Transportation Research Part D 13 (2008) 436–448

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Comparing air quality impacts of hydrogen and gasoline

Guihua Wang [a,c,*], Joan M. Ogden [b,c], Daniel Sperling [a,b,c]

[a] Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA
[b] Department of Environmental Science and Policy, University of California, Davis, CA 95616, USA
[c] Institute of Transportation Studies, University of California, Davis, CA 95616, USA

ARTICLE INFO

Keywords:
Lifecycle analysis (LCA)
Hydrogen transportation fuel
Hydrogen pathways
Light duty fleet
Urban air pollution

ABSTRACT

This paper uses a lifecycle approach to analyze potential air quality impacts of hydrogen and gasoline use in light duty vehicles. The analysis is conducted for scenarios in 2005 and 2025 in Sacramento, California for CO, NO_x, VOC, and PM_{10}. Three natural gas-based hydrogen supply pathways are analyzed: onsite hydrogen production via small-scale steam methane reforming (SMR), central large-scale hydrogen production via SMR with gaseous hydrogen pipeline delivery, and central hydrogen production via SMR with liquid hydrogen truck delivery. These are compared to gasoline pathways with current and advanced technologies, in terms of lifecycle air quality impacts. The centralized/pipeline hydrogen pathway reduces pollution the most, followed by the onsite hydrogen production pathway and the centralized hydrogen production with liquid hydrogen truck delivery. Gasoline pathway scenarios, even with advanced new gasoline vehicles, would lead to much higher ambient concentrations of pollutants than any of the hydrogen pathways, producing 273 times greater CO, 88 times greater VOC, 8 times greater PM_{10}, and 3.5 times greater NO_x concentrations than those caused by the centralized/pipeline hydrogen pathway.

1. Introduction

Petroleum-powered vehicles emit large amounts of criteria pollutants and, as a result, account for a significant fraction of urban air pollution in the US. For example, on-road motor vehicles were estimated to contribute 31–39% of volatile organic compounds (VOCs), 34–62% of nitrogen oxides (NO_x), and 4–6% of particulates (PM_{10}) to annual ambient concentrations in Sacramento, California in 2005 (Wang et al., 2008). Because of the close proximity to people, current mobile emission sources are likely to cause human health damage and significant social costs (ExternE, 1998; McCubbin and Delucchi, 1996; Delucchi and McCubbin, 2004).

To mitigate concerns about urban air pollution, zero emission vehicle (ZEV) mandates have been enacted in California (California Air Resources Board, 2008). Hydrogen fuel cell vehicles (FCVs) are a promising ZEV option, offering good performance, rapid refueling, diverse primary sources for hydrogen fuel, and the potential for very low lifecycle emissions of greenhouse gases and criteria pollutant emissions (Ogden et al., 2004; Jacobson et al., 2005). Colella et al. (2005) examined the potential change in US primary emissions and energy use from adopting a hydrogen FCV fleet, using a lifecycle analysis (LCA) of alternative fuel supply chains. However, very few studies have examined the changes in ambient concentrations (not just emissions) of pollutants resulting from hydrogen supply pathways (Ogden et al., 2004; Wang et al., 2007a,b).

Although hydrogen vehicles emit no criteria pollutants, there are "upstream" emissions associated with hydrogen transportation fuel, from producing, compressing, liquefying, and delivering hydrogen. This study develops hydrogen transporta-

* Corresponding author. Address: Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA.
E-mail address: wghwang@ucdavis.edu (G. Wang).

1361-9209/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.trd.2008.09.006

tion scenarios for Sacramento, California, and investigates three hypothetical natural gas-based hydrogen pathways in terms of the resulting changes in urban air quality. Only primary pollutants directly emitted from sources are included. No secondary atmospheric formation of pollutants like secondary particulate matter or ozone is considered.

We also compare hydrogen scenarios to petroleum pathways with gasoline and diesel vehicles. For simplicity, we use the term "gasoline pathway" to refer to the petroleum-based fuel pathway, including both gasoline and diesel. Unlike hydrogen pathways, where all emissions of criteria pollutants take place upstream of the vehicle, with a gasoline pathway vehicle operation plays an important role. Therefore, our focus is on estimating contributions of gasoline vehicle emissions to urban air pollution, although we also include some upstream gasoline pathway steps like gasoline-delivery truck emissions. The current 2005 light duty (LD) gasoline fleet is used as a reference. To assess the impact of improved gasoline technologies, we compare the 2005 reference case to a projected 2025 light duty gasoline fleet.

In this paper, ground-level concentrations for four pollutants, carbon monoxide (CO), NO_x, VOC, and PM_{10}, are estimated, allowing us to compare air quality impacts among three hydrogen supply pathways and four gasoline pathway scenarios.

2. Hydrogen supply pathway scenarios

From a lifecycle analysis (LCA) perspective, we estimate regional air quality impacts for three different hydrogen production and delivery pathways, based on steam methane reforming (SMR) of natural gas, which is currently the most common approach to producing hydrogen. To link hydrogen pathways to ambient air quality in urban Sacramento, California, we develop a methodological framework (Fig. 1). For more details, see Wang et al. (2007a,b).

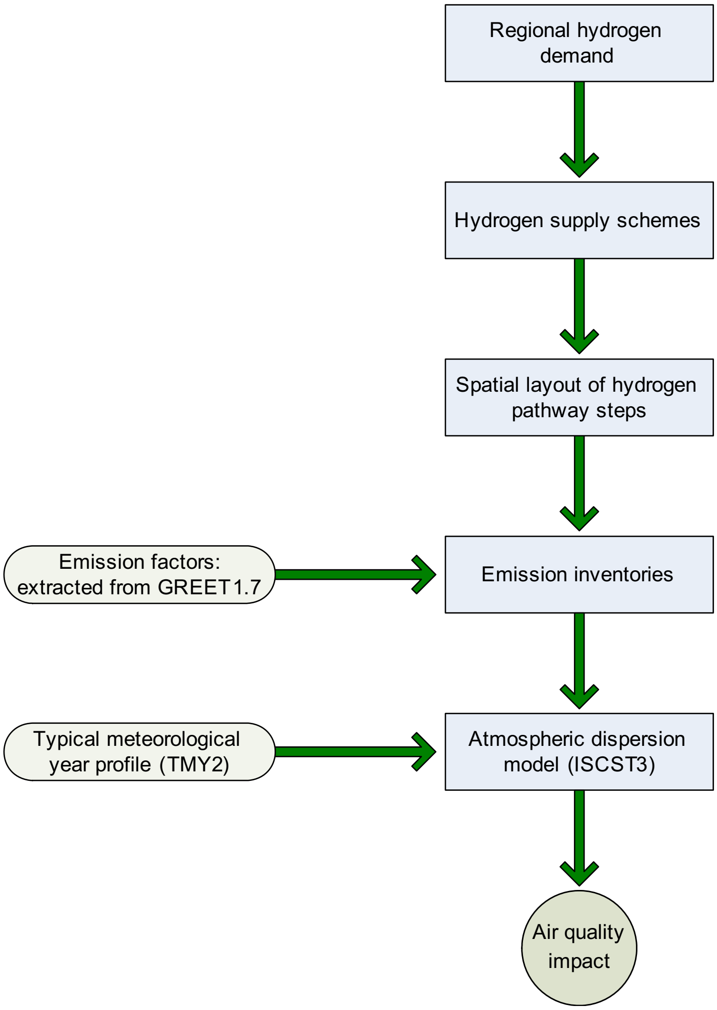

Fig. 1. Methodological framework for analysis of hydrogen pathway scenarios.

