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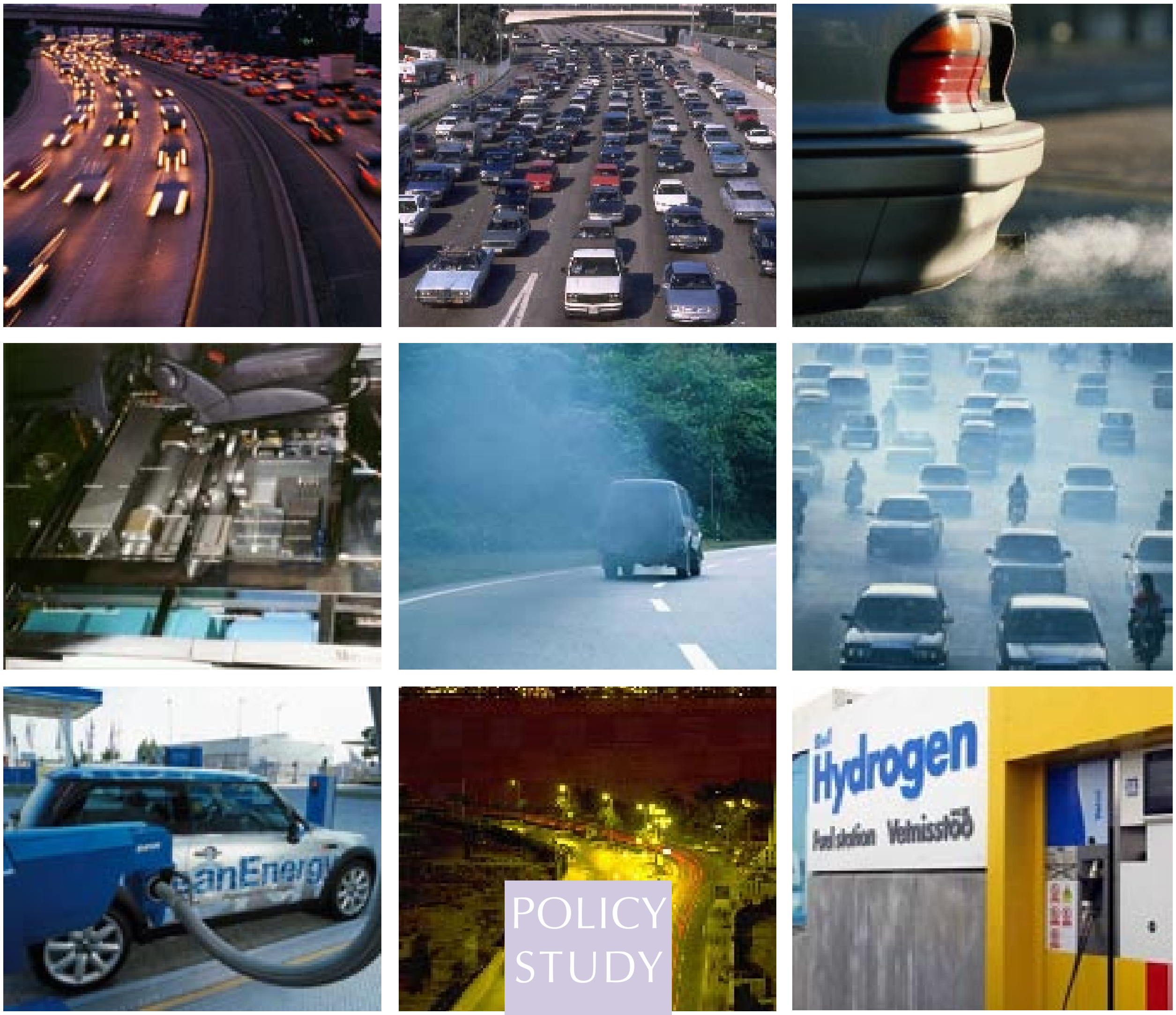
FUELING AMERICA: HOW HYDROGEN CARS AFFECT THE ENVIRONMENT

by William J. Korchinski
Project Director: Adrian T. Moore



POLICY STUDY
322

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Policy Study No. 322

Fueling America:
How Hydrogen Cars Affect the Environment

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Executive Summary

In recent years, the use of hydrogen as a fuel for cars has become an increasingly popular idea. Many influential people endorse the idea as an important milestone on the road to U.S. energy independence. Others support it because they see hydrogen as the ultimate clean fuel to help the environment. But can the mass conversion of vehicles to hydrogen power significantly improve the environment? And given the high cost of building the infrastructure necessary to transport and distribute hydrogen, would it be worth it? This study sets out to answer these very questions.

When a vehicle's engine burns gasoline, carbon dioxide (CO_2) is produced in the exhaust gases that then enter the air around the car. Proponents of using hydrogen to power automobiles generally point out that a hydrogen-fueled car produces only water in its exhaust, and no CO_2. While this is true, it is an incomplete picture. This study, unlike many others, opens the aperture in which CO_2 emissions are measured, to include not only the release caused by vehicles, but the emissions caused by the manufacture, transport and distribution of both hydrogen and gasoline, to foster a more accurate comparison of their relative benefits. Using various hydrogen production methods depicted by 11 case studies, this study measures hydrogen fuel cells and liquid fuel cells against a base case of the modern, internal combustion engine, gasoline-powered vehicle to assess which results in the least CO_2 emissions and the relative value of converting vehicles to hydrogen power.

We performed a simulation for each case study based on a 300-mile drive for the candidate vehicle. Results, including raw materials, energy requirements, and atmospheric CO_2 production, were calculated based on the resources required to generate the fuel necessary to drive the car 300 miles. To standardize for the various types of power generation infrastructures, we used the state of California as the geographic area for this study. Additionally, hydrogen-powered vehicles require a far heavier weight to achieve the same horsepower performance of gasoline-powered vehicles. We therefore did not normalize for relative vehicle performance; as a result, the fuel cell vehicles used in this study will not perform as well as the gasoline-powered one.

We found that while hydrogen fuel cell cars powered by hydrogen manufactured using hydroelectricity resulted in the least CO_2 emissions, this case was rendered impractical due to the limited amount of electricity generated by a hydroelectric source. In California, hydrogen would most likely be manufactured through electrolysis produced via natural gas, which resulted in the highest CO_2 emissions. We found the decline in emissions to be barely discernible, leading to the conclusion that the reduction in CO_2 emissions gained by using hydrogen-powered vehicles is not significant.

To assess the significance of the impact of converting to hydrogen-powered cars we projected the effect on CO_2 emissions if all cars in California had converted to hydrogen in 1981. We found the decline in emissions to be barely discernable and probably not even measurable, leading to the conclusion that the reduction in CO_2 emissions gained by using hydrogen-powered vehicles is not significant.

