20 (PHEV with 20-mile all-electric range) would reduce significantly the consumption of oil, but the estimated high capital costs for longer all-electric ranges would be hardly justified by the savings in fuel consumption. However, there is a high uncertainty in the future price of oil that can affect the economics of PHEV.

For the present study, all-electric ranges of 8, 20 and 40 miles are analyzed. The Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) cycles are used currently by the US Environmental Protection Agency to determine urban and highway gas mileage for vehicles. These two cycles require an energy demand of 5 kWh and a peak power of 45 kW for an all-electric range of 20 miles. Energy and power requirements for 8-mile and 40-mile all-electric ranges can be extrapolated linearly. Some studies suggest that UDDS and HWFET cycles misrepresent present urban and highway driving conditions and that the Unified Driving Cycle – also known as LA92 – and the US06 cycle, which is part of the Supplemental Federal Test Procedure, represent better up-to-date driving conditions. These two newer cycles correspond to more aggressive driving behaviors that would require up to 7.5 kWh of total energy and nearly 150 kW of peak power for an all-electric range of 20 miles (Markel and Simpson, 2005). The UDDS/HWFET and the LA92/US06 energy requirements are used herein as a lower and upper bound, respectively, for the electricity demand for plug-in hybrid vehicles.

Longer all-electric ranges do not imply necessarily downsizing of the internal combustion engine of the PHEV. On the contrary, there is a minimal power requirement for the engine of a hybrid configuration based on performance criteria (Simpson, 2005). As a result, this study assumes that the combustion engine for all the PHEV models is the same as in the 2000 Toyota Prius. Consequently, emissions from PHEV in charge-sustaining mode are equivalent to the emissions from HEV.

2.4 Pure Electric Vehicle (PEV)

Electric vehicle models, such as the General Motors EV1 and the Toyota RAV4EV, have proven mileage range over 100 miles. Such mileage range implies a battery storage capacity of nearly 40 kWh, assuming vehicle electricity consumption of 375 Wh/mile. For this study, no considerations are made in terms of the battery size or cost. The PEV are assumed to consume 7.5 kWh in a 20-mile range for the LA92/US06 cycle, and this level of consumption is used to estimate the total needs of electricity for the PEV.

3. VEHICLE ACTIVITY

Information on vehicle activity, such as hourly distribution of trips and trip length, is necessary to estimate the average mileage of the vehicle fleet considered in this study. For cases in which PHEV are considered, hourly vehicle activity will determine the fraction of vehicles that will be able to operate in purely electric mode, as well as the portion of vehicles that will need to operate in charge-sustaining mode once the all-electric range has been attained. These estimates on battery use and engine use will allow calculating emissions from charging batteries and from HEV operation.

The EMFAC model uses information on daily trip frequency based on California Transportation Department, and hourly vehicle activity collected by the EPA in three different metropolitan areas: Baltimore, Maryland; Spokane, Washington; and Atlanta, Georgia. The pondered values of trip frequency distribution used by EMFAC are shown in Table 4.

Based on current information of vehicle registration from the department of motor vehicles of California and travel surveys by Caltrans, EMFAC projects for the year 2040 a total of 2.23×10^8 miles traveled by light-duty vehicles and a total of 4.19×10^7 daily trips. Using linear extrapolation, total number of daily VMT and trips in 2050 increase up to 2.39×10^8 and 4.48×10^7 , respectively. Then, hourly distribution of trips and VMT – shown in Figure 2(a) and (b) – are obtained using the trip frequency distribution presented in Table 4, and the total daily trips and VMT.

Table 4. Hourly trip frequency distribution as a function of trip length. Values based on information collected by EPA in Baltimore, Maryland; Spokane, Washington; and Atlanta, Georgia.

TIME (hour)	Vehicle Miles Travelled (VMT) Range Bins										
	< 1 (%)	1-5 (%)	5-10 (%)	10-15 (%)	15-20 (%)	20-25 (%)	25-30 (%)	30-35 (%)	35-40 (%)	40-45 (%)	> 45 (%)
0	0.18	0.40	0.11	0.06	0.00	0.01	0.05	0.03	0.00	0.00	0.00
1	0.13	0.14	0.11	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
2	0.01	0.04	0.06	0.03	0.00	0.00	0.01	0.00	0.00	0.00	0.00
3	0.01	0.08	0.05	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.03	0.11	0.03	0.05	0.06	0.00	0.00	0.00	0.00	0.00	0.00
5	0.01	0.17	0.09	0.09	0.05	0.03	0.00	0.00	0.00	0.00	0.00
6	0.28	0.61	0.36	0.19	0.17	0.13	0.06	0.00	0.00	0.01	0.07
7	1.08	2.34	1.03	0.59	0.22	0.19	0.13	0.09	0.00	0.01	0.03
8	1.12	2.21	1.35	0.40	0.20	0.23	0.08	0.01	0.00	0.01	0.02
9	1.25	2.14	0.84	0.26	0.14	0.05	0.00	0.01	0.01	0.00	0.01
10	1.34	2.34	0.73	0.37	0.09	0.15	0.01	0.03	0.01	0.00	0.00
11	2.19	3.32	1.15	0.24	0.14	0.08	0.03	0.01	0.00	0.00	0.03
12	2.72	3.83	1.03	0.43	0.18	0.04	0.05	0.03	0.01	0.00	0.00
13	1.76	3.45	1.07	0.26	0.19	0.06	0.05	0.03	0.03	0.01	0.02
14	2.02	3.37	1.14	0.38	0.19	0.14	0.06	0.01	0.04	0.00	0.04
15	2.36	3.10	1.39	0.37	0.26	0.15	0.04	0.04	0.01	0.01	0.02
16	1.88	3.16	1.33	0.65	0.15	0.13	0.05	0.06	0.01	0.00	0.01
17	1.90	3.46	1.45	0.40	0.29	0.20	0.08	0.05	0.04	0.03	0.00
18	1.80	3.00	0.88	0.37	0.10	0.17	0.03	0.03	0.00	0.03	0.01
19	1.49	2.34	0.73	0.32	0.10	0.05	0.03	0.04	0.01	0.01	0.00
20	0.96	1.39	0.64	0.26	0.06	0.03	0.06	0.00	0.01	0.00	0.01
21	0.80	1.19	0.43	0.26	0.14	0.06	0.04	0.03	0.03	0.00	0.00
22	0.54	0.82	0.36	0.19	0.09	0.04	0.01	0.03	0.01	0.01	0.00
23	0.59	0.68	0.26	0.08	0.05	0.03	0.05	0.00	0.03	0.00	0.00

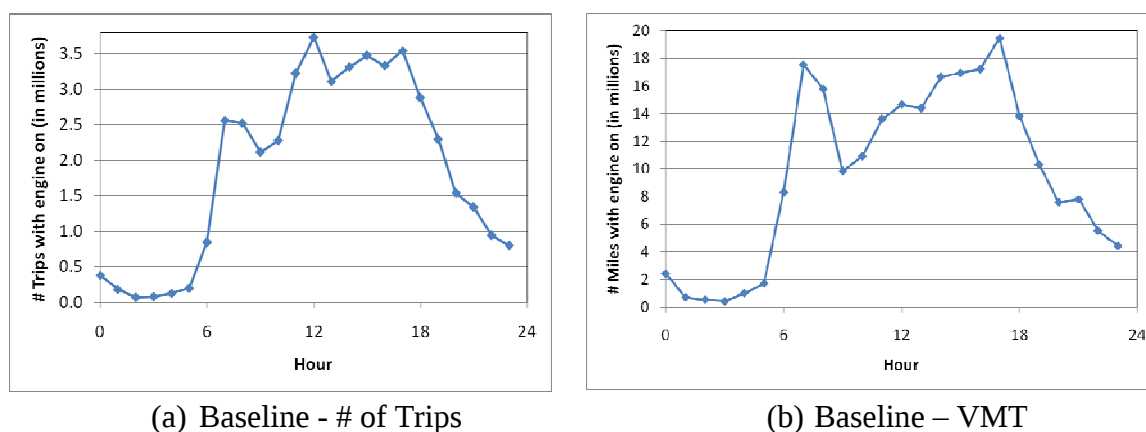


Figure 2. Hourly distribution of number of trips and vehicle miles traveled of all light-duty vehicles estimated for the South Coast Air Basin of California in the year 2050.

Once the overall vehicle activity is obtained, information on vehicle daily mileage is needed to determine the overall daily range of a vehicle. For a given all-electric range of a PHEV, information on daily mileage per vehicle allow calculating the fraction of miles that a PHEV can drive with the electric motor, as well as the fraction of miles for which a PHEV need to use the internal combustion engine. For a scenario that assumes that 100% of light-duty vehicles are PHEV_x, being *x* the all-electric range for that PHEV, the methodology to obtain the total miles under conditions of all-electric charge depleting and charge sustaining modes is as follows:

1. Assume hourly distribution of trips by vehicle and a charging cycle:

According to EMFAC, the number of daily trips per vehicle is 6.15. Additionally, the distribution of number of trips can be calculated from adding the hourly frequencies of trips for all mileage ranges presented in Table 4. Assuming one charge per day and the start of the daily activity at 6 am, the cumulative number of trips as a function of time is calculated and presented in Table 5.