Table 1
Hydrogen demand/supply assumptions for hydrogen pathway scenarios

	Basic assumptions	Scenario 1	Scenario 2
LD gasoline vehicle population (2000)[1]	1.114 million		
Number of added hydrogen FCVs		111,400	278,600
Hydrogen fuel demand		78,000 kg/day	195,000 kg/day
Number of hydrogen stations		27	66
Fuel economy of the hydrogen FCV	60 miles/kg hydrogen		
Vehicle miles traveled (VMT)	15,000 miles/year/vehicle		
Hydrogen consumption	0.7 kg/day/vehicle		
Hydrogen station size	3000 kg/day		
Liquid truck capacity	3000 kg liquid hydrogen		

[1] The 2000 LD gasoline vehicle population in urbanized Sacramento is calculated as: Sacramento city population × LD vehicle ownership = 1.393 million × 0.8 vehicles/person = 1.114 million. The Sacramento city population is obtained from the 2000 US Census (US Census Bureau, 2006).

2.1. Regional hydrogen demand

Estimating the regional demand for hydrogen is the first step in the analysis. We use the urbanized Sacramento conventional gasoline light duty (LD) fleet in 2000 as the baseline. We consider two scenarios (shown in Table 1). Scenario 1 assumes a hydrogen system with 111,400 fuel cell vehicles, a number equal to 10% of the LD gasoline fleet in urbanized Sacramento in 2000. Similarly, scenario 2 assumes introduction of 278,600 fuel cell vehicles (25% of the gasoline fleet in urbanized Sacramento in 2000). We are not replacing gasoline vehicles with hydrogen FCVs in these scenarios: we add hydrogen vehicles and hydrogen supply systems to the region, and estimate the incremental effect on ambient air pollutant concentrations. Because we consider only physical transport of pollutants, the background ambient pollution levels do not influence the results for the incremental ambient concentrations due to hydrogen vehicles.

2.2. Hydrogen supply schemes

For each hydrogen scenario, we assume that hydrogen supply meets steady-state regional hydrogen demand on a daily basis. The following three hypothetical hydrogen supply pathways are investigated, all based on steam methane reforming

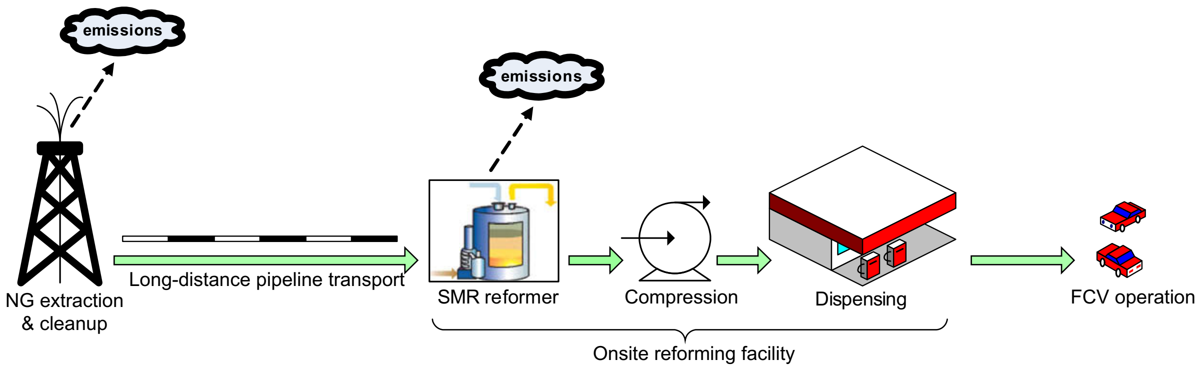

Fig. 2. Onsite pathway with distributed production.

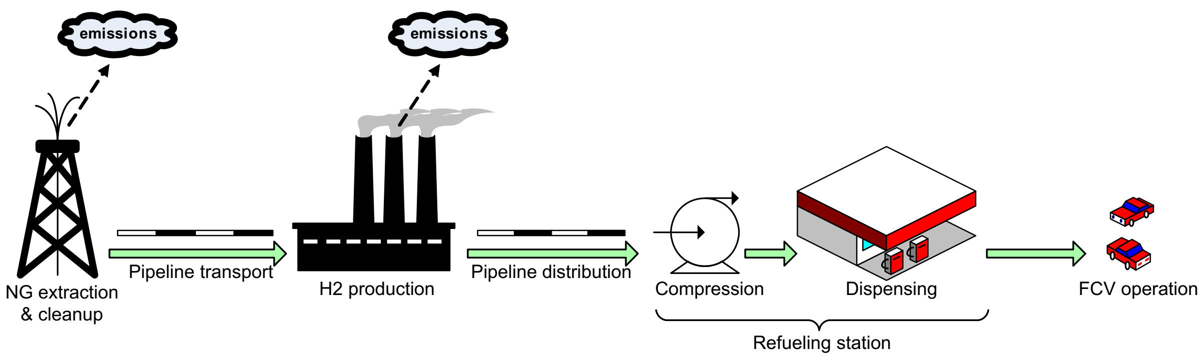

Fig. 3. Pipeline pathway with centralized production and gaseous hydrogen delivery.

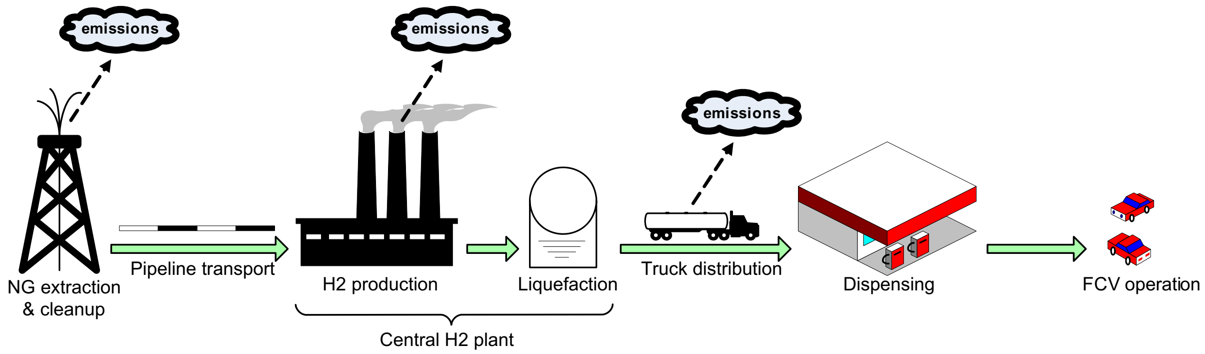

Fig. 4. Truck pathway with centralized production and liquid hydrogen delivery.

(SMR) of natural gas and likely to be the lowest cost near-term options of supplying hydrogen over the next few decades (National Research Council, 2004): (1) onsite pathway, with hydrogen production at refueling stations (Fig. 2); (2) pipeline pathway, with centralized hydrogen production and gaseous hydrogen pipeline delivery systems (Fig. 3); and (3) truck pathway, with centralized hydrogen production and liquid hydrogen (LH2) truck delivery systems (Fig. 4).

For simplicity, emissions associated with electricity used for compressing, liquefying, or transporting hydrogen are not shown in Figs. 2–4, although they are included in our calculations of emissions.