The most compelling reason for the inability of hydrogen-powered vehicles to significantly affect CO_2 emissions is that total vehicular emissions pale in comparison to the total CO_2 emitted statewide from all hydrocarbon (fossil fuel) combustion. In fact, this study found that if vehicular emissions were entirely eliminated, total emissions statewide would fall by 10 percent or less. This fact, combined with the CO_2 emissions generated by hydrogen manufacture and distribution, calls into question the value of converting the present gasoline-powered vehicle into the expensive hydrogen-powered vehicle considered by so many to be the answer to today’s global warming problems.

Our study concludes that converting vehicles to run on hydrogen would have at best a marginal effect on CO_2 emissions. In fact, if hydrogen-powered vehicles are made to have the same performance characteristics as gasoline-powered ones, the use of hydrogen may actually *increase* atmospheric CO_2 emissions.

There are far simpler, less expensive, and more effective ways to reduce carbon dioxide emissions. People and businesses already have strong incentives to conserve energy, and competitive electricity markets and real-time pricing of electricity will strengthen those incentives. Gasoline cars are increasingly efficient and targeting gross polluting vehicles on the road today will greatly reduce auto emissions. None of these alternatives requires constructing a hydrogen generation and distribution infrastructure, a massive and expensive undertaking.

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Part I

Introduction

Many well-intentioned, influential people endorse the idea as an important milestone on the road to U.S. energy independence. Others are supportive because they see hydrogen as the ultimate clean fuel. President Bush, in his 2003 State of the Union address, supported powering cars with hydrogen. In October 2003, during the California recall election, environmentalists challenged candidate Arnold Schwarzenegger on the fact that he drives a Humvee. His reply? "If elected Governor, I'll make the Hummer run on hydrogen."

Mr. Schwarzenegger's response typifies the new role that hydrogen has come to play in the public discourse regarding energy and the environment. The effect of hydrogen-powered cars on the global energy market is yet to be determined, but its environmental impact is rarely analyzed or challenged. Facts are generally absent in this often-emotional discussion. What effect does powering a car with hydrogen really have on the environment? What are the environmental costs and benefits? This study focuses on quantitative links between hydrogen-powered cars and atmospheric carbon dioxide (CO_2) levels.

A. CO_2 and the Greenhouse Effect

Many people are concerned that there is a deep connection between rising levels of atmospheric CO_2 and man's activity, e.g. the burning of fossil fuels and deforestation.[1] This rise in atmospheric CO_2 is assumed to cause an increase in the mean temperature of the earth's surface. This link between rising atmospheric CO_2 and increasing mean surface temperature continues to be debated and remains an open question.[2] Global warming, the carbon cycle, and long-term climate change have become areas of intense research, leading to a climate change industry that produces large amounts of sophisticated data and analysis.

Irrespective of which set of arguments ultimately prevails, one of the main driving forces behind the emerging hydrogen economy is the belief that we should attempt to control CO_2 emissions as a way to slow or reverse global warming.

1) Sources of CO_2

Earth's carbon cycle is rich and well-documented.[3] In the simplest view, carbon is stored in life forms and rocks. These eventually decompose via biological processes, combustion or geological processes, releasing CO_2, which then enters the atmosphere. The CO_2 is fixed via biological and geophysical processes into hydrocarbons and minerals, ending up as people, animals, plants and rocks, thus completing the cycle.

One of the consequences of the continuing industrial revolution is the accelerating use of combustible fuels which, when burned to supply power, contribute to the carbon dioxide entering the earth's atmosphere. For example, when a vehicle's engine burns gasoline, CO_2 is produced in the exhaust gases that then enter the air around the car. Proponents of using hydrogen to power automobiles generally point out that a hydrogen-fueled car produces only water in its exhaust, and no CO_2. While this is true, it is an incomplete picture that will be analyzed later in this study.

B. Sources of Hydrogen

Today, hydrogen is being explored as an alternative to gasoline for use in automobiles. While it is common knowledge that gasoline is refined from crude oil, a common misperception is that hydrogen is somehow "harvested" from the air. In fact, there are two main industrial sources of hydrogen, both manufactured. In the first, electrolysis, an electrical current is run through clean water, which then dissociates into its constituent molecules oxygen (O_2) and hydrogen (H_2). The H_2 can then be collected, compressed and transported to users. The second source of commercial hydrogen is via the reforming of hydrocarbons. There are many variations of this process involving heating a light hydrocarbon stream (methane, ethane and propane are typically used as feedstocks) in the presence of a catalyst and water to produce a stream of H_2(hydrogen), H_2O(water), CO(carbon monoxide) and CO_2 (carbon dioxide).[4] After additional steps to remove CO, CO_2 and excess H_2O, nearly pure hydrogen is available for transmission to users. Note that one of the main byproducts of the reforming process is CO_2, which is normally either vented to the atmosphere or sold to a user of the gas. The net hydrogen-producing reaction is shown in Equation 1:

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$$

Fuel Cells

The most efficient way to use hydrogen to power a car is to combine the gaseous hydrogen fuel with air in a fuel cell, which produces electricity. The electricity is then used to power a motor to drive the wheels of the car. The efficiency of a hydrogen fuel cell is around 80 percent, and the efficiency for an inverter/motor is around 80 percent.[5] At an overall 64 percent, the hydrogen fuel-cell vehicle has the theoretical potential to be a very effective way to convert fuel into motion. By contrast, the efficiency of a gasoline-powered car is around 20 to 25 percent.[6]

C. The Link Between Hydrogen and CO_2

Clearly, burning gasoline yields carbon dioxide, as illustrated in Equation 2.

$$C_8H_{18} + 12\tfrac{1}{2}\ O_2 \rightarrow 9H_2O + 8CO_2$$

As Equation 1 shows, making hydrogen via reforming also results in carbon dioxide. What about manufacturing hydrogen via electrolysis?

In fact, the production of all types of fuels, including hydrogen and gasoline, requires energy in the form of electricity. One of the most common ways to make electricity in the United States is to burn hydrocarbons, namely, coal, fuel oil and natural gas, to produce steam to drive turbine generators. Burning these hydrocarbons produces CO_2. With rare exceptions then, it turns out that making, compressing, and transporting hydrogen ends up indirectly generating significant amounts of carbon dioxide through the electricity consumed in the process.

When a driver powers his car with hydrogen, it's a fact that he won't be leaving any CO_2 behind in the exhaust. However, in getting the hydrogen manufactured and transported to his car, he will have already been responsible for creating plenty of CO_2.

The central question is "What is the total amount of CO_2 generated per mile of driving for a gasoline-powered car, compared to a hydrogen-powered one?" As one would expect, the answer is… "It depends."