Table 5. Hourly distribution of trip starts and estimated hourly cumulative number of trips of an average light-duty vehicle assuming the start of daily activity at 6 am.

Time of day	(hour)	0	1	2	3	4	5	6	7	8	9	10	11
Trip starts	(%)	0.8	0.4	0.2	0.2	0.3	0.5	1.9	5.7	5.6	4.7	5.1	7.2
Cumulative number of trips		6.1	6.1	6.1	6.1	6.1	6.2	0.1	0.5	0.8	1.1	1.4	1.9

Time of day	(hour)	12	13	14	15	16	17	18	19	20	21	22	23
Trip starts	(%)	8.3	6.9	7.4	7.8	7.4	7.9	6.4	5.1	3.4	3	2.1	1.8
Cumulative number of trips		2.4	2.8	3.3	3.7	4.2	4.7	5.1	5.4	5.6	5.8	5.9	6.0

2. Multiply the cumulative number of trips by the average mileage in each mileage bin:

This step assumes that every single vehicle drive the same length of a trip daily. For example, a vehicle that starts at 6 am a trip that is 3 miles long will travel 6.2 times the same distance. In reality, vehicles undergo trips of different length during a day. Trips from home to work and the way back can be longer than short trips for grocery shopping. However, there is no available information on connectivity between trips. As a result, this step is a first approximation to determine how many daily trips could accumulate enough miles to go over the all-electric range of a PHEV.

Table 6 presents the results of multiplying the values of Table 5 by the average trip length in each VMT range bins. The result is the cumulative mileage per trip length bin and per hour, $CMT_{VMT,h}$. For the case of PHEV40, vehicles with trips in the 5-10 mile range will exceed the 40-mile range at 7 pm, whereas vehicles with trips in the 25-30 range will exceed the 40-mile range at 11 am. In conclusion, based on this methodology most trips in the morning will be able to operate in all-electric mode and the demand for charge sustaining operation, i.e. use of the internal combustion engine, will increase in the afternoon hours.

Table 6. Cumulative mileage per trip length bin, $CMT_{VMT,h}$, assuming hourly distribution of trips presented in Table 5

TIME (hour)	Vehicle Miles Travelled (VMT) Range Bins										
	< 1	1-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
	Average mileage in each VMT range										
	0.5	3.0	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5
0	3	18	45	76	106	136	167	197	227	258	288
1	3	18	46	76	107	137	167	198	228	259	289
2	3	18	46	76	107	137	168	198	229	259	290
3	3	18	46	76	107	137	168	199	229	260	290
4	3	18	46	77	107	138	168	199	230	260	291
5	3	18	46	77	108	138	169	200	231	262	292
6	0	0	1	1	2	3	3	4	4	5	6
7	0	1	4	6	8	11	13	15	18	20	22
8	0	2	6	10	14	18	22	27	31	35	39
9	1	3	8	14	19	25	30	36	41	47	53
10	1	4	11	18	25	32	39	46	53	60	67
11	1	6	14	23	33	42	51	60	70	79	88
12	1	7	18	30	42	53	65	77	89	101	113
13	1	8	21	35	49	63	77	91	105	119	133
14	2	10	24	41	57	73	89	106	122	138	154
15	2	11	28	47	65	84	103	121	140	159	177
16	2	13	31	52	73	94	115	136	157	178	199
17	2	14	35	58	82	105	129	152	175	199	222
18	3	15	38	63	89	114	139	165	190	215	241
19	3	16	40	67	94	121	148	175	202	229	256
20	3	17	42	70	98	126	154	182	210	238	266
21	3	17	43	72	101	130	159	188	217	245	274
22	3	18	44	74	103	133	162	192	221	251	280
23	3	18	45	75	105	135	165	195	225	256	286

- Determine the cumulative mileage in each mileage bin that exceeds x -mile range:

The values calculated in the previous step, $CMT_{VMT,h}$, determine the time of the day that trips in a particular VMT range will require starting the internal combustion engine of PHEV vehicles. If CMV at an hour h in the trip length range VMT is equal to or larger than the all-electric range x , the number of trips at that (VMT,h) coordinate are accounted for the total number of trips that require using the engine. For example, for a PHEV40, the resulting distribution of trips that require using the engine by hour and by VMT range is presented in Table 7. Results show that all trips from 6 am to 8 am are exclusively within the all-electric range. Consequently, there are no emissions associated with the engine at

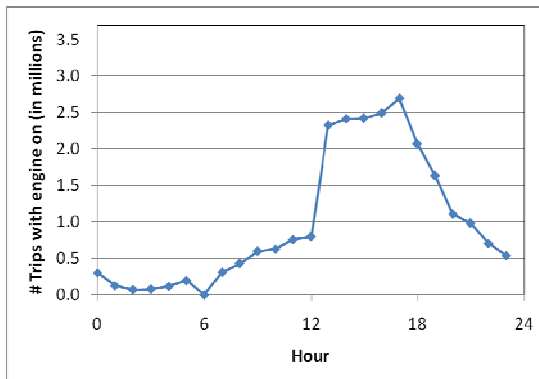
those particular hours, which implies a significant reduction in emissions from automobiles during the morning commute.

Table 7. Distribution of trips that exceed the all-electric range of 40 miles and that require the use of the internal combustion engine

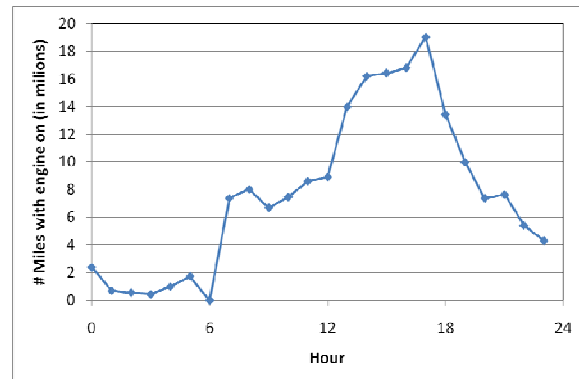
TIME (hour)	Vehicle Miles Travelled (VMT) Range Bins										
	< 1 (%)	1-5 (%)	5-10 (%)	10-15 (%)	15-20 (%)	20-25 (%)	25-30 (%)	30-35 (%)	35-40 (%)	40-45 (%)	45-50 (%)
0	0	0	49281	26880	0	4480	22400	13440	0	0	0
1	0	0	49281	4480	4480	0	0	0	0	0	0
2	0	0	26880	13440	0	0	4480	0	0	0	0
3	0	0	22400	13440	0	0	0	0	0	0	0
4	0	0	13440	22400	26880	0	0	0	0	0	0
5	0	0	40320	40320	22400	13440	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	4480	0	0
10	0	0	0	0	0	0	0	13440	4480	0	0
11	0	0	0	0	0	35840	13440	4480	0	0	0
12	0	0	0	0	80641	17920	22400	13440	4480	0	0
13	0	0	0	0	85121	26880	22400	13440	13440	4480	4480
14	0	0	0	170242	85121	62721	26880	4480	17920	0	4480
15	0	0	0	165762	116481	67201	17920	17920	4480	4480	0
16	0	0	0	291203	67201	58241	22400	26880	4480	0	0
17	0	0	0	179202	129921	89601	35840	22400	17920	13440	0
18	0	0	0	165762	44800	76161	13440	13440	0	13440	0
19	0	0	327044	143362	44800	22400	13440	17920	4480	4480	0
20	0	0	286723	116481	26880	13440	26880	0	4480	0	4480
21	0	0	192642	116481	62721	26880	17920	13440	13440	0	0
22	0	0	161282	85121	40320	17920	4480	13440	4480	4480	0
23	0	0	116481	35840	22400	13440	22400	0	13440	0	0

Figure 3 shows the hourly distribution of trips and VMT that require the engine on for scenarios with PHEV8, PHEV20 and PHEV40. Based on the methodology described above, the number of trips and total VMT that require the engine on are significantly lower than the total number of trips and miles travelled by all vehicles, as shown in Figure 2. The number of trips with the engine on decrease dramatically with respect to total number of trips as the all-electric range increases, because a high fraction of trips correspond to short range trips, which in cumulative terms do not exceed the all-electric range. The number of miles travelled with the engine on does not decrease with

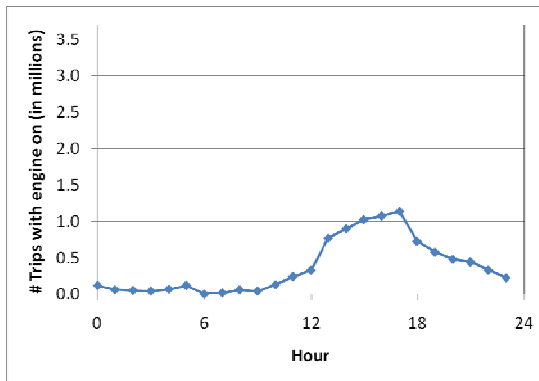
increasing the all-electric range as dramatically as the number of trip, because the highest percentage of trips with the engine on corresponds to trips with a long range of VMT.