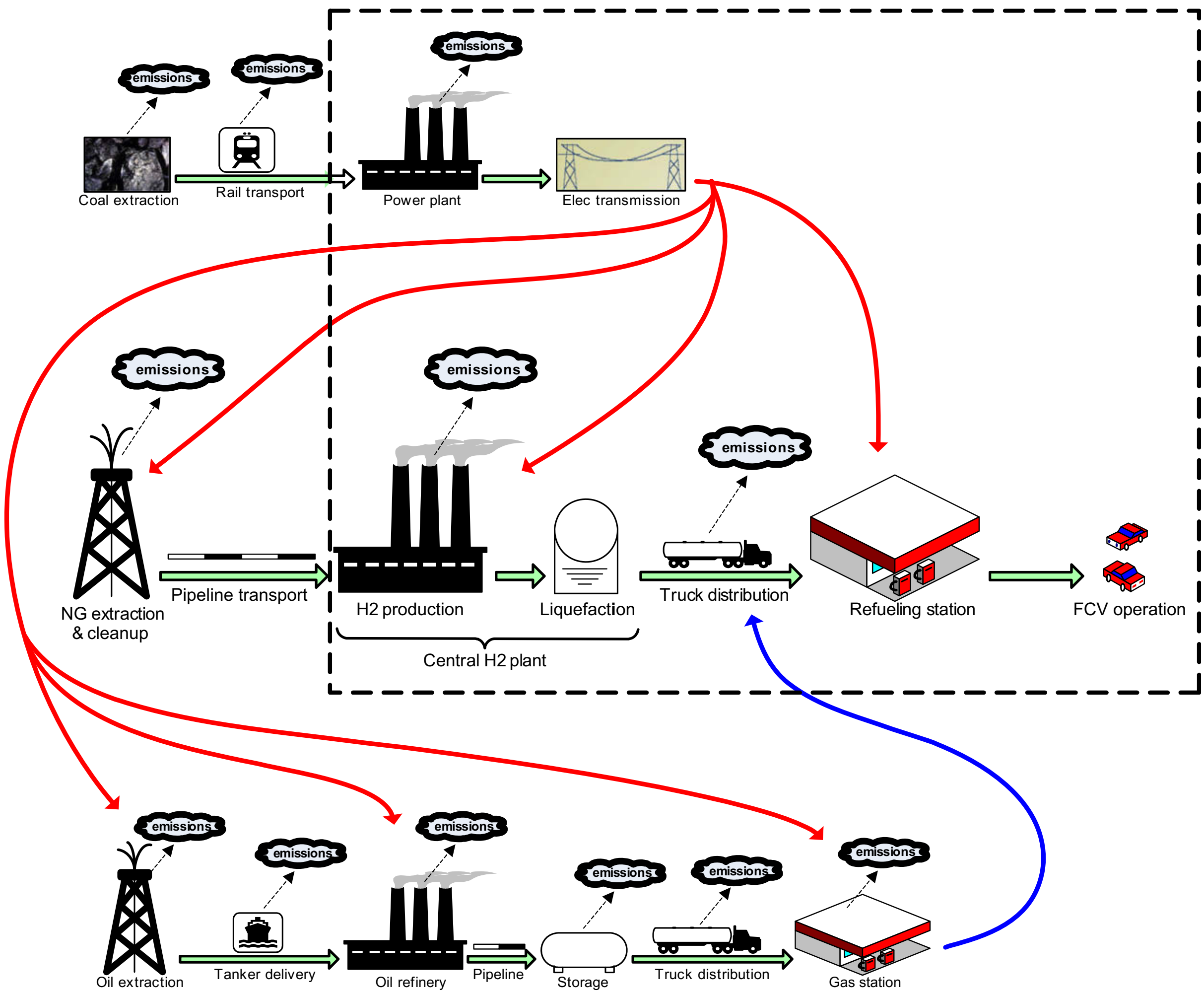

Fig. 5. Integrated natural gas to hydrogen pathways (with liquid hydrogen truck delivery and diesel fuel use in delivery trucks).

2.3. Spatial layout of hydrogen pathway steps

The lifecycle emissions associated with each hydrogen pathway are used to determine the impact on urban air quality within the Sacramento region. Lifecycle emissions include all the emissions involved in producing and delivering hydrogen to vehicles, as well as emissions from electricity generation (for hydrogen compression or liquefaction) and diesel fuel combustion (in hydrogen delivery trucks). Fig. 5 illustrates the various steps in the fuel lifecycle of one of the three integrated natural gas to hydrogen pathways considered (Wang and Delucchi, 2005). The parts of the system included in this analysis are enclosed by the dashed line. The parts outside the dashed line are assumed to be either remote enough or low-emitting enough to have little or no impact on air quality in urban Sacramento. Because emissions outside the "dashed lines" could impact air quality in regions outside the Sacramento area, by focusing on the Sacramento region, our method tends to underestimate the "global" impact of the hydrogen pathway.

The spatial locations of emission sources have a strong influence on the regional air pollutant concentrations. We assume particular spatial locations for each step of the hydrogen pathway: natural gas extraction, hydrogen production, hydrogen delivery, refueling stations, and hydrogen vehicle operation. The spatial layout of the hypothetical stations and hydrogen plant (for scenario 1) is shown in Fig. 6. It is similar for scenario 2, except that the number of stations is different. Emission locations of each pathway step are separated as:

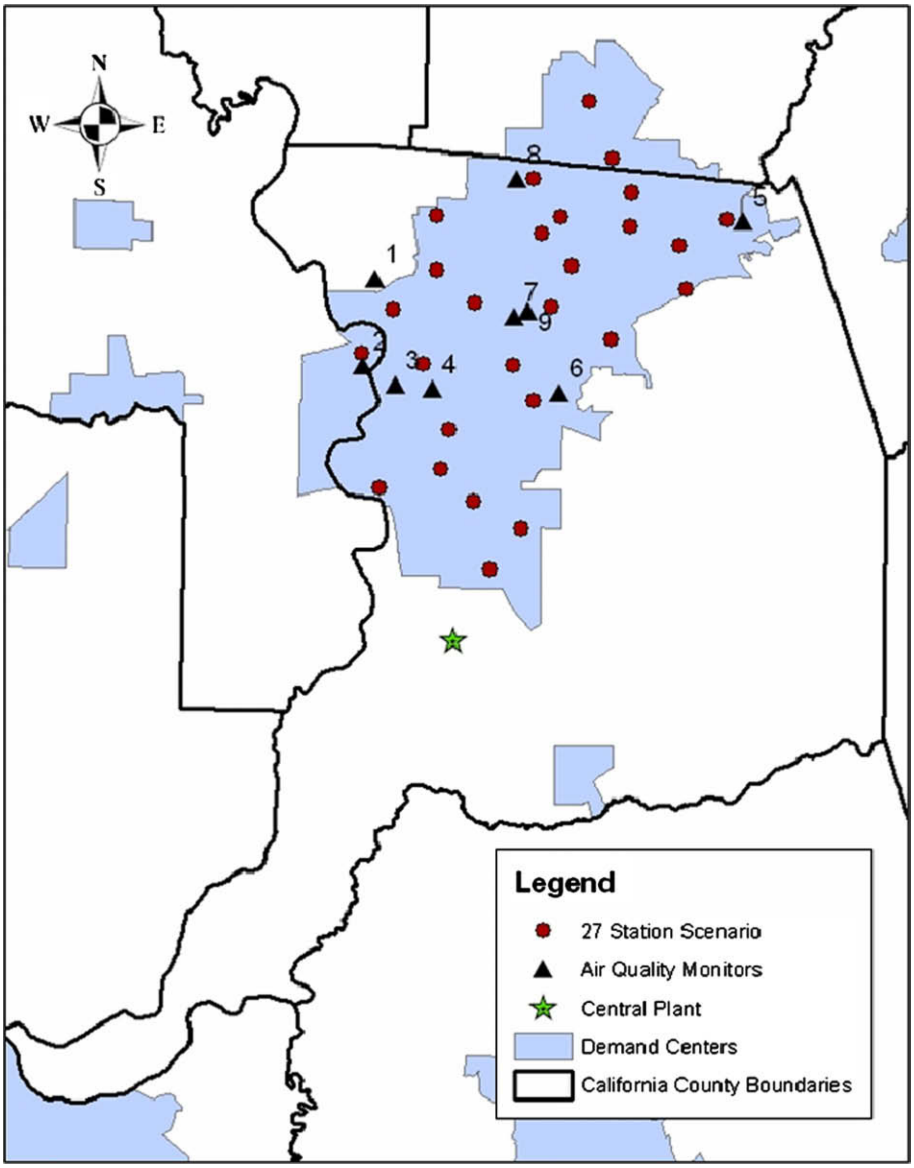

Fig. 6. Spatial layout of refueling stations, central plant, and air quality receptors (scenario 1).