D. Analyzing Hydrogen Use in Cars

In order to make a valid comparison between hydrogen and gasoline as fuels, it's necessary to draw the correct envelope around the process under consideration. Cleary, if one draws the envelope only around the vehicle itself (Figure 1), the hydrogen car is the hands-down winner because it produces zero atmospheric CO_2. However, if all processes are included in the analysis (Figure 2), the comparison becomes richer and more valid.[7]

Figure 1: Envelope Only Around Car
Top: Hydrogen-fueled, Bottom: Gasoline

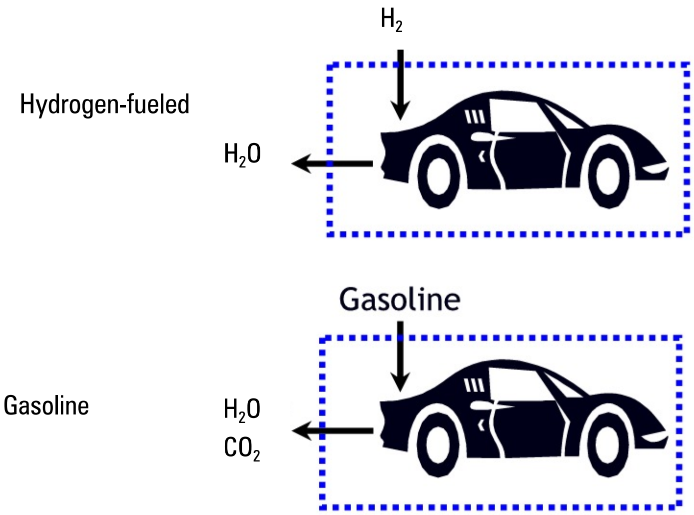
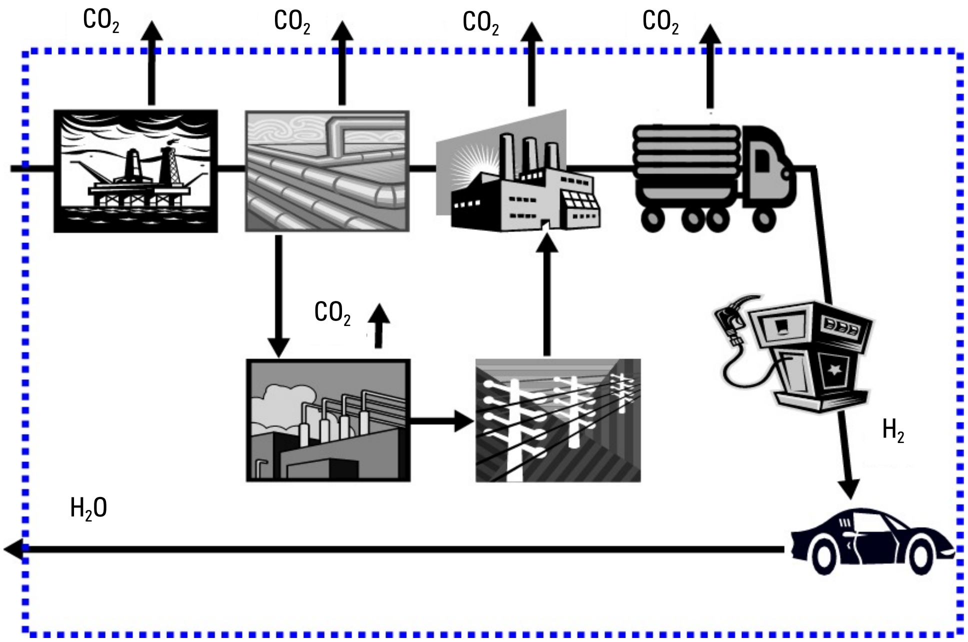


Figure 2: Manufacturing and Transporting Hydrogen Makes CO_2



Clearly CO_2, while not emitted directly from the exhaust pipe of a hydrogen-powered car, is released during several stages of hydrogen's manufacture and distribution, rendering claims of fuel "cleanliness" only part of the story. But how does hydrogen power affect the environment and the economic picture? This study addresses these concerns.

Part 2

The Basis and Methodology for this Study

The results in this study are derived from a series of computer simulations. Each simulation is based on publicly available data for different combinations of vehicle types and fuels, and assumes that the candidate vehicles are driven 300 miles (about one tank of fuel). All processes needed to generate and transport the fuel are included in each simulation, as illustrated in Figure 2. Because electricity source is a geographically important consideration in the analysis, a single state (California) was used as the basis.

As additional processes are included in the analysis, such as the obtaining of raw materials and transporting them, the comparisons between the environmental merits of each fuel become more valid. For the work presented here, these are the basic processes:

- Production and recovery of raw materials
- Transportation of raw materials
- Production of intermediates and finished fuels
- Pumping, compressing and transporting intermediates and fuels
- Storage of fuels
- Refilling of vehicle
- Driving of vehicle a standard distance (300 miles)

In addition the processes for manufacturing hydrogen include:

- Reforming
- Electrolysis

Finally, electrical generation was assumed to be one of the following:

- Gas-fired combined cycle turbine
- Gas-fired non-combined cycle turbine
- Hydroelectric

Different combinations of the above assumptions yield a model of the fuel-production/car driving process, for which the materials and energy flows can be tracked, and for which the carbon dioxide generation can be estimated for each step in the process. The detailed simulation work relies on published results and methodologies developed by others[8] as well as detailed modeling technology developed by the author.[9]

A. Processes Examined

Table 1 shows the set of unit processes used to build each simulation case study. In order to generate each case study, the unit processes are assembled into a different combination, as outlined below. The energy requirements for each unit process and carbon dioxide generated are known and are based on publicly available information.

Table 1: Unit Processes

#	Unit Process Description
1	Natural gas production and recovery
2	Compress and transport natural gas by pipeline
3	Crude oil production and recovery—Middle East
4	Crude oil transport by tanker
5	LPG production at refinery
6	LPG transport by truck
7	Gasoline production at refinery
8	Gasoline transport by truck
9	H_2 generation by central SMR—CH_4(methane) feed
10	H_2 generation by central SR—LPG(liquid petroleum gas) feed
11	H_2 generation by central electrolysis
12	Compress and transport H_2 by truck
13	H_2 storage at filling station
14	Gasoline storage at filling station
15	H_2 refueling at filling station
16	Gasoline refueling at filling station
17	Drive internal combustion engine car
18	Drive H_2 fuel cell car
19	Drive liquid fuel cell car
20	Generate electricity—natural gas cogeneration
21	Generate electricity—natural gas single cycle
22	Generate electricity—hydroelectric
23	Transport electricity

Power Generation

Since the type of power generation heavily influences the study results, and since the geographical basis for the study is the state of California, it is critical to understand the makeup of the electricity generation infrastructure of California[10] (Table 2). This study focuses on the three most common types of electricity generation: gas-fired cogen (Unit Process 20), gas-fired single cycle (Unit Process 21) and hydroelectric (Unit Process 22).