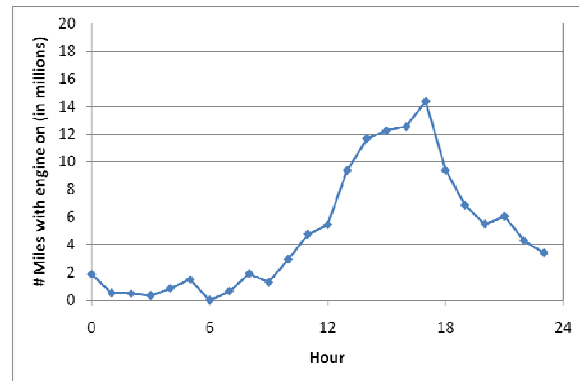
(a) PHEV8 - # of Trips



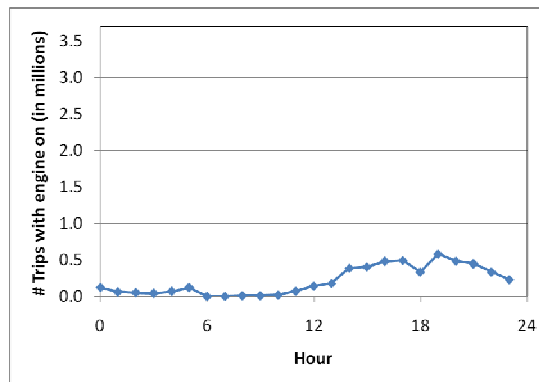
(b) PHEV8 – VMT



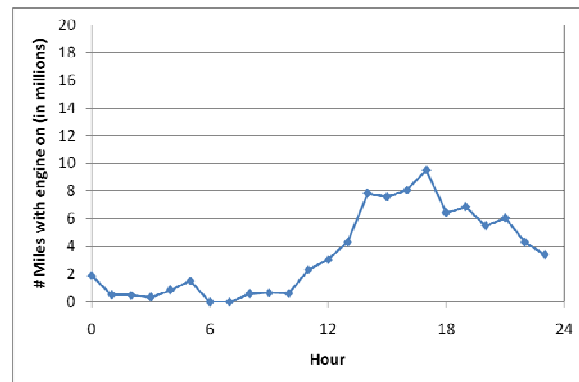
(c) PHEV20 - # of Trips



(d) PHEV20 – VMT



(e) PHEV40 - # of Trips



(f) PHEV40 - VMT

Figure 3. Hourly distribution of number of trips and vehicle miles traveled that require the internal combustion engine of PHEVs in four different scenarios: PHEV8, PHEV20, PHEV40 and Baseline

Table 8 presents the percentage of total number of trips and VMT that require the use of the internal combustion engine for four different cases: 1) all light-duty vehicles are PHEV8, 2) all light-duty vehicles are PHEV20, 3) all light-duty vehicles are PHEV40, 4) all light-duty vehicles are EV. As mentioned above, there is a dramatic reduction in the fraction of trips that require the engine – from 52.8 % to 11.1 % – as the all-electric range increases from 8 to 40 miles. On the other hand, although only 11.1% of the trips would require the use of engine if all light-duty vehicles were PHEV40, these trips correspond to 35.6 % of the total miles traveled.

Table 8. Percentage of total trips and total miles that require the use of the internal combustion engine, the total electricity needed to re-charge batteries, and the total power needed using 8-hour and 24-hour re-charging cycles, for four different PHEV cases: PHEV8, PHEV20, PHEV40 and EV

Case	% Trips with engine on	% Miles with engine on	Total electricity (GWh)	Total power (8-hour charging cycle, GW)	Total power (24-hour charging cycle, GW)
PHEV8	52.8	79.6	17.71	2.21	0.74
PHEV20	19.9	51.0	42.55	5.32	1.77
PHEV40	11.1	35.6	55.92	6.99	2.33
EV	--	--	86.86	10.86	3.62

The widespread use of PHEV presents an opportunity for utility companies to use excess power capacity that is available during off-peak hours. On the other hand, PHEV could significantly increase the peak power demand if these vehicles are re-charged during peak demand hours. Hence, the need for extra power capacity due to widespread use of PHEV will depend strongly on the strategy used and control systems developed for vehicle re-charging. Some studies even suggest that PHEV could be connected to the grid bi-directionally, being able to act as a buffer to provide additional capacity to the grid during peak demand hours and using the grid to re-charge the battery during off-peak hours. This vehicle-to-grid concept could help improve grid stability in the future, although currently there are plentiful challenges that need to be overcome to enable vehicle-to-grid power, including design of the vehicle batteries for more cycling and longer life, controls, interconnection hardware, billing and payment structures, monitoring equipment, utility pricing and rate policies, etc. As a result, a scenario that includes vehicle-to-grid power is not considered herein.

Table 8 presents the amount of electricity needed to power the PHEV vehicles as a function of the all-electric range. Note that the PHEV20 scenario implies that nearly half the total daily mileage in the SoCAB will be all-electric. As a result, the PHEV20 scenario would require nearly half the electricity of the case in which all LDA are EV.

Doubling the all-electric range from PHEV20 to PHEV40 would increase the all-electric mileage to 65% of total light duty VMT, whereas the PHEV8 case would provide all-electric range for only 20% of the total light duty VMT. Table 8 also presents the capacity of power generation needed to recharge all vehicles using two different charging cycles: (1) all vehicles are charged at night (from 10 pm to 6 am) in an 8-hour charging cycle, and (2) all vehicles are constantly being charged (evenly distributed opportunity charging) during the day. The 8-hour charging cycle requires three times more capacity than the case of a 24-hour charging cycle. However, the power demand for the 8-hour cycle could be absorbed completely by the excess power capacity not used during off-peak power demand hours, whereas the 24-hour cycle could require additional installed capacity for the power demand during periods of peak power demand.

In summary, the methodology to establish the demand for all-electric range and for charge-sustaining mode range suggest that early-morning trips and short trips will be able to occur within the all-electric range. Conversely, for trips in the afternoon hours, and especially for long trips, the cumulative daily mileage range will exceed the all-electric range, and hence, will need to use the internal combustion engine. The additional power needed for PHEV will depend on the all-electric range as well as on the charging cycle for the PHEV.

4. PRODUCTION OF ELECTRICITY FOR VEHICLES

The increase in electricity demand due to widespread commercialization of PHEV and/or EV technologies will add to the currently increasing demand for electricity, which is increasing at a rate of 1.5% per year. Conventional power generation outside of the air basin could be used to meet the increasing demand, although this type of generation is constrained by electricity transmission capacity and resistance to introducing new transmission lines. An alternative that could provide power for the increasing demand is distributed generation. The implementation of DG implies the installation of electricity generators near the place of use. This strategy reduces the transmission losses that conventional electricity from a remote power plant to the end users. In addition, the excess heat from most DG technologies can be used for space heating and air conditioning, and hence, reducing the energy use from a boiler. The cogeneration of electricity and heat is commonly referred as Combined Heating and Power (CHP). The use of CHP improves the overall efficiency of DG and can provide net emission reductions with respect to power generation without heat recuperation. On the other hand, large fraction of central electricity generation is produced outside the air basin in which the power is used, as opposed to DG, which is installed inside the air basin in which the electricity is consumed. As a result, this potential shift from central to distributed power generation may increase pollutant emissions in an air basin and lead to higher levels of ambient ozone and particulate matter concentrations.

There are numerous studies that analyzed the potential impacts on pollutant emissions that DG would cause in California (Iannuci et al., 2000; Allison and Lents (2002); Heath et al. (2004)). In addition, Medrano et al. (2008) developed a methodology to create spatially- and temporally-resolved pollutant emissions from DG. Rodriguez et al. (2006) applied that methodology to assess the air quality impacts of DG implementation scenarios in the South Coast Air Basin of California for the year 2010. The methodology considered information from DG market studies, spatial distribution of economic sectors, and emission regulations, among other factors. Rodriguez et al. used a three-dimensional air quality model to assess the impacts of DG on ozone and secondary particulate matter formation, and concluded that realistic implementation of DG technologies would have a marginal effect on air quality by 2010. However, they suggested that increased DG penetration in future years could affect compliance with air quality standards.

An ongoing effort by the Advanced Power and Energy Program is considering long-term effects of DG implementation by the year 2030. This study is building upon the work presented by Rodriguez et al. (2006), and uses the methodology described by Medrano et al. (2008) to estimate the future penetration of DG technologies in the SoCAB. The study uses updated information on DG market studies (EPRI, 2005) and updated emissions factors for DG technologies (E2I, 2004). Results suggest that DG implementation will mostly consist in gas turbine and natural gas internal combustion

engines (as shown in Figure 4). However, recent regulations related to the Assembly Bill 32 could for the DG market to adopt cleaner technologies, such as fuel cells, in addition to renewable technologies.