(1) **Natural gas extraction and transport.** Natural gas fields are located far from Sacramento, and therefore the impacts of natural gas extraction and pipeline transport on air quality in urban Sacramento are neglected;
(2) **Centralized hydrogen production.** A central hydrogen production plant is assumed to be near existing natural gas-fired power plants in south Sacramento, and is treated as a point source of emissions;
(3) **Refueling stations.** Sites for hydrogen stations are chosen from among existing gasoline station locations in Sacramento. Hydrogen station sites are selected to minimize the average travel time from home to the closest station for all customers, given a certain number of stations. Customer locations are approximated using traffic analysis zones (TAZs). The method employs geographic information system (GIS) data and optimization techniques (Nicholas, 2004);
(4) **Onsite hydrogen production at refueling stations.** Emissions associated with hydrogen production from small steam reformers at refueling stations occur at the station sites. They are assumed to be point sources of emissions;
(5) **Hydrogen delivery.** Heavy heavy-duty diesel-fueled trucks (HHDTs) delivering liquid hydrogen are mobile sources of emissions. Liquid hydrogen (LH2) trucks are assumed to travel on real-world highways and the actual route that each truck follows from the central hydrogen plant to the station is determined using GIS data on a minimum travel time basis. The number of truck trips is estimated based on the assumed station size and truck capacity (Table 1). At the steady state, the road segments of the truck routes are treated as thin-and-long area sources of emissions;
(6) **Electricity for hydrogen compression and liquefaction.** Actual locations of electric power plants in the Sacramento area are used to estimate incremental emissions associated with electricity for hydrogen compression or liquefaction at the hydrogen plant. Electric power plants are treated as point sources of emissions; and
(7) **Vehicle operation.** Hydrogen vehicle operation is assumed to emit no criteria air pollutants (Ogden et al., 1999), meaning vehicle locations are not important for the analysis.

2.4. Lifecycle emission inventories

By using information on both emission rates and locations, we can develop a spatially deterministic emission inventory, an important input to the subsequent air quality model. We consider the following direct emission sources/sites: hydrogen plant or onsite production stations, electric power plants, and diesel delivery-trucks (Fig. 5). Note that electricity consumed in both the primary hydrogen pathway and sub-pathways is assumed to come from the average power mix for Sacramento. No matter where the electricity is used, its associated emissions are assumed to be occurring at the power plants which are treated as point sources.

Four primary types of emissions, CO, NO_x, VOC, and PM_{10}, are considered. We do not account for re-entrainment of PM_{10} and other particulates from tire wear and brake wear. The data on emission factors and energy consumption are extracted from GREET1.7, a full fuel cycle energy use and emissions model (GREET1.7, 2006). We assume that hydrogen energy production corresponds to the 2005 technology represented in GREET1.7.

2.5. The ISC model and TMY2 dataset

To estimate atmospheric concentrations of pollutants, we employ a steady state Gaussian plume dispersion model, Industrial Source Complex Short Term (ISCST3), maintained by US Environmental Protection Agency (EPA) (ISCST3, 2006). This model can include point, area, volume, and open pit sources of pollution. Line sources of pollution can be approximated as a sequence of long, thin area or volume sources (US Environmental Protection Agency, 1995). This model also can be used to assess air pollution from a variety of sources simultaneously.

By using our estimated emission inventories as input to the ISCST3 model, along with typical meteorological condition data inputs, we can estimate the impacts of hydrogen pathways on urban air quality. The Typical Meteorological Year (TMY2) dataset, developed by the National Renewable Energy Laboratory (NREL), consists of months selected from 30 years (from 1961 through 1990) to form a hypothetical complete year, so it is the statistically most typical meteorological condition rather than the worst-case conditions (TMY2, 2006). We use Sacramento County TMY2 data to represent the whole region. The air quality prediction results associated with TMY2 conditions would be statistically meaningful for a future year.

For benchmarking, we compare our estimates for incremental impacts of hydrogen pathways to actual air quality data from EPA monitoring stations. We estimate air pollutant concentrations at the nine air monitoring stations officially maintained within or near urban Sacramento (Fig. 6) (US Environmental Protection Agency, 2006).

3. Gasoline pathway scenarios

3.1. Overview of gasoline pathway scenarios

Gasoline and diesel fuels produced from petroleum and used in internal combustion engine (ICE) vehicles are examined. For simplicity, we use the term "gasoline pathway" to refer to the petroleum-based fuel pathway, including both gasoline and diesel: about 1.5% of LD vehicles were running on diesel in Sacramento in 2005 (EMFAC2007, 2007).

From a lifecycle analysis perspective, a petroleum-based fuel pathway gives rise to a series of emissions occurring at various locations. The dashed line area (Fig. 7) shows the portion of the gasoline pathway lifecycle system that is included in this analysis, because these stages are located within the Sacramento metropolitan region.

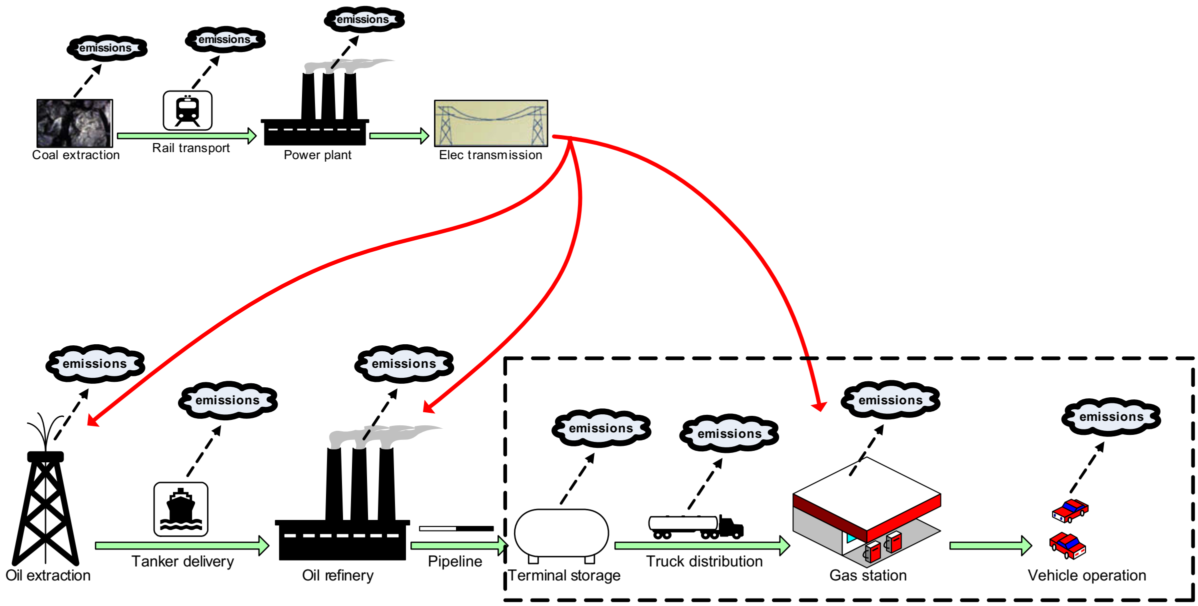

Fig. 7. Integrated gasoline pathways.

Vehicle operation accounts for the majority of air pollution impacts for a petroleum-based transportation system, for both current and future technologies. In this analysis, as illustrated in Fig. 7, we include only emissions from vehicles and fuel delivery trucks. We exclude upstream emissions from crude oil extraction and refineries, as well as from the electricity sub-pathways, because these are mostly or totally located outside the Sacramento region (refineries are located in Richmond and Martinez, California). We also exclude emissions associated with the gasoline terminal storage and the small amounts of VOC emitted at gasoline service stations, because these are quite small in our scenarios.

The primary focus of gasoline pathway analysis is on gasoline vehicle operation, although fuel delivery is given important consideration. Therefore, our analysis understates air quality impacts of the gasoline pathway scenario. Including upstream and neglected within-Sacramento emissions would make the hydrogen pathway scenarios even more favorable by comparison. Thus, this approach is a conservative one that gives the "benefit of the doubt" to conventional fuels.