Table 2: Electric Generation in California by Type

Type	On-line MW(megawatts)	% of total
Oil/gas	28,957	53.74
Hydroelectric	14,117	26.20
Nuclear	4,310	8.00
Geothermal	2,562	4.75
Wind	1,815	3.37
Biomass	763	1.42
Coal	550	1.02
Solar	413	0.77
MSW	202	0.38
Landfill gas	174	0.32
Digester gas	22	0.04
TOTAL	53,883	100

Table 3: The Percentage of Gas Fired by Combined Cycle (meaning both a gas turbine and steam turbine are used to generate electricity)

% of total gas fired	
Cogenerated	Not cogenerated
22.6	77.4

Vehicles

Three vehicles are included in this analysis:

- Internal Combustion Engine (ICE)—This is a conventional gasoline-burning car.
- H_2 Fuel Cell (FC- H_2)—This is a car which uses hydrogen to power a fuel cell.
- Liquid fuel cell (FC- naphtha)—This is a car which converts gasoline to hydrogen which then drives a fuel cell.

In order to be included, each vehicle must exist as an advanced prototype or better, and must have sufficient data available for analysis. Vehicle specifications are summarized in Tables 4, 5 and 6.

Table 4: 2001 Ford Focus LX (4-Door Sedan)[11]

Internal Combustion Engine Vehicle	
Curb weight (lb)	2,564
Engine size (liters)	2
Fuel tank capacity (gallons)	13.
Horsepower	110
Miles per gallon : City	28
Miles per gallon : Highway	36
Overall length (inches)	174.9
Torque (foot pounds)	125
Transmission type	5M
Vehicle width (inches)	66.9
Wheelbase (inches)	103
BTU consumed / mile driven	3,424

Table 5: NECAR 4 - Manufacturer Specifications[12]	
Hydrogen Fuel Cell Vehicle	
Curb weight (lb)	3,476
Horsepower	94
Motor type	Ballard twin-stack PEM fuel cell
BTU consumed / mile driven	2,033

Table 6: GM S-10 - Manufacturer Specifications	
Naphtha Fuel Cell Vehicle	
Curb weight (lb)	4,185
Horsepower	34
Motor type	PEM fuel cell
Miles per gallon : City	35
Miles per gallon : Highway	40
Overall length (inches)	206.1
Vehicle width (inches)	67.9
Wheelbase (inches)	117.9
BTU consumed / mile driven	3,013

No attempt was made to normalize for relative vehicle performance. For example, each of the three vehicles has a different curb weight and has a different horsepower-to-weight ratio, which will result in different handling characteristics such as acceleration. The alternative vehicles do not have the same performance characteristics as the conventional gasoline-powered one. One measure of this performance is the horsepower-to-weight ratio, which for the gasoline-powered car is 0.041 HP / lb. For the hydrogen fuel cell car the ratio is 0.027 and for the naphtha fuel cell vehicle the ratio is 0.008 (see Table 7).

The fuel cell vehicles used in this study will therefore not perform at the same level as the gasoline-powered one. Although desirable, normalizing the simulation results for vehicle performance will be possible only when there are more detailed vehicle data available.

Table 7: Gasoline Vehicle Has Highest Horsepower-to-Weight Ratio

Vehicle type	Curb weight (lb)	Engine Horsepower	Horsepower / weight ratio
Gasoline car	2,564	110	0.041
Hydrogen fuel cell car	3,476	94	0.027
Naphtha reformer fuel cell car	4,185	34	0.008

Other Fuels, Other Processes

This work has a deliberately confined scope. For example, a large number of alternative fuels could have been considered in this work, including ethanol, methanol, bio-diesel, corn-based fuels and others. These fuels are all hydrocarbon-based, so will have CO_2 impacts similar to gasoline. In addition, there are many alternative processes, including solar electricity generation and filling-station-based hydrogen generation, which could have been considered. Finally, a wide variety of greenhouse gases of interest, including methane and other volatile compounds such as nitrogen and sulfur-based ones, have important environmental impact. All of these various processes have been intentionally omitted from this work for brevity and simplicity.

Part 3

Hydrogen Vehicle Emission Simulations

We developed and simulated in detail twelve case studies—a base case and 11 alternates. These reflect various combinations of vehicle type, fuel source, electricity source and hydrogen generation and are summarized in Table 8.

Table 8: Summary of Study Cases

Case	Car type	Electricity	H_2 generation
Base	ICE	Gas cogen	n/a
1	FC- H_2	Gas cogen	SMR(Steam methane reformer) using CH_4 (methane)
2	FC- H_2	Hydro	SMR using CH_4
3	FC- H_2	Gas cogen	Electrolysis
4	FC- H_2	Hydro	Electrolysis
5	FC- H_2	Gas cogen	SR(steam reformer) using LPG
6	FC- H_2	Hydro	SR usingLPG
7	FC-naphtha	Gas cogen	n/a
8	FC- H_2	Gas single	SMR using CH_4
9	FC- H_2	Gas single	Electrolysis
10	FC- H_2	Gas single	SR using LPG
11	FC-naphtha	Gas single	n/a

We performed a simulation for each case study, the basis of which is a 300-mile drive for the candidate vehicle. We calculated the results, including raw materials and energy requirements, and atmospheric CO_2 production, based on the resources required by each of the unit processes to generate the fuel necessary to drive the car 300 miles.

The base case, or common internal combustion engine, is composed of the following unit processes:

Table 9: Definition of Base Case

Base case	Unit Process Description
3	Crude oil production and recovery- Middle East
4	Crude oil transport by tanker
7	Gasoline production at refinery
8	Gasoline transport by truck
14	Gasoline storage at filling station
16	Gasoline refueling at filling station
17	Drive internal combustion engine car
20	Generate electricity—natural gas cogen
23	Transport electricity

For comparison, Case 1 is composed of the following unit processes (Table 10):

Table 10: Definition of Case 1

#	Unit Process Description
1	Natural gas production and recovery
2	Compress and transport natural gas by pipeline
9	H_2 generation by central SMR- CH_4 feed
12	Compress and transport H_2 by truck
13	H_2 storage at filling station
15	H_2 refueling at filling station
18	Drive H_2 fuel cell car
20	Generate electricity—natural gas cogen
23	Transport electricity

1) Comparing Two Case Study Results

When a person drives an internal combustion engine vehicle, most of the atmospheric CO_2 emissions occur when the gasoline in the car is burned (Base Case: Table 11, Figure 3). The second largest contributor happens during the refining of crude oil into gasoline. By contrast, a hydrogen fuel cell car driven the same distance, emits no CO_2 from the tailpipe (Case 1: Table 12, Figure 4). In this case, the largest emissions source is in the hydrogen generation plant—via the furnace stack and the CO_2 vent. The next largest contributor results from the natural-gas-fired power generation required for electricity, much of which is used to compress the hydrogen for transportation.