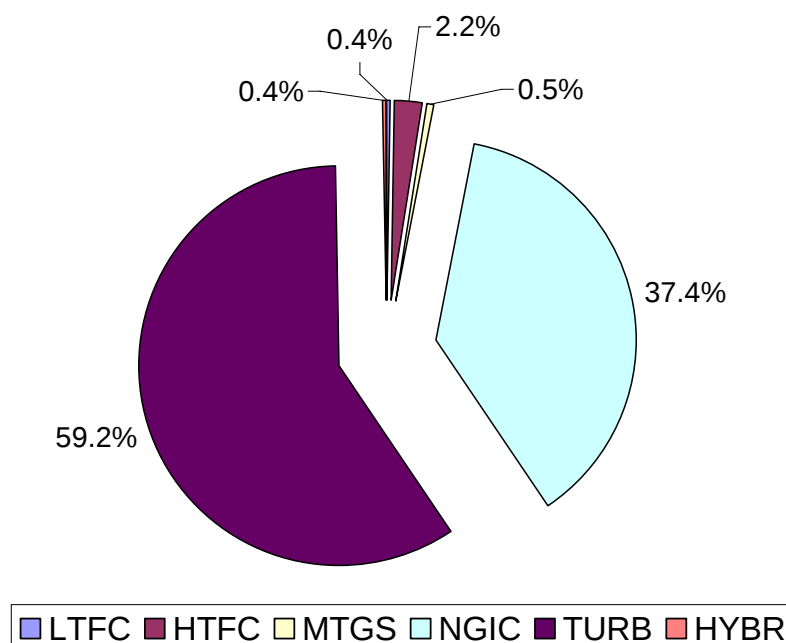


Figure 4. Distribution of technologies for DG implemented in the SoCAB for the year 2030 (from Samuelson et al. 2008). LTFC: low-temperature fuel cell; HTFC: high-temperature fuel cell; MTG: micro-turbine generators; NGIC: natural gas internal combustion engines; TURB: gas turbines; HYBR: fuel cell-gas turbine hybrid system

This study assumes that DG will be used for in-basin generation of electricity and that DG implementation takes place following the technology mix presented in Figure 4. Using the methodology presented by Medrano et al. (2008), DG units are spread throughout the SoCAB following land use distribution. The resulting emissions from this mix for the all-EVcase, which would require 86.9 GWh of electricity, are presented in Table 9. For sake of comparison, Table 9 presents emissions from DG per total miles traveled by the EV. In comparison with the emission factors for the HEV, the emissions from DG are significantly lower, except for PM emissions. Emissions of NO_x and VOC from DG in the EV case are 43% and 81% lower than in the case of all HEV. In addition, start-up emissions from HEV make these differences even bigger. Emissions of $\text{PM}_{2.5}$ in the EV case are 15% higher if start-up emissions in the HEV are not accounted for.

Table 9. Total emissions from distributed generation to produce electricity for a pure electric vehicle fleet in the SoCAB by the year 2050 (in tons per day), emissions from DG per mile, and DG emission factors relative to the HEV emission factors

	Total emissions (t/d)	DG Emission Factor (g/mile)	(DG EF) / (HEV EF)
VOC	0.308	0.001	0.19
NO _x	1.868	0.007	0.57
CO	3.406	0.013	0.12
SO _x	0.233	0.001	0.63
PM _{2.5}	1.885	0.007	1.15

5. PERSONAL VEHICLE SCENARIOS

5.1 All-electric vehicle scenarios

These set of scenarios consists in substituting all light-duty vehicles with all-electric vehicles. Hence, this scenario assumes that in the future, battery technology will be developed enough to allow a substantially long range that will not require additional power by internal combustion engines or other type of propulsion. As a result, emissions from conventional automobiles are removed from the basin. However, production of electricity to power the electric vehicle will introduce new foci of emissions in the basin, unless this electricity is produced by renewable sources, such as photovoltaics or wind power, by nuclear energy, or by any type of generation that is located outside the air basin. To analyze the effect of emissions from electricity generation needed for electric automobiles, two scenarios are developed:

- (1) All-electric vehicle with no emissions from electricity production (EV): all emissions from light-duty vehicles are removed. No additional emissions are introduced as electricity generation is assumed to be non-emitting or located outside the domain.
- (2) All-electric vehicle with in-basin electricity production by distributed generation (EVDG): all emissions from light-duty vehicles are removed. Generation of electricity to power the electric vehicles is produced inside the basin by distributed generation, which includes gas turbines, reciprocating engines, and fuel cells.

5.2 All hybrid electric vehicle scenario

This scenario consists in substituting all light-duty vehicles with hybrid electric vehicles as described in Section 2.2. This case assumes that the emission factors for all light-duty vehicles correspond to those of a 2000 Toyota Prius. As shown in Section 2, emission factors for the Toyota Prius are significantly smaller than the emission factors for an average LDA estimated by EMFAC. As a result, important emissions reductions with respect to the baseline are obtained in this scenario. Additionally, HEV have better gas mileage than conventional LDA, and could lead to additional emission reductions in the fuel supply chain, as gasoline demand in an all-HEV case could be lower than in the baseline. However, this study does not account for emissions associated to gasoline production.

5.3 All-plug-in hybrid electric vehicle scenarios

This set of scenarios consists in substituting all light-duty vehicles with plug-in hybrid electric vehicles. In practical terms, these scenarios are a combination between the all-electric case and the HEV, as there are emissions associated with electricity production, as well as with the operation of the engine. To analyze the effect of the all-

electric range on the resulting emissions, in addition to the effect of electricity production, the following scenarios are developed:

- (1) All plug-in hybrid electric vehicles (PHEV40) with no emissions from electricity production: all emissions from light-duty vehicles are removed. Emissions associated to HEV are only introduced when the 40-mile all-electric range is exceeded, as described in Section 3. No additional emissions are introduced as electricity generation is assumed to be non-emitting or located outside the domain.
- (2) All plug-in hybrid electric vehicles with in-basin electricity production (PHEV40DG): all emissions from light-duty vehicles are removed. Emissions associated to HEV are only introduced when the 40-mile all-electric range is exceeded, as described in Section 3. Generation of electricity to power the electric vehicles is produced inside the basin by distributed generation, which includes gas turbines, reciprocating engines, and fuel cells.
- (3) All plug-in hybrid electric vehicles with in-basin electricity production and no start-up emissions (PHEV40DGnosu): all emissions from light-duty vehicles are removed. Emissions associated to HEV are only introduced when the 40-mile all-electric range is exceeded, as described in Section 3. Generation of electricity to power the electric vehicles is produced inside the basin by distributed generation, which includes gas turbines, reciprocating engines, and fuel cells. Start-up emissions from the operation of the engine when the all-electric range is exhausted are eliminated. Certain control strategies that are under development are aiming to reduce emissions from PHEV by heating the catalyst some time before the battery reaches the minimum state of charge and the internal combustion engine is started.
- (4) All plug-in hybrid electric vehicles with in-basin electricity production (PHEV20DG): all emissions from light-duty vehicles are removed. Emissions associated to HEV are only introduced when the 20-mile all-electric range is exceeded, as described in Section 3. Generation of electricity to power the electric vehicles is produced inside the basin by distributed generation, which includes gas turbines, reciprocating engines, and fuel cells.

6. AIR QUALITY MODEL FORMULATION

The University of California, Irvine - California Institute of Technology (UCI-CIT) atmospheric chemical transport model is used to analyze the air quality in the SoCAB. The computational domain corresponds to an irregular region composed of 994 columns of cells (See Figure 5). Each column corresponds to a 5 km by 5 km region in the x, y plane and extends 1100m in height. The columns are partitioned into 5 cells in the z direction.

The UCI-CIT model includes the CalTech Atmospheric Chemistry Mechanism (CACM) (Griffin et al., 2002a; Pun et al., 2002; Griffin et al., 2002b). This chemical mechanism is intended for use in three-dimensional urban/regional atmospheric models, with O₃ formation and secondary organics aerosol (SOA) production. CACM includes 191 species and 361 reactions attaining an accurate description of the chemical processes.

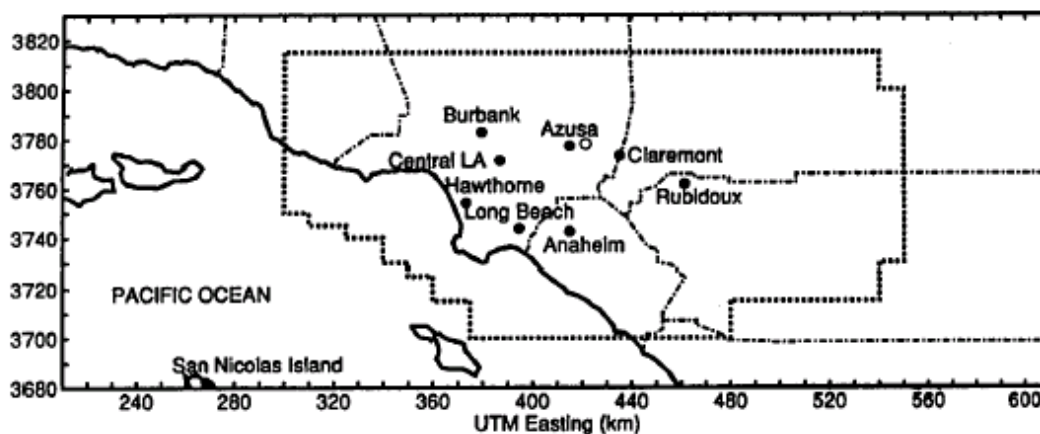


Figure 5. UCI-CIT Airshed modeling domain of the South Coast Air Basin of California.