3.2. Gasoline fleets considered

We include all light duty vehicles, defined as 8500 lbs or less. These are categorized as vehicle classes 1–4 in EMFAC2007, which are part of a total of 13 vehicle classes defined in the EMFAC2007 model (EMFAC2007, 2007).

The following four light duty (LD) fleets running on roads in the six-county Sacramento metropolitan area are included here. Vehicle miles traveled (VMT) and the fleet compositions are extracted from EMFAC2007 using its default assumptions. We choose these four cases, including both current and advanced gasoline technologies:

(1) Year 2005 on-road light duty fleet, which includes a mix of 1,510,255 vehicles from 1965–2005;
(2) Year 2005 new light duty fleet, which includes the 95,874 vehicles (the number of new vehicles in 2005);
(3) Year 2025 on-road light duty fleet, which includes a mix of projected 2,091,542 vehicles from 1981–2025; and
(4) Year 2025 new light duty fleet, which includes the 127,802 vehicles (the projected number of new vehicles in 2025).

3.3. Methodology

The modeling domain (the Sacramento metropolitan area) comprises the six counties – Sacramento, Yolo, Sutter, Yuba, Placer, and El Dorado – that correspond to the Sacramento Area Council of Governments (SACOG).

To estimate air quality impacts of gasoline pathways, we use a series of models including the regulatory emissions model, transportation planning model, gridded emission inventory model, and air quality model. The methodology is presented in a flow chart showing the model running sequence (Fig. 8). The procedure is briefly described as follows (Wang et al., 2008).

3.3.1. The EMFAC model

The EMFAC2007 model is the California mobile source emissions model which calculates emission inventories for motor vehicles operating on roads in California (EMFAC2007, 2007). We use the EMFAC model for several purposes. As stated ear-

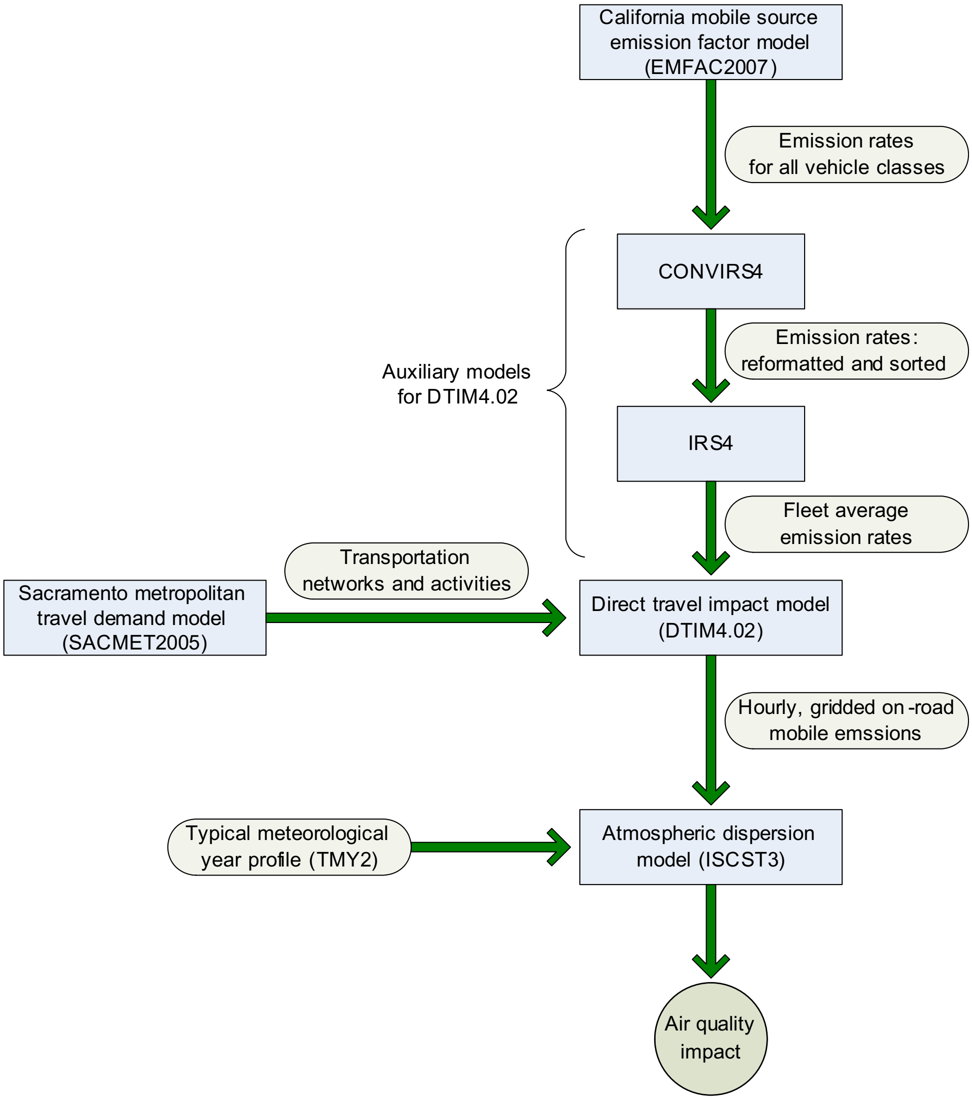

Fig. 8. Methodological framework and model running sequence for gasoline fleet scenarios.

lier, we extract LD fleet data for both 2005 and 2025 from EMFAC. We also run EMFAC2007 to provide emission rates for the predefined four vehicle classes noted above. The following types of air pollutants and their associated emission processes are considered: CO, NO_x, total organic gases (TOGs) or VOC, and PM_{10}. Note that we do not account for re-entrainment of PM_{10} and other particulates from tire wear and brake wear (which should be largely constant across gasoline and hydrogen vehicles). Because gasoline vehicles produce very small amounts of PM_{10} relative to other sources, we focus on the other three pollutants. For TOG or VOC, we account for both vehicle tailpipe exhaust and vehicle evaporative emissions. For the other pollutants, we just consider direct tailpipe emissions.

The default values in the EMFAC2007 model, which we use, likely overestimate future emissions under some special conditions. This is because the default values are based on an increasing proportion of vehicles being classified in the most stringent regulatory categories that exist today (PZEV and SULEV), but even more stringent emission categories and overall emission reductions are likely to be required in the future. Indeed, a new emission reduction rulemaking process for vehicles is already planned for 2009–2010. If emissions are reduced further than indicated by the EMFAC model, then the gasoline pathway will not be as inferior to hydrogen as is found in this study. However, the differences we find between the hydrogen and gasoline pathways are so huge, as indicated later, that the overall conclusions of this paper are not sensitive to concerns about overestimation of gasoline vehicle emissions by the EMFAC model.

3.3.2. The CONVIRS and IRS models

The application of CONVIRS4 reformats and sorts the emission rates generated by EMFAC, and then IRS4 calculates fleet average emission rates. In this step, vehicle class weights are used to define the fleet of interest, and weighted average emission rates for the special fleet are derived. The vehicle class weights are usually the proportions of VMT by each vehicle class in the fleet (Caltrans, 2001). Because we are only interested in LD fleets, the vehicle class weights for classes other than 1–4 are set to zero. This produces a new LD fleet averaged emission factor, which is applied throughout the region.

3.3.3. The SACMET model

We employ data on the regional transportation networks and activities from a traditional four-step travel demand model, SACMET2005, which gives spatially detailed traffic flows for each road link in the six-county Sacramento metropolitan area, for several multi-hour time periods for a typical weekday (DKS Associates, 2002; SACMET2005, 2005).