Table 11: Base Case ICE (Internal Combustion Engine) CO_2 Emissions

Process	Description	CO_2 produced (lb)
3	Produce crude	7.6
4	Transport crude	2.2
7	Produce gasoline	25.2
8	Transport gasoline	3.3
14	Gasoline storage	0.0
16	Gasoline refueling	0.0
17	Drive ICE car	171.4
20	Generate electricity	4.5
23	Transport electricity	0.0
	Total	214.2

Table 12: Case 1 CO_2 Emissions

Process	Description	CO_2 produced (lb)
1	Produce Natural Gas	4.5
2	Transport natural gas	2.2
9	Generate H_2	112.7
12	Transport H_2	0.2
13	H_2 storage	0.0
15	H_2 refueling	0.0
18	Drive H_2 fuel cell car	0.0
20	Generate electricity	38.7
23	Transport electricity	0.0
	Total	158.3

Figure 3: Base Case ICE (Internal Combustion Engine) CO_2 Emissions (CO_2 produced (lb))

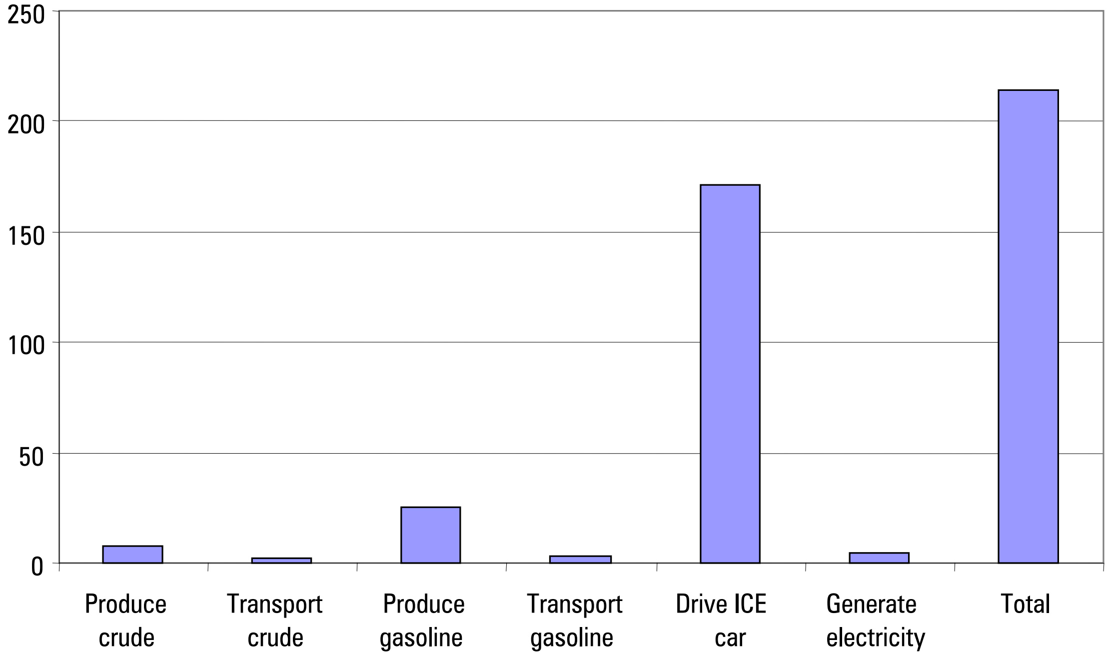
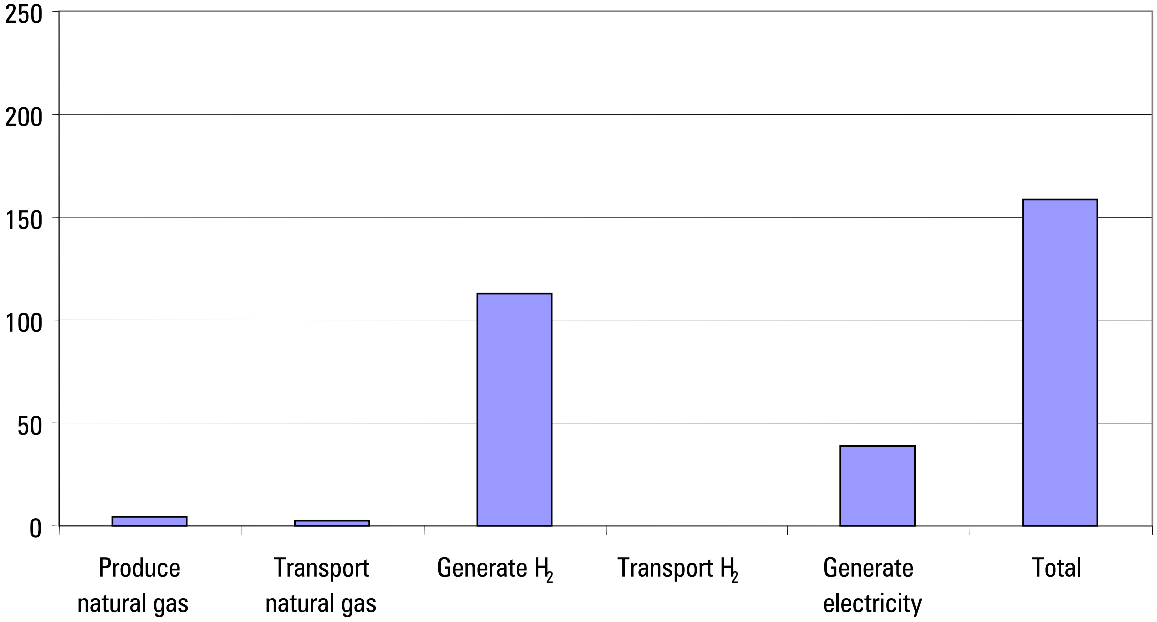


Figure 4: Case 1 CO_2 Emissions (CO_2 produced (lb))



2) CO_2 Summary of all Case Studies

The CO_2 produced for each of the case studies is summarized in Table 13. The lowest CO_2 emissions result when a pure hydrogen fuel cell vehicle runs on hydrogen produced by electrolysis whose power source is hydroelectricity (Case 4). If our main electricity source were pure hydroelectric power, then hydrogen fuel cell cars would indeed solve a lot of emissions problems! The highest CO_2 emissions result when electrolysis-produced hydrogen is made with gas turbine-produced power, as in Cases 3 and 9. However, since hydroelectric power is limited in many places, electrolysis is generally not a particularly efficient way to make H_2.