6.1 Meteorological Conditions

The Southern California Air Quality Study (SCAQS) was a comprehensive campaign of atmospheric measurements that took place in the SoCAB, during August 27-29, 1987. The study collected an extensive set of meteorological and air quality data that has been used widely to validate air quality models (Meng et al., 1998; Griffin et al., 2002a; Pun et al., 2002; Griffin et al., 2002b; Moya et al., 2002; Knipping and Dabdub, 2002). Zeldin et al. (1990) found that August 28, 1987 is representative of the meteorological conditions in the SoCAB, which makes it suitable for modeling. In addition, the August 27-28, 1987 episode is statistically within the top 10% of severe ozone-forming meteorological conditions. Hence, meteorological conditions for August 28 are used here as the basis to evaluate the effects of changes in vehicle emissions.

The SCAQS episode in August 27-29, 1987 was characterized by a weak onshore pressure gradient and warming temperatures aloft. The wind flow was characterized by a sea breeze during the day and a weak land-mountain breeze at night. The presence of a well-defined diurnal inversion layer at the top of neutral and unstable layers near the surface, along with a slightly stable nocturnal boundary layer, facilitated the accumulation of pollutants over the SoCAB, which lead to high ozone concentration occurrence.

6.2 Baseline Emissions

Currently, there are no emission estimates available beyond 2023. Only EMFAC, a model used to generate on-road mobile emissions, is capable of estimating emissions for years up to 2040. The EMFAC model is developed by the ARB, and uses information on vehicle activity from the Department of Motor Vehicles and the California Transportation Department. The total emissions from vehicles can then be calculated using emission factors derived from vehicle testing. These emission factors depend on the number of starts, the ambient conditions and the speed of the vehicle, among other factors. Results from the EMFAC model provide emissions from vehicle operation, as well as evaporative emissions of VOC, and particle emissions from braking and tire wear (ARB, 2007).

Figure 1 shows the relative change in vehicular activity, emissions from on-road mobile sources and fuel use for the period 2010-2040. Although the number of vehicles, trips and vehicle miles traveled are estimated to increase, emissions of criteria pollutants are expected to decrease due to reduction of vehicle tailpipe emissions. This reduction is caused by the progressive market penetration of low-emitting vehicles, and the gradual retirement of higher-emitting older models.

Emission source apportionment for the 2023 inventory is presented in Table 10. Emissions from on-road mobile sources account for 24%, 40% and 36% of the total ROG, CO and NO_x, respectively, in the emission inventory estimated by ARB for the year 2023. Assuming that emissions from all the sources except on-road mobile sources stay constant, emissions for up to the year 2050 may be estimated by extrapolating the emission reductions to the mobile sources, as shown in Figure 1. As a result, baseline emissions of ROG, NO_x and CO for the year 2050 decrease to 373 tpd, 94 tpd and 1522 tpd, respectively, whereas PM_{2.5} emissions increase to 92 tpd.

Table 10. Source apportionment of the 2023 emissions inventory for the South Coast Air Basin of California

	Emissions by major source % with respect to total emissions in 2023				2023 Emissions
	Stationary Sources	Petroleum Production	Off-Road Vehicles	On-Road Vehicles	(t/d)
VOC	44.7	6.5	25.2	23.6	420
NO_x	14.4	0.0	50.0	35.6	114
CO	6.1	0.3	53.2	40.4	1966
SO_x	16.8	2.1	78.9	2.1	19
PM_{2.5}	67.6	1.0	17.6	13.7	88

Table 11. Source apportionment of the 2050 emissions inventory for the South Coast Air Basin of California, using 2023 emissions inventory and extrapolating on-road emissions using EMFAC estimates

	Emissions by major source % with respect to total emissions in 2050				2050 Emissions
	Stationary Sources	Petroleum Production	Off-Road Vehicles	On-Road Vehicles	(t/d)
VOC	50.3	7.3	28.3	14.1	373
NO_x	17.4	0.0	60.3	22.3	94
CO	7.9	0.4	68.7	23.0	1522
SO_x	13.4	1.7	62.9	22.0	24
PM_{2.5}	64.8	1.0	16.9	17.4	92

7. AIR QUALITY IMPACTS OF VEHICLE SCENARIOS

7.1 Baseline air quality

The synoptic conditions in the SoCAB create a regime of circulation that favors transport of pollutants, emitted mainly in Los Angeles and Long Beach, towards the north east. In the northeastern part of the domain there are mountain ranges that trap the pollution arriving from upwind, leading to accumulation of ozone. Near Riverside, a high density of dairy farms produces ammonia, which reacts with nitric acid formed via oxidation of nitrogen oxides emitted upwind. Nitric acid and ammonia react to form secondary particulate matter leading to the high PM_{2.5} near Riverside. Two other foci of PM_{2.5} concentration develop near Central Los Angeles and the port of Long Beach. The former is due to direct emissions from vehicles, whereas the latter comes from the activity at the port, where there are high emissions from trucks and ships.

Although baseline simulations for the year 2050 are based upon emission inventories for 2023 that have been developed for the 2007 AQMP to demonstrate attainment of ozone and PM_{2.5} air quality standards, ozone and PM_{2.5} concentrations exceed the established air quality standards (84ppb ozone; 50 µg/m³ PM_{2.5}) as shown in Table 12. Jimenez et al. (2003) and Carreras-Sospedra et al. (2006) suggest that the CACM chemical mechanism predicts higher oxidative capacity that leads to higher concentrations of O₃ than those predicted by other chemical mechanisms, such as SAPRC-99, which was used to produce the results in the AQMP. Nonetheless, simulation results by UCI-CIT model using CACM agree reasonably well with observations (Griffin et al. 2002a).

Table 12. Maximum concentration of pollutants for the 2050 baseline case and California Ambient Air Quality Standards (CAAQS)

Pollutant	Year 2050	CAAQS
1-hour O ₃	139 ppb	90 ppb
8-hour O ₃	118 ppb	70 ppb
1-hour CO	1.3 ppm	20 ppm
1-hour NO ₂	69 ppb	180 ppb
24-hour PM _{2.5}	66 µg/m ³	35 µg/m ³

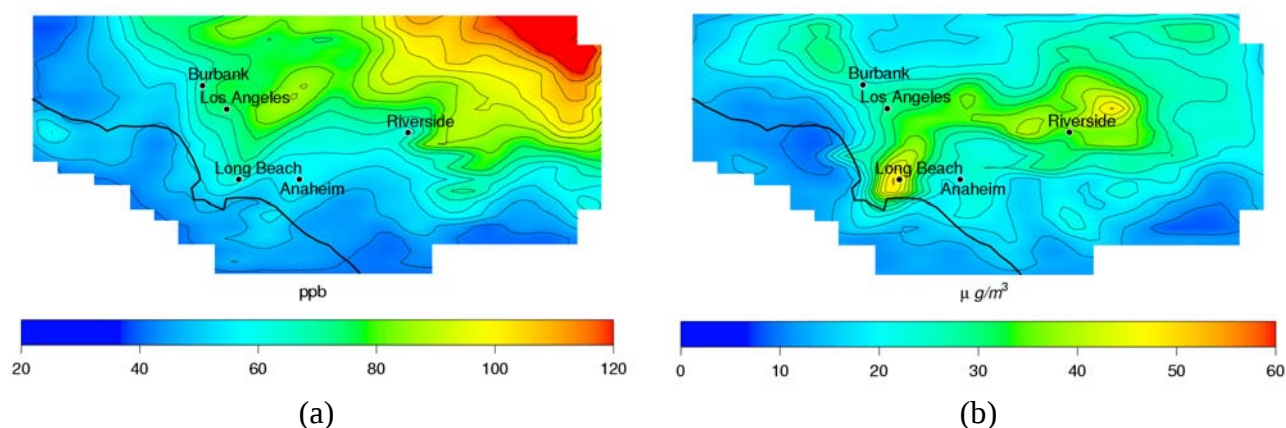


Figure 6. Baseline pollutant concentrations in the year 2050 in the South Coast Air Basin of California: (a) peak ozone concentrations, (b) 24-hour average PM_{2.5} concentrations

7.2 Impacts of vehicle scenarios on pollutant emissions

The impacts of the vehicle scenarios presented in Section 5 on basin-wide emissions are analyzed in this section. The differences in emissions due to the implementation of each scenario can be analyzed with respect to baseline light-duty emissions (see Figure 7) and with respect to total baseline emissions (see Figure 8).