3.3.4. The DTIM model

The Direct Travel Impact Model (DTIM4.02), maintained by the California Department of Transportation, is capable of generating hourly, gridded emission inventories to address temporal and spatial distributions of motor vehicle emissions (Caltrans, 2001). Running DTIM is based on two prerequisite inputs: transportation networks and activities from SACMET and LD fleet average emission rates from IRS. We divide the modeling domain into 48400 (220×220) grid cells at a 1×1 km resolution, and then run DTIM to assign regional emissions to these grid cells by hour to address the temporal and spatial differences, which are important to the subsequent atmospheric dispersion model.

3.3.5. The ISC model and TMY2 dataset (revisited)

Following DTIM, we run the Gaussian dispersion model ISCST3. Grid-based emissions from LD vehicles are treated as area sources of pollution. Air pollutant receptors are the same as those for the hydrogen pathways (Fig. 6). By inputting the 24 hourly dynamic (time-varying) emission rates of the grid cell area sources to the ISCST3 model, along with typical meteorological year (TMY2) data inputs, we can estimate the impacts of mobile sources on urban air quality.

4. Results and discussion

4.1. Incremental concentrations caused by hydrogen pathways

We compare onsite, pipeline, and truck pathways looking at CO, NO_x, VOC, and PM_{10}. To better represent a typical pollution level caused by hydrogen pathways, we estimate the annual mean incremental concentrations to ambient pollution due to hydrogen pathways, averaged over the nine receptors (Table 2), although environmental impacts vary with receptor site.

All hydrogen pathways would result in negligible pollution levels, compared to current ambient measurements (last column of Table 2). The incremental pollution differs across hydrogen pathways. Among the hydrogen supply options, it is found that the central SMR with pipeline delivery systems is the lowest-pollution option available, provided the hydrogen production plant is located to avoid transport of pollutants into the city via prevailing winds. The onsite hydrogen pathway is almost comparable to the central hydrogen pathway with pipeline delivery systems in terms of the resulting air pollution. Both pathways are very clean. The truck pathway also results in extremely low pollution levels, although they are higher than concentrations resulting from the other two hydrogen pathways. Most emissions for the truck pathway are from diesel trucks delivering liquid hydrogen and electricity used to liquefy the hydrogen.

The onsite pathway and the pipeline pathway result in very similar ground-level pollution levels, especially in terms of VOC and PM_{10}. However, the onsite pathway leads to more CO and less NO_x pollution than the pipeline pathway. This makes sense because CO tends to be released from incomplete combustion or partial oxidation, which is more likely to occur at a small-scale onsite station, whereas NO_x tends to be released from large stationary sources resulting from combustion, e.g., to produce the high temperature steam which is used in the central hydrogen plant or in a power plant.

In contrast to the pipeline pathway, the incremental pollution due to each of the other two hydrogen pathways is not exactly proportional to regional hydrogen demand, denoted by the number of hydrogen FCVs served (Table 2). When the

Table 2
Annual mean incremental concentrations due to hydrogen pathway scenarios

Pollutant	# of FCVs served	Onsite pathway (μg/m^3)	Pipeline pathway (μg/m^3)	Truck pathway (μg/m^3)	Sac. 2000 ambient measurement (μg/m^3)
CO	111,400	0.0047	0.0032	0.0085	640
	278,600	0.0142	0.0079	0.0233	
NO_x	111,400	0.0065	0.0090	0.0191	56.6 (NO_2)
	278,600	0.0197	0.0224	0.0539	
VOC	111,400	0.0004	0.0004	0.0011	74.8 (NMOC)
	278,600	0.0013	0.0011	0.0033	
PM_{10}	111,400	0.0005	0.0005	0.0009	22.5
	278,600	0.0015	0.0012	0.0023	

Source: Wang et al. (2007a).

Table 3
Annual mean incremental concentrations (i.e., C_1) resulting from the four LD fleets

	On-road 2025 LD fleet	New 2025 LD fleet	On-road 2005 LD fleet[2]	New 2005 LD fleet
# of gasoline vehicles	2,091,542	127,802	1,510,255	95,874
VMT (miles/day)	66,498,532	6,750,272	51,124,896	5,083,584
CO (μg/m^3)	29.78	0.99	113.36	1.39
NO_x (μg/m^3)	1.335	0.032	5.585	0.068
VOC[1] (μg/m^3)	2.689	0.042	8.327	0.054
TOG (μg/m^3)	2.922	0.046	9.051	0.059
PM_{10} (μg/m^3)	0.261	0.0042	0.173	0.0035

[1] VOC concentrations are obtained by scaling the TOG data, as TOG is used in a series of transportation models like EMFAC2007. VOC accounts for 92% of the mass fraction of TOG on an on-road mobile source basis, derived from on-road mobile emissions data for the Sacramento metropolitan area (California Air Resources Board, 2007). For non-mobile sources, this mass fraction does not necessarily hold.

[2] For example, the resulting concentration for the 2005 on-road LD fleet, shown in column 4 of Table 3, is derived using Eq. 1 as follows: $C_1 = \frac{C_0}{\mathrm{VMT}_0} \times \mathrm{VMT}_1 = \frac{C_0}{57{,}203{,}211} \times 51{,}124{,}896 = C_0 \times 0.894$; that is, the concentration results shown in columns 4 are equal to those outputs from our model running sequence scaled by 0.894. The same approach applies to the other fleets, listed in columns 2–5 of this table.

hydrogen vehicle population increases by 2.5 times – from 10% to 25% of the 2000 conventional LD fleet – the pollution ratio increases by slightly over 2.5 times. For the pipeline pathway, pollution levels are exactly 2.5 times greater when the hydrogen vehicle population increases by 2.5 times, as we assume that the natural gas to hydrogen conversion efficiency remains constant as hydrogen demand goes up, holding the electric generation resource mix constant.

4.2. Air pollutant concentrations caused by gasoline vehicle operation

Air pollutant emissions depend heavily on the magnitude of vehicle miles traveled (VMT). In our modeling, we use the SACMET2005 model for traffic flow data, which is appropriate for 2005 traffic conditions only. SACMET2005 gives us an estimate of the number of vehicle miles traveled by all vehicle types including light duty vehicles plus heavy duty vehicles and buses. But in our gasoline fleet scenarios, we want to model LD vehicle traffic flows in two different years: 2005 and 2025. First we define a base VMT level, VMT_0, which is equal to the number of vehicle miles traveled by all vehicle types in 2005; then, we use a scaling method to account for the VMT variability for various gasoline fleet scenarios.

Recall that the travel activity level represented by SACMET2005 is used in the methodology (flow chart in Fig. 8). This means when we use our methodology for various fleet scenarios, the regional transportation activity level (say VMT) for 2005 is always used by default; that is, the procedure automatically keeps VMT and traffic flows unchanged for any fleet mix modeled. To make the framework more broadly applicable, we define the scaled concentration C_1 as

$$C_1 = \frac{C_0}{\mathrm{VMT}_0} \times \mathrm{VMT}_1, \tag{1}$$

where C_1 refers to the concentration resulting from the LD fleet of interest and C_0 refers to the concentration output from our model running sequence (Fig. 8). C_0 represents the predicted concentration resulting from the hypothetical LD fleet whose travel activity level is assumed to be equal to VMT_0[1]. Table 3 presents estimated annual mean incremental concentrations to ambient pollution resulting from the four LD fleet scenarios, averaged over the nine receptors.

To compare with hydrogen pathways, the concentrations in Table 3 are further scaled to make the number of LD vehicles for each gasoline fleet scenario equal to the number of FCVs served by a hydrogen pathway. Table 4 presents estimated annual mean incremental concentrations to ambient pollution due to gasoline vehicle operation, averaged over the nine receptors. Given the same number of vehicles or on a per vehicle basis, the on-road 2025 LD fleet results in much less pollution, with the exception of PM_{10}, than the on-road 2005 LD fleet. Similarly, for a scenario year, the new LD vehicle fleet would lead to much lower concentrations than the on-road fleet, assuming the same vehicle population. On one hand, this reflects progress in technologies and standards in California. On the other hand, the energy consumption and emission performance of a conventional vehicle deteriorates as the vehicle age or mileage increases. Thus, fleet turnover is conducive to reducing vehicle emissions and improving urban air quality.