Table 13: CO_2 Emissions in Order of Amount for All Cases

Case	Car type	Electricity	H_2 generation	CO_2(lb)
4	FC- H_2	Hydro	Electrolysis	0
2	FC- H_2	Hydro	SMR- CH_4	120
1	FC- H_2	Gas cogen	SMR- CH_4	158
6	FC- H_2	Hydro	SR- LPG	183
8	FC- H_2	Gas single	SMR- CH_4	183
7	FC- Gas	Gas cogen	n/a	189
11	FC- Gas	Gas single	On-board	191
Base	ICE	Gas cogen	n/a	214
5	FC- H_2	Gas cogen	SR- LPG	230
10	FC- H_2	Gas single	SR- LPG	260
3	FC- H_2	Gas cogen	Electrolysis	270
9	FC- H_2	Gas single	Electrolysis	444

3) Discussion of Cases

Case 1 is attractive. This is a hydrogen fuel cell vehicle that runs on hydrogen produced by a methane-fed reformer with the electricity source being gas-fired cogen. However, note that the CO_2 production of Case 1 is not all that much better than the straight Internal Combustion Engine (Base Case). In fact, if a more efficient vehicle were used in the base case, the difference could be much smaller.

Cases 5 and 10 are interesting. Both of these assume that hydrogen is produced in a reformer, using an LPG feed that is a 50/50 mix of propane and butane. LPG is a likely source for hydrogen reforming feed, particularly given the recent high prices of natural gas. However, for both of these cases, the CO_2 produced is higher than for a straight gasoline engine (Base Case). The reason is that because LPG has a higher carbon/hydrogen ratio than natural gas, more CO_2 must be vented from the system to produce a given amount of hydrogen. So if high natural gas prices come to dictate the use of LPG to make hydrogen, increasing atmospheric CO_2 emissions will be one result.

Case 11 is appealing. This is a vehicle with an on-board reformer that converts naphtha into hydrogen, which then is fed to a fuel cell. Theoretically, the thermodynamic efficiency of such a system is higher than an internal combustion engine. This is reflected in the vehicle used in this study, which although heavier, has a slightly better gas mileage than the base-case vehicle (3,010 BTU/mile driven vs. 3,424 for the internal combustion vehicle as per Table 4 and Table 6).

Under the circumstances, the internal combustion engine burning gasoline fared pretty well. Although there are better alternatives in terms of straight CO_2 emissions, some of these may be precluded by high feed costs, while others are not feasible due to the type of electricity that is available.

At this point, we should ask: “How significant would the impact be on California’s atmospheric carbon balance in the event that large numbers of vehicles were converted to run on hydrogen?” The following section sets out to answer this question.

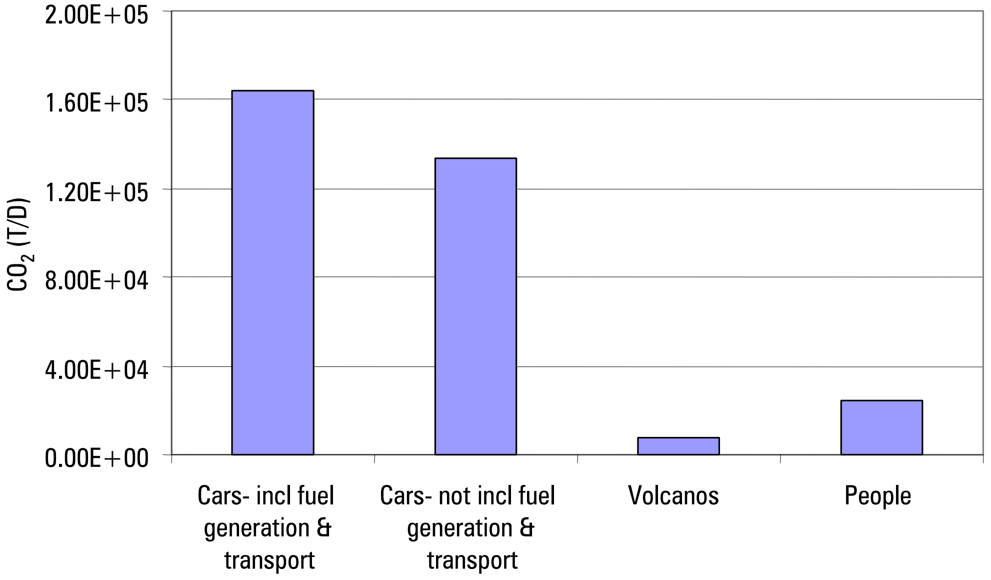
Part 4

The Impact of the Hydrogen Vehicle on Atmospheric CO_2 Using California as the Example

A. Sources of Atmospheric CO_2 in California

Figure 5 compares vehicle-based CO_2-based emissions with those from other common sources. There are between 22 and 26 million cars in California.[13] When combined these emit approximately 135,000 tons per day (T/D) of CO_2 as tailpipe emissions, or 164,000 T/D including emissions from related sources (e.g. manufacture of gasoline). This is undeniably a significant amount of carbon dioxide, especially when compared with other common sources, including California's human population (24,000 T/D), and California's six active volcanoes (7,800 T/D).[14]

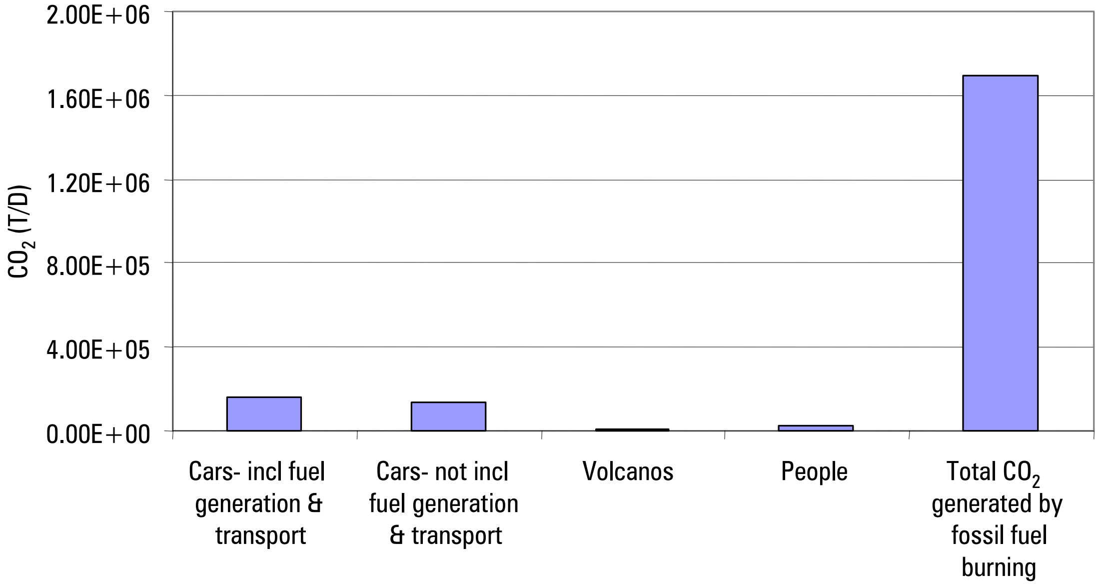
Figure 5: Car-based CO_2 Emissions Compared to Other Sources (Relative CO_2 Emissions)



Source: Sorey, " Michael L., et al, "Invisible CO_2 Gas Killing Trees at Mammoth Mountain, California", U.S. Geological Survey Fact Sheet-172-96 http://quake.wr.usgs.gov/prepare/factsheets/CO2/

However, when put in a broader perspective, the total vehicular emissions pale in comparison to the total carbon dioxide emitted statewide from all hydrocarbon combustion. Figure 6 contrasts the total vehicle-based emissions with those from the burning of all fossil fuels in the state, which are larger by an order of magnitude. At this point, it is clear that even if all vehicle-based carbon dioxide emissions are eliminated entirely, this will reduce total emissions statewide by 10 percent at most. So, how much can hydrogen-fueled cars actually reduce the CO_2 load statewide?