As shown in Figure 7, all scenarios lead to decreases in emissions with respect to baseline light-duty vehicle emissions of 50% or higher. Note that the all EV scenario implies the total elimination of tail-pipe emissions from light-duty vehicles and represents the case with the lowest emissions. On the other end, the all HEV scenario represents the case with the highest emissions. In the case of all-EV with emissions from electricity production through DG, total emissions are lower than in the case of all-HEV, suggesting that EV can potentially reduce emissions further than any hybrid-ICE strategy, even if emissions from electricity production are included. Results show that use of PHEV will reduce emissions with respect to using HEV, even if emissions from electricity production are accounted for. Increasing the all-electric range reduces the total emissions from automobiles, except for PM emissions because per-mile PM emissions from DG are slightly higher than from HEV (as shown in Table 9). Removing start-up emissions from the PHEV40 case reduces by 2% further the total emissions from light-duty vehicles, with respect to conventional LDA emissions.

Overall, the scenarios with alternative vehicle technologies could reduce total basin-wide emissions. Total basin-wide emissions of NO_x and CO could decrease by up to 10%, whereas VOC, SO_x and PM emissions could decrease by up to 5%, with respect to baseline 2050 emissions. These are moderate decreases that could be augmented if hybrid or battery-electric technologies are implemented in vehicles of higher sizes. Although light-duty vehicles contribute with nearly half of the total VMT, vehicles in

higher weight classes contribute significantly to total emissions, because of much higher emissions on a per-mile basis.

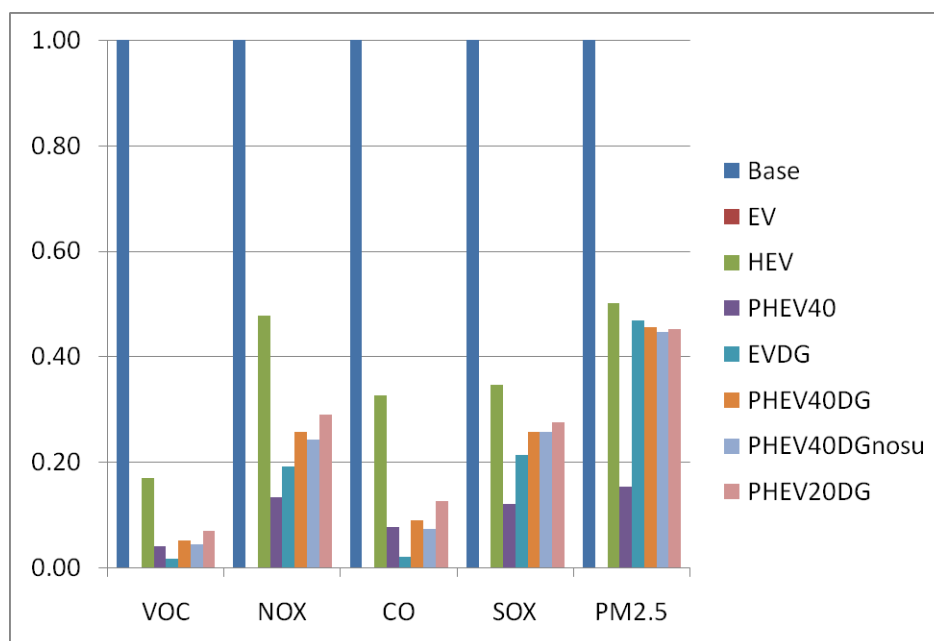


Figure 7. Total light-duty vehicle emissions of criteria pollutants from all scenarios relative to baseline light-duty vehicle emissions in 2050

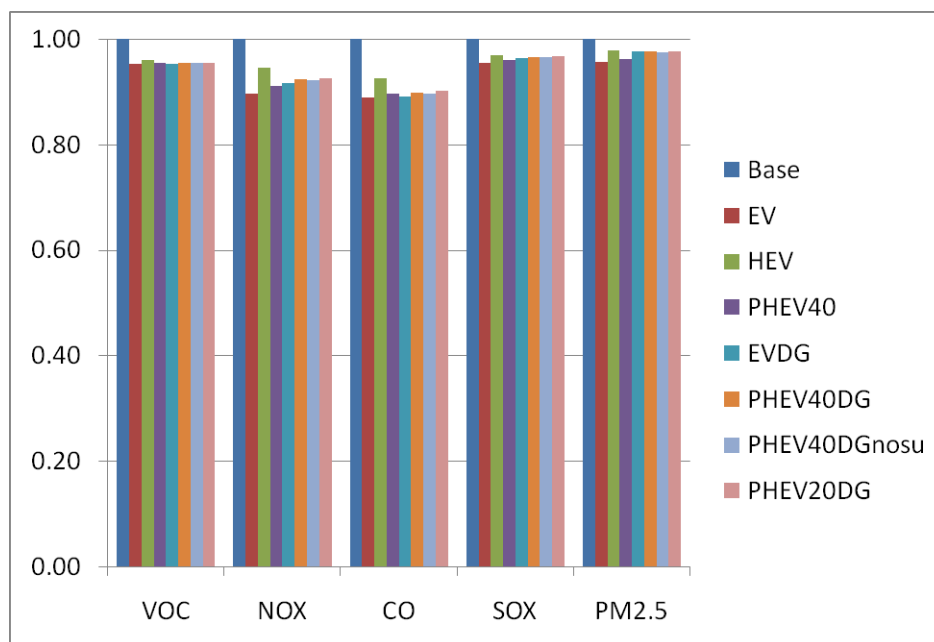


Figure 8. Total basin-wide emissions of criteria pollutants from all scenarios relative to baseline basin-wide emissions in 2050

7.3 Air quality impacts of vehicle scenarios

All vehicle scenarios reduce emissions of ozone precursors, NO_x and VOC, which results in decreases in ozone and particulate matter. Reductions of VOC and NO_x emissions are approximately 5% and 10%, respectively, relative to basin-wide baseline emissions. These emission reductions result in a decrease in peak ozone concentration and in 8-hour average ozone concentration of 4 ppb, as shown in Table 13. There are some localized increases in ozone concentration in areas under VOC limited conditions. The reactivity of the atmosphere in such conditions tends to increase ozone concentrations when NO_x emissions are reduced. This phenomenon typically occurs in regions with extremely high NO_x emissions, such as Los Angeles. However, increases in ozone concentrations occur where ozone concentration is consistently low or at night, when NO_x , with the absence of light, act as a scavenger for ozone. Hence, reducing NO_x leads to an increase in ozone concentrations at night. On the other hand, maximum decreases occur in the northeastern part of the domain, where the peak ozone concentration occurs (as shown in Figure 9). In other words, reductions in ozone occur where mostly needed.

The vehicle scenarios also lead to decreases in emissions of aerosol precursors. Besides reductions of NO_x emissions, which can react to form nitrate particles, the vehicle scenarios also produce reductions in emissions of SO_x and particles of approximately 5%, relative to basin-wide baseline emissions. As a result, maximum decreases in 24-hour average $\text{PM}_{2.5}$ concentrations are nearly $3 \mu\text{g}/\text{m}^3$ (as shown in Table 14). As in the case with ozone concentrations, maximum decreases in $\text{PM}_{2.5}$ are located in the areas where high concentrations of particles typically occur (See Figure 10).

The all-electric vehicle scenario represents the lower bound for basin-wide emissions among all the vehicle scenarios. Consequently, the all-EV case produces the deepest reduction in ozone and $\text{PM}_{2.5}$ concentrations. On the opposite end, the all hybrid electric vehicle scenario represents the upper bound for ozone precursor emissions. As a result, the all-HEV case produces the smallest reductions in ozone concentration with respect to baseline concentration. The all-electric vehicle scenario with in-basin production of electricity by DG and the all-PHEV40 with in-basin production of electricity by DG represent the upper bound for PM emissions. However, the all-EVDG case introduces lower emissions of NO_x and VOC than the all-PHEV40DG case. Since NO_x and VOC are also precursors of secondary aerosols, the all-PHEV40DG case produces the smallest reduction in $\text{PM}_{2.5}$ amongst the vehicle cases.