On a per vehicle basis, a new vehicle of the model year 2025 is cleaner than a new vehicle of the model year 2005 in terms of the resulting concentrations of all four pollutants. However, PM_{10} concentrations for the model year 2025 vehicle are just slightly lower than for the model year 2005 vehicle, because the EMFAC model assumes minimal improvements in reducing particulate matter from LD vehicles.

[1] VMT_0 = 57,203,211 miles/day refers to vehicle miles traveled for all the vehicles, composed of vehicle classes 1–13 defined in EMFAC2007, operating in the Sacramento metropolitan area in 2005. The number is obtained from EMFAC2007 by adding up VMT for six individual counties. This level of traffic flow and activity corresponds to that represented by the travel demand model SACMET2005 and is a very important metric, as our estimation is built upon the framework of the SACMET2005 model; and VMT_1 refers to VMT for a light duty fleet, composed of vehicle classes 1–4 only, projected or observed to be operating in the Sacramento metropolitan area in 2005 or 2025; e.g., VMT_1 = 51,124,896 miles/day for the on-road LD fleet in 2005. The numbers are obtained from EMFAC2007 by adding up LD vehicle VMT for six counties.

Table 4
Estimated annual mean incremental concentrations due to gasoline vehicle operation

Pollutant	# of gasoline vehicles	On-road 2025 LD fleet ($\mu g/m^3$)	New 2025 LD fleet ($\mu g/m^3$)	On-road 2005 LD fleet ($\mu g/m^3$)	New 2005 LD fleet ($\mu g/m^3$)
CO	111,400	1.5860	0.8629	8.3618	1.6153
	278,600	3.9665	2.1581	20.9119	4.0397
NO_x	111,400	0.0711	0.0276	0.4120	0.0787
	278,600	0.1778	0.0690	1.0304	0.1969
VOC	111,400	0.1432	0.0370	0.6143	0.0631
	278,600	0.3581	0.0925	1.5362	0.1579
PM_{10}	111,400	0.0139	0.0037	0.0128	0.0040
	278,600	0.0347	0.0092	0.0319	0.0101

4.3. Treatment of gasoline-delivery trucks

The treatment of trucks delivering gasoline fuel has a minor effect on ambient air quality, since their emissions are dwarfed by the emissions from the vehicles fueled by their delivered fuel.

Major oil refineries serving the Sacramento metropolitan area are located outside the local airshed in Richmond and Martinez, California. Gasoline comes to Sacramento via pipeline, is stored in terminals near urban Sacramento, and is then trucked from there to refueling stations. If we assume the terminals are about as far away from the stations on average as the central hydrogen plant, we could simply scale the liquid hydrogen (LH2) truck based concentrations to estimate the air quality impact of diesel trucks delivering gasoline. The truck emissions estimated for the LH2 truck pathway were for delivery trucks going to each of 27 (or 66) stations. To do this scaling, we need to know how many deliveries would be made by gasoline-delivery trucks versus LH2 trucks to fuel the same number of vehicles at these stations.

Table 5 shows estimated annual mean incremental concentrations due to gasoline-delivery truck emissions for each fleet scenario. For the treatment of gasoline-delivery trucks, we make a simplifying assumption that, on average, a gasoline vehicle (either new or on-road) served by the delivery trucks has the same annual VMT level as a hydrogen FCV, as the air quality influence of truck delivery is relatively small.

4.4. Comparison of hydrogen and gasoline pathways

The air quality impact of gasoline pathways is taken simply as the sum of incremental concentrations due to both the gasoline fleet operation and gasoline-delivery trucks. For comparison purposes, we use the metric "concentration ratio", which is defined as the concentration resulting from a hydrogen or gasoline pathway relative to that resulting from the hydrogen pathway with pipeline delivery systems. Keep in mind that we are comparing the incremental concentrations, not including any ambient background of CO, VOC, etc. Table 6 summarizes the comparison of concentration ratios relative to the centralized/pipeline hydrogen pathway, for scenarios of three hydrogen pathways and four LD gasoline pathways, assuming the same size vehicle population (the results do not change much if we assume the same size VMT level, so in this paper we only focus on the results corresponding to the same size population).

Using the centralized/pipeline hydrogen pathway with the same vehicle population as the reference scenario, an onsite hydrogen pathway has an almost identical impact on air quality, especially for VOC and PM_{10} concentrations. The onsite pathway would lead to slightly greater CO and lower NO_x concentrations, as CO tends to be released from incomplete combustion or partial oxidation that more often occurs at a small-scale onsite station, whereas NO_x tends to be released from large-scale stationary sources related to high temperature processes, such as those found at a central hydrogen or power plant. The centralized hydrogen production with liquid hydrogen truck delivery is the least clean option among these three

Table 5
Annual mean incremental concentrations due to gasoline-delivery truck emissions

Pollutant	# of gasoline vehicles served	On-road 2025 LD fleet ($\mu g/m^3$)	New 2025 LD fleet ($\mu g/m^3$)	On-road 2005 LD fleet ($\mu g/m^3$)	New 2005 LD fleet ($\mu g/m^3$)
CO	111,400	0.0016	0.0015	0.0122	0.0121
	278,600	0.0055	0.0054	0.0429	0.0427
NO_x	111,400	0.0028	0.0027	0.0138	0.0137
	278,600	0.0098	0.0095	0.0486	0.0483
VOC	111,400	0.0003	0.0003	0.0015	0.0015
	278,600	0.0010	0.0010	0.0051	0.0051
PM_{10}	111,400	0.0001	0.0001	0.0005	0.0005
	278,600	0.0003	0.0003	0.0019	0.0019

Table 6
Comparison of concentration ratios relative to the hydrogen pipeline pathway

Pollutant	# of FCVs or gasoline vehicles	Onsite pathway	Pipeline pathway	Truck pathway	On-road 2025 LD fleet	New 2025 LD fleet	On-road 2005 LD fleet	New 2005 LD fleet
CO	111,400	1.5	1.0	2.7	502	273	2646	514
	278,600	1.8	1.0	2.9	502	273	2648	516
NO_x	111,400	0.7	1.0	2.1	8.2	3.4	47	10.3
	278,600	0.9	1.0	2.4	8.4	3.5	48	10.9
VOC	111,400	1.0	1.0	2.7	336	87	1443	151
	278,600	1.2	1.0	3.1	337	88	1446	153
PM_{10}	111,400	1.0	1.0	1.8	29	7.9	28	9.5
	278,600	1.2	1.0	1.9	29	8.0	28	10.0

means of hydrogen supply, for the four pollutant types examined. The extra energy consumed to liquefy hydrogen plays an important role, and the diesel-truck delivery also matters in terms of emissions and air pollution.

The gasoline pathways representing the situation today, with the model year 2005 vehicles, would lead to 510 times greater CO, 150 times greater VOC, 10 times greater PM_{10}, and 10 times greater NO_x concentrations than those caused by the centralized/pipeline hydrogen pathway (Table 6), assuming the same number of vehicles.

The gasoline pathways with the model year 2025 vehicles (advanced gasoline vehicles) would lead to 273 times greater CO, 88 times greater VOC, 8 times greater PM_{10}, and 3.5 times greater NO_x concentrations than those caused by the centralized/pipeline hydrogen pathway (Table 6), assuming the same number of vehicles. The resulting CO and VOC pollution is about two orders of magnitude greater than that of the truck pathway, the least clean hydrogen scenario. Again, the 2025 new-vehicle gasoline pathways cause significantly higher PM_{10} and NO_x pollution than any of the hydrogen pathways. Considering that we have not included emissions from the gasoline terminal storage and refueling stations, it is safe to say that hydrogen pathways with commercially available (2005) production technology would be significantly less polluting than any LD gasoline fleet scenarios examined (assuming either the full on-road fleet or just new vehicles), from a lifecycle analysis perspective. In short, introducing any of the hydrogen pathways analyzed would improve urban air quality compared to the 2005 on-road scenario in the following order of concentration ratio: CO > VOC > >NO_x > PM_{10}.