Figure 6: Car-based CO_2 Emissions Compared to All Sources (Relative CO_2 Emissions)



Source: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, http://cdiac.esd.ornl.gov/

B. Hydrogen Vehicle Impact on CO_2 in California

Using information described earlier in this paper, along with reasonable assumptions, good estimates can be made for the predicted impact of hydrogen fuel cell cars on the California environment.

The first and most important assumption is how electricity is made in the state. As described previously, gas-powered and hydroelectric facilities account for three quarters of the electrical capacity in the state of California. For analysis purposes, this mix of electrical generation is the basis.

The second important assumption is how hydrogen is generated. A mix of hydrogen generation sources was considered in the analysis, including:

- H_2 from reforming CH_4(methane)
- H_2 from reforming LPG(liquid petroleum gas)
- H_2 from electrolysis

A third assumption is what role on-board reforming of naphtha (hydrogen fuel cell vehicle running of hydrogen produced from naphtha) will play.

A fourth important factor is how fast hydrogen fuel cell cars will be introduced into the economy.

One final assumption is that the number of cars in the state remains constant over the years. While unrealistic, this makes for an easier comparison of results.

The above assumptions were combined into simulation cases (Table 14) that were used to estimate the impact of hydrogen-fueled cars on California's environment. Each factor in Table 14 was assigned a Low and a High value. Three simulations were then run with one representing the base case (gasoline vehicle), a second with all factors at the "Low" value, and a third with all factors at the "High" value.

Table 14: Cases Used to Project Future CO_2 Emissions

Assumption	Low	High
Electricity generation (% of total)		
Gas fired- single stage	52	52
Gas fired- cogen	15	15
Hydroelectric	33	33
Fleet Conversion to H_2 fuel cell (% of all cars per year)	0.5	5
Hydrogen sources (% of total)		
Reformer CH_4 Feed	70	10
Reformer LPG Feed	10	70
Electrolysis	20	20
Naphtha on-board reformer (% of fuel cell vehicles)	0	20

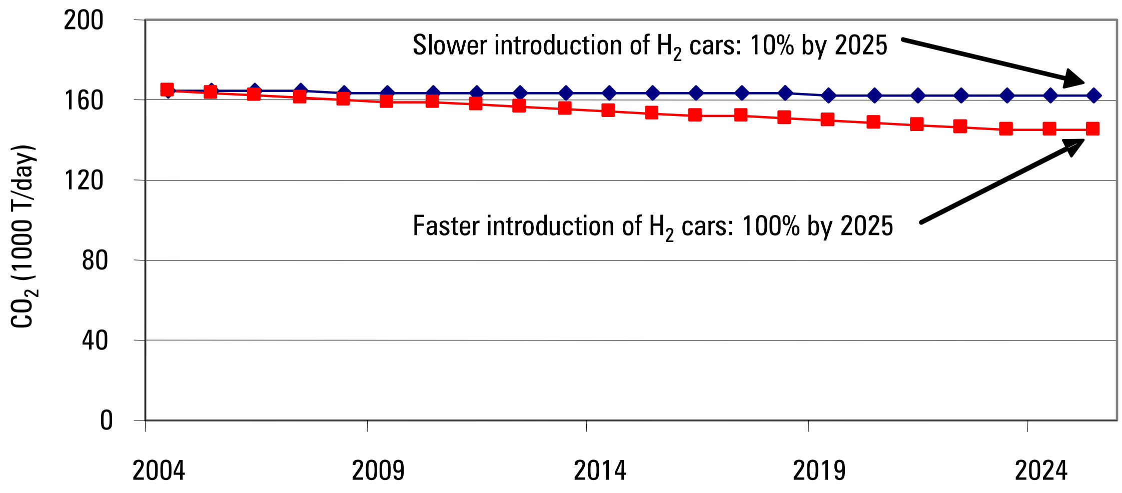
Table 15 summarizes the simulation results. Coincidentally, the "Low" and "High" cases result in roughly the same carbon dioxide emissions for a 300-mile drive. This is due to the relative efficiency tradeoffs between the hydrogen generation method and the percentage of naphtha reformer cars. Both cases do, however, result in lower emissions than the Base Case, which is a conventional gasoline car driven 300 miles.

Table 15: Potential CO_2 Reductions Using Hydrogen Cars

Case	Lb CO_2 per 300 miles driven
Base Case (gasoline car)	214.2
Low Case	188.5
High Case	188.9

As hydrogen-fueled cars are introduced into California, one would expect atmospheric CO_2 release to decline, but how fast? Figure 7 shows how California's carbon dioxide emissions are reduced over time as hydrogen cars are introduced at different rates. If by the year 2025 10 percent of the fleet is hydrogen fuel-cell cars, the total CO_2 emissions decline from 164 T/D to 162 T/D. If by year 2025, 100 percent of the fleet is hydrogen fuel-cell cars, the emissions drop from 164 T/D to 145 T/D. Are these changes significant?

Figure 7: CO_2 Emissions Reduction as Hydrogen Cars are Introduced



C. Historical Perspective

One way to judge the significance of the above analysis is to ask what would happen if all vehicles in California were immediately converted to run on hydrogen. Let's say that the entire fleet of cars in California had been converted to run on hydrogen fuel cells in 1981. How much impact would this have had on the total statewide CO_2 emissions since then?