Table 13. Maximum 1-hour peak O₃ concentration in all cases and maximum differences in peak O₃ and 1-hour average O₃ concentration with respect to Baseline

	[O₃]_{peak} (ppb)	Δ[O₃]_{peak} (ppb)		Δ[O₃]_{8-hour} (ppb)	
	Max	Max	Min	Max	Min
Baseline	139.5	--	--	--	--
EV	135.5	1.0	-4.0	0.6	-3.5
EVDGup	136.2	0.8	-3.3	0.5	-2.8
HEV	136.7	0.6	-2.8	0.4	-2.3
PHEV40	135.8	0.7	-3.7	0.5	-3.2
PHEV40DGup	136.1	0.7	-3.4	0.4	-2.9
PHEV40DGupnosu	136.8	0.5	-2.7	0.4	-2.2

Table 14. Maximum 24-hour PM_{2.5} concentration in all cases and maximum differences in 24-hour PM_{2.5} concentration with respect to Baseline

	[PM_{2.5}]_{24-hour} (μg/m³)	Δ[PM_{2.5}]_{24-hour} (μg/m³)	
	Max	Max	Min
Baseline	65.9	--	--
EV	63.9	0.1	-2.8
EVDGup	64.9	0.1	-2.4
HEV	64.7	0.2	-2.0
PHEV40	64.1	0.1	-2.6
PHEV40DGup	65.2	0.1	-2.3
PHEV40DGupnosu	66.8	0.9	-1.7

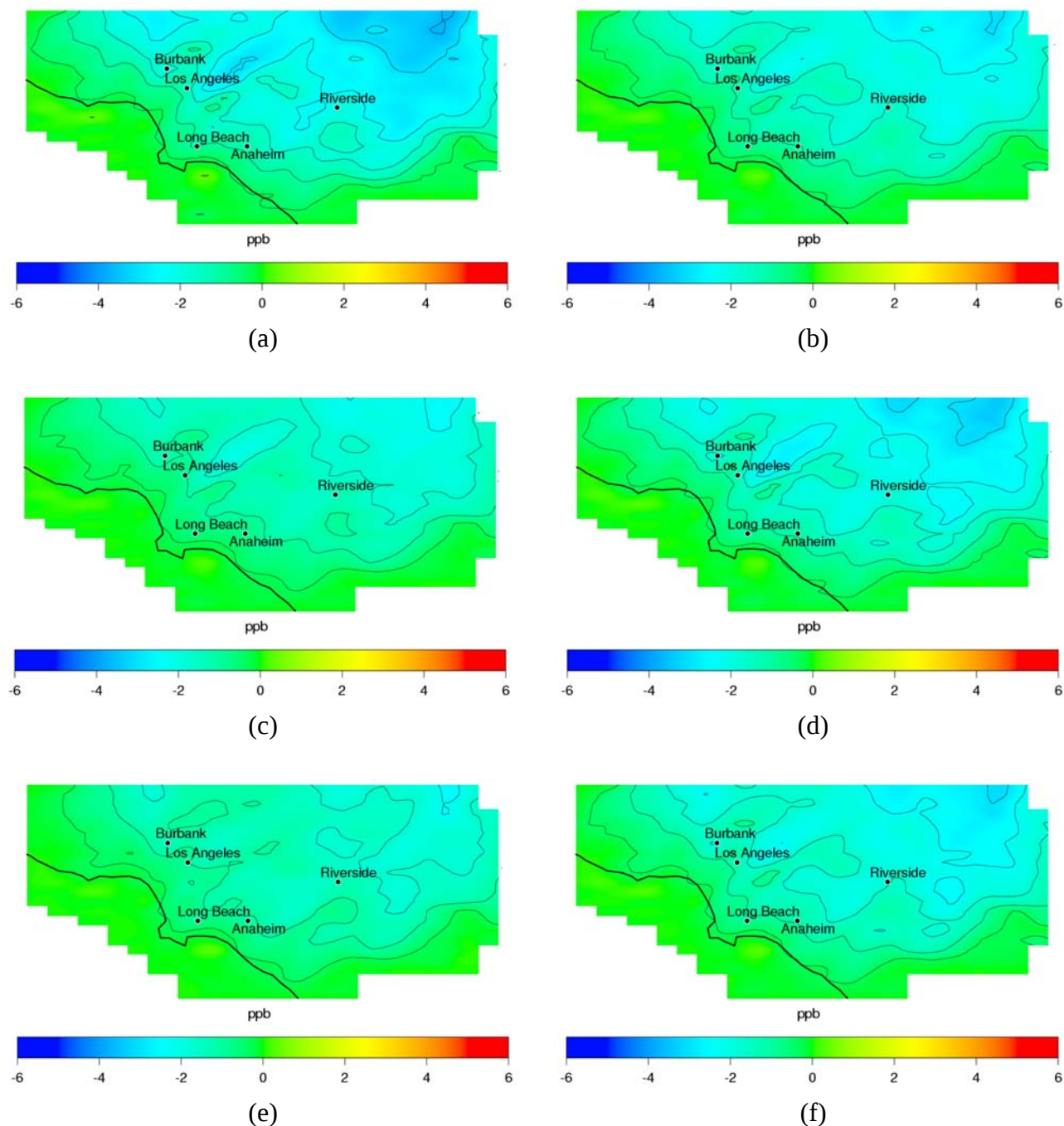


Figure 9. Differences in peak ozone concentration in various vehicle scenarios with respect to the 2050 baseline: (a) All electric vehicle case without emissions from electricity production; (b) All electric vehicle case with in-basin electricity production via distributed generation; (c) All hybrid electric vehicle case; (d) All plug-in hybrid electric vehicle case without emissions from electricity production; (e) All plug-in hybrid electric vehicle case with in-basin electricity production via distributed generation; (f) All plug-in hybrid electric vehicle case with in-basin electricity production via distributed generation and no start-up emissions

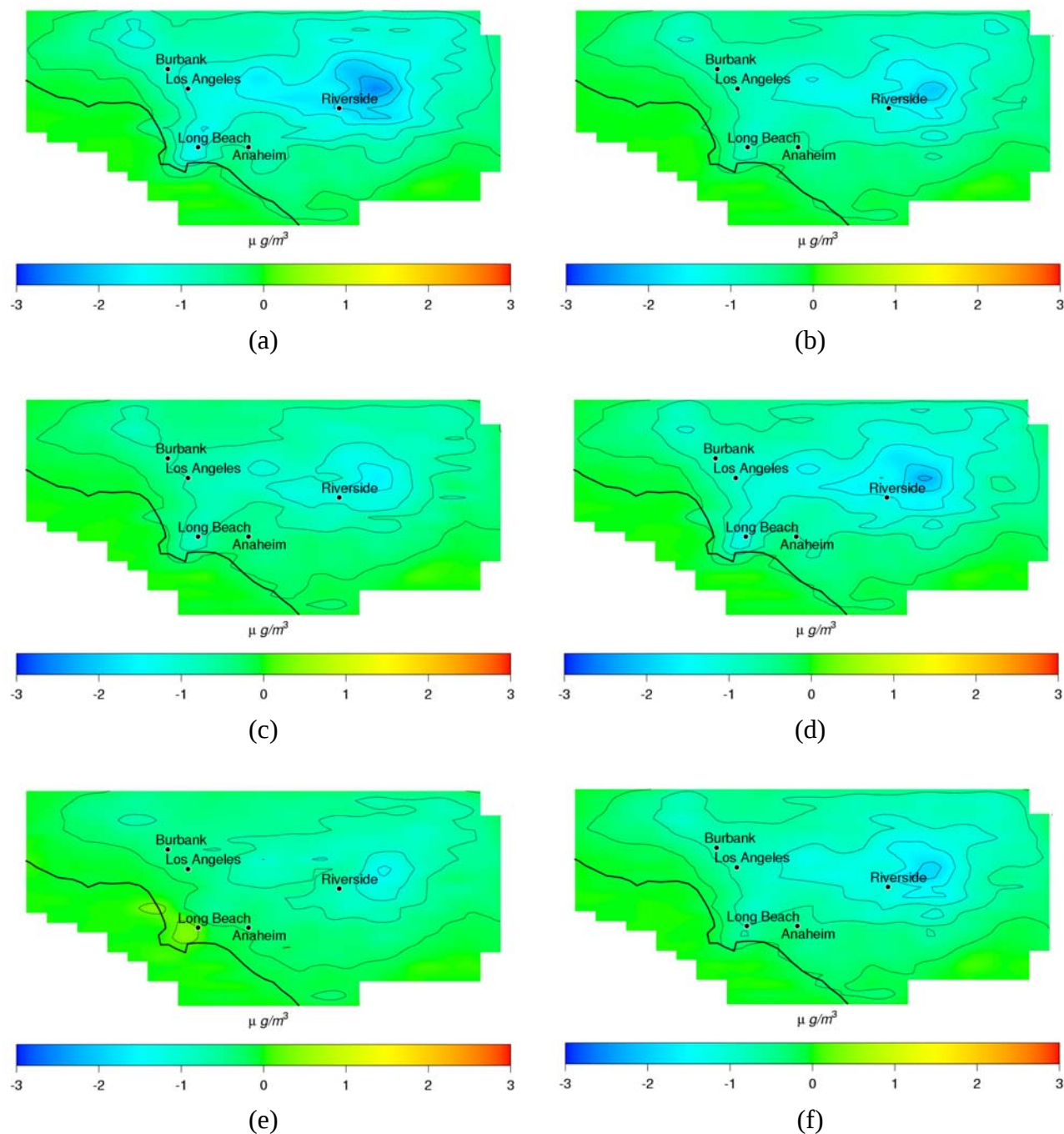


Figure 10. Differences in 24-hour average $PM_{2.5}$ concentration in various vehicle scenarios with respect to the 2050 baseline: (a) All electric vehicle case without emissions from electricity production; (b) All electric vehicle case with in-basin electricity production via distributed generation; (c) All hybrid electric vehicle case; (d) All plug-in hybrid electric vehicle case without emissions from electricity production; (e) All plug-in hybrid electric vehicle case with in-basin electricity production via distributed generation; (f) All plug-in hybrid electric vehicle case with in-basin electricity production via distributed generation and no start-up emissions

8. CONCLUSIONS

This study analyzes the emissions and resulting air quality impacts of several scenarios that implement novel vehicle technologies such as battery-electric, hybrid-electric and plug-in hybrid-electric configurations. This report presents a methodology to account for the fraction of vehicle-miles-travelled that would require the use of the electric motor or the internal combustion engine as a function of the all-electric range of plug-in hybrid vehicles. This methodology is based on overall hourly vehicle activity and can estimate the hourly changes in battery-electric and combustion-engine power demand. Results from this methodology can be used to estimate the emissions – produced by the internal combustion engine – that result from use of various vehicle types as well as the emissions from any electricity generation that is used to charge on-board batteries.