For the new fleet scenarios, 2025 vehicles would have far fewer emissions than year 2005 vehicles (except for PM_{10}, which are only slightly better). Thus, it is not necessary to compare hydrogen pathways with the 2005 new fleets (and, hence, the on-road fleets in 2005 or 2025), as we have done this for the 2025 new gasoline fleets. That is, the superiority of the hydrogen pathway scenarios, compared to the best-case gasoline scenario of all-new 2025 vehicles, is even more pronounced when compared to gasoline scenarios involving older vehicles. This reflects the trend of improving vehicle emission performance over time. Moreover, due to the methodological limitation of directly using travel demand model data (from SACMET) for air quality research, transportation-related air pollution tends to be underestimated (Wang et al., 2008), indicating that the improvement offered by hydrogen pathways is even greater than shown.

Hydrogen demand is estimated based on the population in urbanized Sacramento, whereas the SACMET2005 modeling domain is made up of six counties. This is not an inconsistency, as hydrogen vehicles could be running anywhere in the six counties, and they are zero emission vehicles so that we do not need to locate hydrogen FCVs.

4.5. Further discussion on gasoline vehicle emission trends

For the on-road fleet scenarios, the year 2025 fleet would make dramatic progress in environmental impacts, with the exception of PM_{10}, over the 2005 fleet (Table 6). The PM_{10} pollution is the least accurate in the light duty emissions modeling. Also, PM_{10} emissions of gasoline vehicles are much less than PM_{10} emissions from heavy trucks and other stationary sources.

Based on the EMFAC dataset, the level of CO, TOG, and NO_x emissions from an on-road LD fleet averaged vehicle would steadily decrease between 2005 and 2025, on a per-mile-traveled basis. This explains the steady annual improvements in air quality for the on-road fleet scenarios.

5. Conclusions

We have examined the potential regional air quality impacts of hydrogen transportation fuel from a lifecycle analysis perspective, including impacts from fuel production, fuel delivery, and vehicle use. Four pollutants and three hypothetical natural gas-based hydrogen pathways were examined. We compared these to gasoline pathway scenarios for 2005 and 2025, respectively. We sequentially applied a series of models to estimate the contributions of light duty gasoline fleets to urban air pollution using travel forecasting model data.

We found that all the hydrogen pathways analyzed have an extremely low impact on air pollutant concentrations. Centralized hydrogen production with liquid hydrogen truck delivery is the least clean option among these three means of hydrogen supply. All the gasoline pathways studied yield much higher pollutant concentrations than the hydrogen pathways. The best gasoline scenario, assuming year 2025 advanced gasoline vehicles, would lead to 273 times greater CO, 88 times greater VOC, 8 times greater PM_{10}, and 3.5 times greater NO_x concentrations than those caused by the centralized/pipeline hydrogen pathway, assuming the same size vehicle population.

Acknowledgements

The authors would like to thank the Sustainable Transportation Energy Pathways program at the Institute of Transportation Studies at the University of California, Davis for its support, and Patricia Mokhtarian and Dan Chang for their many insights.

References

California Air Resources Board, 2007. Estimated Annual Average Emissions. California Air Resources Board. <http://www.arb.ca.gov/app/emsinv/emssumcat.php> (accessed 09.29.07.).

California Air Resources Board, 2008. Zero emission vehicle program. <http://www.arb.ca.gov/msprog/zevprog/zevprog.htm> (accessed 04.13.08.).

Caltrans, 2001. DTIM4 user's guide. Office of Travel Forecasting and Analysis, California Department of Transportation, Sacramento.

Colella, W.G., Jacobson, M.Z., Golden, D.M., 2005. Switching to a US hydrogen fuel cell vehicle fleet: the resultant change in emissions, energy use, and greenhouse gases. Journal of Power Sources 150, 150–181.

Delucchi, M., McCubbin, D., 2004. The Contribution of Motor Vehicle and Other Sources to Ambient Air Pollution. Report #16 in the Series: The Annualized Social Cost of Motor-Vehicle Use in the United States, Based on 1990-1991 Data. University of California, Davis, Institute of Transportation Studies, Publication No. UCD-ITS-RR-96-3 (16) rev. 1.

DKS Associates, 2002. Model Update Report: Sacramento Regional Travel Demand Model Version 2001 (SACMET01). Sacramento Area Council of Governments, SACOG-02-003, Sacramento.

EMFAC2007, 2007. Version 2.30 user's guide: calculating emission inventories for vehicles in California. <http://www.arb.ca.gov/msei/onroad/latest_version.htm> (accessed 06.19.07.).

ExternE, 1998. Externalities of Energy, Methodology 1998 Update. European Commission. <http://www.externe.info/reportex/vol7.pdf> (accessed 06.10.05.).

GREET1.7, 2006. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. Argonne National Laboratory. <http://www.transportation.anl.gov/software/GREET/index.html> (accessed 05.25.06.).

ISCST3, 2006. Industrial Source Complex Model (Short Term 3). US EPA. <http://www.epa.gov/scram001/dispersion_alt.htm> (accessed 05.25.06.).

Jacobson, M.Z., Colella, W.G., Golden, D.M., 2005. Cleaning the air and improving health with hydrogen fuel-cell vehicles. Science 308, 1901–1905.

McCubbin, D., Delucchi, M., 1996. The Social Cost of the Health Effects of Motor-Vehicle Air Pollution. University of California, Davis, Institute of Transportation Studies, Publication No. UCD-ITS-RR-96-03(11).

National Research Council, 2004. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. National Research Council – Board on Energy and Environmental Systems, Washington, DC.

Nicholas, M.A., 2004. Hydrogen Station Siting and Refueling Analysis Using Geographic Information Systems: A Case Study of Sacramento County. Masters Thesis. University of California, Davis.

Ogden, J.M., Steinbugler, M.M., Kreutz, T.G., 1999. A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development. Journal of Power Sources 79, 143–168.

Ogden, J.M., Williams, R.H., Larson, E.D., 2004. Societal lifecycle costs of cars with alternative fuels/engines. Energy Policy 32, 7–27.

SACMET2005, 2005. SACMET2005 model package. Sacramento Metropolitan Travel Demand Model.

TMY2, 2006. National Renewable Energy Laboratory (NREL). <http://rredc.nrel.gov/solar/pubs/tmy2/> (accessed 05.25.06.).

US Census Bureau, 2006. Population, Area and Population Density of US Urbanized Areas from 2000 US Census. <http://www.census.gov/geo/www/ua/ua2k.txt> (accessed 01.25.06.).

US Environmental Protection Agency, 1995. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, vol. 1 – User Instructions. EPA-454/B-95–003a. US Environmental Protection Agency. North Carolina. <http://www.epa.gov/scram001/userg/regmod/isc3v1.pdf> (accessed 05.25.06.).

US Environmental Protection Agency, 2006. Air Quality System (AQS). US Environmental Protection Agency. <http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm> (accessed 03.02.06.).

Wang, G., Delucchi, M.A., 2005. Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials, APPENDIX X: Pathways Diagrams. University of California, Davis, Institute of Transportation Studies, Publication No. UCD-ITS-RR-03-17X.

Wang, G., Ogden, J.M., Nicholas, M.A., 2007a. Lifecycle impacts of natural gas to hydrogen pathways on urban air quality. International Journal of Hydrogen Energy 32, 2731–2742.

Wang, G., Ogden, J.M., Chang, D.P.Y., 2007b. Estimating changes in urban ozone concentrations due to life cycle emissions from hydrogen transportation systems. Atmospheric Environment 41, 8874–8890.

Wang, G., Bai, S., Ogden, J.M., 2008. Identifying contributions of on-road motor vehicles to urban air pollution using travel demand model data. Institute of Transportation Studies. University of California, Davis.