Results suggest that by the year 2050, the electricity demand of an implementation scenario that assumes all the light-duty vehicles in the South Coast Air Basin are battery electric vehicles is 87 GWh per day. This electricity demand could be supplied by a mix of distributed generation technologies that includes mostly gas turbines and natural gas internal combustion engines. Emissions from DG on a per-mile basis are typically lower than the equivalent emissions from an HEV. As a result, emissions from vehicles decrease as the all-electric range increases even when electricity emissions are released in the basin. Results from the methodology show that a scenario that assumes all light-duty vehicles become PHEV20, that is PHEV with 20 miles all-electric range, would allow half of the total VMT be driven within the all-electric range. As a result, the electricity demand for such a scenario is a continuous 44 GWh per day, half the electricity demand in the all-EV case.

Implementation of battery-electric and hybrid-electric technologies would lead to decreases in emissions from light-duty vehicles of 50% or more. If emissions from electricity are included, maximum decreases in emissions would occur in the case that all light-duty vehicles are EV. Such a scenario would reduce light-duty vehicle emissions of VOC and CO by 98%, NO_x and SO_x emissions by 80% and PM emissions by 53%. Scenarios with PHEV produce slightly more moderate emissions reductions, and in general, the shorter the all-electric range, the higher the emissions from vehicles. For the all-PHEV40 case with electricity generation by DG, light-duty vehicle emissions of NO_x and SO_x decrease by 74%, and VOC, CO and PM emissions decrease by 95%, 91% and 54%, respectively. If start-up emissions from PHEVs are eliminated, as some control strategies are trying to accomplish by preheating the catalyst before the engine is expected to turn on, total emissions from light-duty vehicles could decrease up to 2% further compared to baseline 2050 light-duty vehicle emissions.

A detailed atmospheric chemistry and transport model was used to solve the 3-dimensional field of more than 150 pollutant compounds in the South Coast Air Basin using a parallel 252-node super-computer. The emissions reductions from changing light-duty vehicles to the alternative vehicles considered were predicted by the model to lead to reductions in total basin-wide NO_x and CO emissions of 10%, and reductions in total VOC, SO_x and PM of approximately 5%. Such basin-wide reductions lead to decreases in peak ozone concentrations of up to 6 ppb, and to decreases of up to 3 µg/m³ in 24-hour average concentration of PM_{2.5}. The most significant reductions in ozone and PM_{2.5} occur where the peak concentrations of these pollutants are typically located. Consequently, the implementation of battery-electric and hybrid-electric vehicle technologies in the light duty transportation sector of SoCAB could contribute significantly to reducing criteria pollutant concentrations and help with attainment of air quality standards.

9. RECOMMENDATIONS

The investigators recommend further research in the following specific areas:

- Conduct analyses that consider more widespread adoption of alternative vehicle technologies, especially in the medium and heavy duty vehicle sectors.
- Consider the impacts of market penetration associated with the lower cost of some types of alternative vehicle technologies (e.g., blended PHEV) with more limited zero emissions range compared to the higher cost of other alternative vehicle technologies (e.g., pure battery electric) with larger zero emissions range.
- Conduct analyses that develop emissions scenarios and air quality impacts associated with other alternative technologies such as biofuel engines (e.g., ethanol, biodiesel), natural gas engines, hydrogen internal combustion engines, hydrogen fuel cell engines, etc.
- Conduct analyses that develop emissions scenarios and air quality impacts associated with other alternative transportation technologies and systems such as mass transit, facilitated car-sharing, mass-transit linked zero emissions vehicles (e.g., ZEV-NET), etc.
- Conduct analyses that consider the emissions and air quality impacts of vehicle-to-grid technologies including the impacts of various technological (e.g., battery life, charge-discharge frequency and magnitude, interconnection hardware) and policy (e.g., utility prices and rates) issues.
- Publish papers in these areas to inform the public and scientific community of the air quality impacts of the various options under consideration.

10. REFERENCES

- Allison, J. E.; Lents, J. Encouraging distributed generation of power that improves air quality: can we have our cake and eat it too? *Energy Policy*, **2002**, *30*, 737-752.
- ARB (2007). On-road Emission Model Methodology Documentation. Available at: http://www.arb.ca.gov/msei/onroad/doctable_test.htm
- Colella W.G., Jacobson M.Z., Golden D.M. Switching to a U.S. hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse gases. *Journal of Power Sources*, **2005**, *150*, 150-181.
- E2I. Distributed Energy Resources Emissions Survey and Technology Characterization, E2I, Palo Alto, CA: **2004**.
- EPRI (2005). Assessment of California Combined Heat and Power Market and Policy Options for Increased Penetration. CEC-500-2005-173.
- Graham, L. Chemical characterization of emissions from advanced technology light-duty vehicles. *Atmospheric Environment*, **2005**, *39*, 2385-2398.
- Griffin R. J., Dabdub D., Kleeman M. J., Fraser M. P., Cass G. R., Seinfeld J. H. Secondary organic aerosol - 3. Urban/regional scale model of size- and composition-resolved aerosols. *J. Geophys Res-Atmos.* **2002**, *107*(D17), 4334
- Griffin R. J., Dabdub D., Seinfeld J. H. Secondary organic aerosol - 1. Atmospheric chemical mechanism for production of molecular constituents. *J. Geophys Res-Atmos.* **2002**, *107*(D17), 4332
- Heath, G. A.; Granvold, P. W.; Hoats, A. S.; Nazaroff, W. W. (2003), Intake fraction assessment of the air pollutant exposure implications of a shift toward distributed electricity generation. *Atmos. Environ.* **2006**, *40*, 7164-7177.
- Ianucci, J.; Horgan, S.; Eyer, J.; Cibulka, L. Air Pollution Emissions Impacts Associated with the Economic Market Potential of Distributed Generation in California., Distributed Utility Associates, prepared for The California Air Resources Board, Contract #97-326; **2000**.
- Jacobson M.Z., Colella W.G., Golden D.M. Cleaning the air and improving health with hydrogen fuel-cell vehicles. *Science*. **2005**, *308*, 1901-1905.

- Jimenez P., Baldasano J. M., Dabdub D. Comparison of photochemical mechanisms for air quality modeling. *Atmos. Environ.*, **2003**, 37, 4179-4194
- Knipping E. M., Dabdub D. Modeling surface-mediated renoxification of the atmosphere via reaction of gaseous nitric oxide with deposited nitric acid. *Atmos. Environ.* **2002**, 36, 5741-5748
- Markel, T.; Simpson, A. Plug-In Hybrid Electric Vehicle Energy Storage System Design. Conference Paper NREL/CP-540-39614. Presented at Advanced Automotive Battery Conference, Baltimore, Maryland, May 17–19, 2006
- Medrano, M.; Brouwer, J.; Carreras-Sospedra, M.; Rodriguez, M.A.; Dabdub, D.; Samuelsen, G.S. A Methodology for Developing Distributed Generation Scenarios in Urban Areas using Geographical Information Systems. *Int. J. Energy Tech. Pol.*, **2007**, in press.
- Meng Z. Y., Dabdub D., Seinfeld J. H. Size-resolved and chemically resolved model of atmospheric aerosol dynamics. *J. Geophys Res-Atmos.* **1998**, 103(D3), 3419-3435
- Moya M., Pandis S. N., Jacobson M. Z. Is the size distribution of urban aerosols determined by thermodynamic equilibrium? An application to Southern California. *Atmos. Environ.* **2002**, 36(14), 2349-2365
- Rodriguez, M.A.; Carreras-Sospedra, M.; Medrano, M.; Brouwer, J.; Samuelsen, G.S.; Dabdub, D.; Air quality impacts of distributed power generation in the South Coast Air Basin of California 1: Scenario development and modeling analysis. *Atmos. Environ.*, **2006**, 40, 5508-5521.
- Simpson, A. Cost-benefit analysis of plug-in hybrid Electric vehicle technology. Conference Paper NREL/CP-540-40485, Presented at the 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition (EVS-22), Yokohama, Japan, October 23–28, 2006
- Zeldin, M. D., Bregman L. D., and Horie Y. (1990) "A Meteorological and Air Quality Assessment of the Representativeness of the 1987 SCAQS Intensive Days." Final report to the South Coast Air Quality Management District.