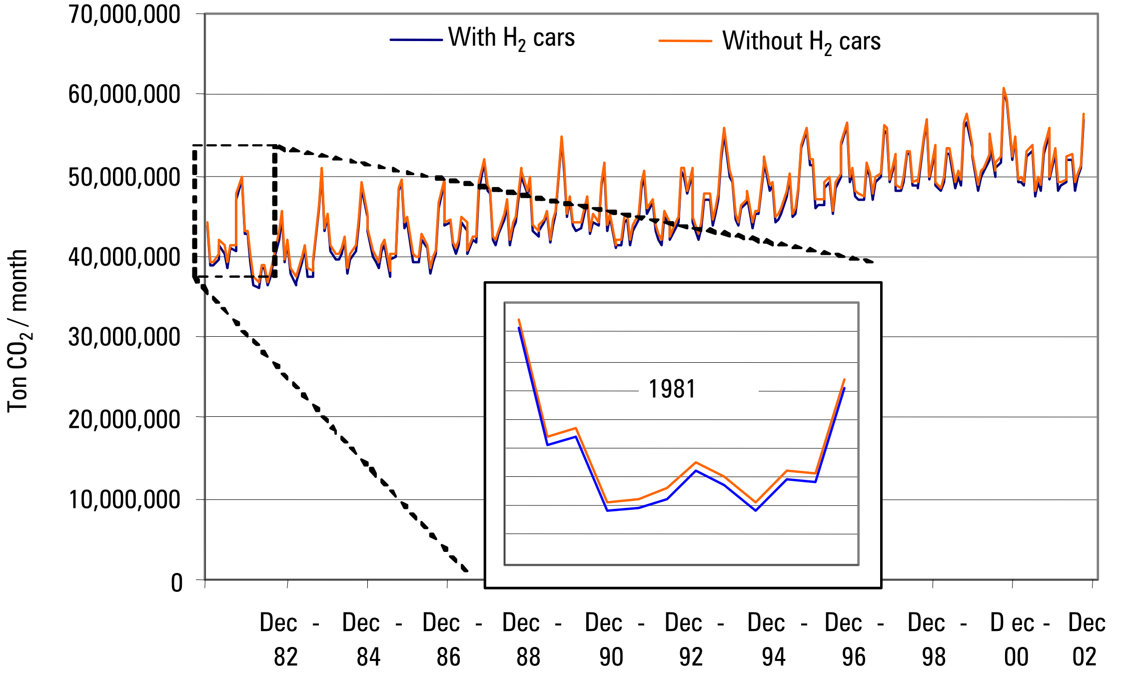
Figure 8 shows national historical carbon dioxide emissions data that have been normalized for California State. The data show total CO_2 emissions per month from all fossil fuel sources in the state. As expected, there are seasonal variations as well as a general increasing trend (red line).

Superimposed on Figure 8 is a second trend line (black line) which represents the assumption that all vehicles were converted to run on hydrogen in 1981. Given the scale of the plot, it is hard to see the difference between the trend lines. The figure shows an exaggerated inset for the year 1981, magnifying that year in an attempt to discern more clearly the difference between the lines showing CO_2 emissions with and without conversion to hydrogen-powered vehicles. In this inset for the year 1981, this difference—which is about 1 percent—is somewhat visible, but still difficult to see, illustrating how little of an effect a 1981 conversion to hydrogen-powered vehicles would have had.

Put into the context of California's total fossil fuel-based CO_2 emissions, it seems that hydrogen fuel-cell cars hardly make a dent. In fact, it is unlikely that the difference would be measurable.

Are there other more effective and significant ways to reduce atmospheric carbon dioxide releases?

Figure 8: CO_2 Hydrogen Fuel Cell Cars Introduced in 1981
Effect on Total California CO_2 Emissions H_2 Cars in Use Beginning Jan



D. Hydrogen Infrastructure

Another major consideration for widespread hydrogen vehicle use is the necessity for an infrastructure for producing, transporting and delivering hydrogen to the user. To do this would mean the equivalent of replacing the gasoline production and distribution network with one for hydrogen. Converting to a hydrogen distribution infrastructure engenders significant issues. Chief among these are safety and cost. Assuming that hydrogen is made on-site at refueling stations, infrastructure costs are estimated at about $4.8 billion for enough capacity to handle about one-fourth of California's cars.[15]

An infrastructure large enough to handle all of California's cars would be in the neighborhood of $20 billion. Again this is an economic choice based on how much people in the state are willing to pay to somewhat reduce CO_2 in their air.

E. Other Factors

Other impacts are inherent in switching to a hydrogen-based economy. The first of these is the increased demand for electricity required to manufacture and transport the hydrogen, which requires an additional investment in infrastructure for power generation and transmission. The cost of this additional electricity infrastructure must be borne by the users of hydrogen.

The next impact is where the electricity will come from. Even though hydroelectricity is an efficient way to make electricity, for the foreseeable future most of the incremental power generation capacity in California will be natural gas-based. As noted earlier, using natural gas to produce electricity generates carbon dioxide, which must be accounted for in the analysis to use hydrogen for cars.

Perhaps the most significant issue relates to the various liabilities associated with transporting, storing and delivering on-board hydrogen. For example, constructing a natural gas pipeline in California takes years, involving multiple studies, environmental reviews, local communities, permitting and sometimes legislation. There is no reason to believe that constructing hydrogen pipelines will be simpler—in fact, given hydrogen's high explosiveness relative to natural gas, the design, review and permitting process may be more involved for hydrogen than for natural gas.

In addition to the obstacles to pipeline construction is the fact the hydrogen gas is prone to leakage. Furthermore it can migrate into the pores in many metals, leading to embrittlement and eventual failure.[16] Given that hydrogen must be stored at high pressure (10,000 pounds per square inch or PSI for on-board vehicle storage and 12,000 PSI for refueling stations), the combination of metal embrittlement and the propensity for leakage poses serious liability concerns.

One final question is what the impact on our country's crude oil consumption will be, assuming LPG is used as a feedstock for hydrogen generation. Because LPG is refined from crude oil, the refining process must be adjusted to significantly increase (or decrease) LPG yield. Such adjustments will affect the yields of other refined products such as gasoline and diesel and will probably affect the types and volumes of crude oil run by refiners. The impact on cost-per-mile-driven remains therefore an open and important question.

It is unclear where this funding would come from--whether private sector investors would willing fund such an effort or whether taxpayer funding would be needed.   If the private sector is not willing to fund such an effort independent of public funds, policymakers should be all the more cautious.

Part 5

Conclusions and Recommendations

A. Conclusions

Using hydrogen to power vehicles has entered the popular vocabulary of politicians, environmentalists and citizens alike. Yet, rarely are the practical implications of such a move considered. In most cases, it is simply assumed that hydrogen is better. The actual impact of transitioning to hydrogen fuel clearly demonstrated that this is not necessarily the case.

Even when one considers the example of the "Hydrogen Hummer," the actual impacts are different than the assumed effects. Using prior results, a simple calculation shows that a Hummer H2 with a curb weight of 6,400 lb will produce just over 600 pounds of CO_2 per 300 miles driven.[17] The same vehicle outfitted with a hydrogen fuel cell will be roughly 1,000 pounds heavier. Adding 50 horsepower to give the fuel-cell version the same performance as the stock Hummer results in 740 pounds of CO_2 per 300 miles driven, a 20 percent *increase* over a stock gasoline-powered Hummer.

This paper has examined in detail the quantitative effects of how such a decision would affect the environment. The results, based on publicly available data, demonstrate that the effect of converting vehicles to run on hydrogen would be marginal at best, especially when compared to other larger sources of carbon dioxide emissions. In fact, if hydrogen-powered vehicles are made to have the same performance characteristics as gasoline-powered ones, the use of hydrogen may actually *increase* atmospheric emissions of CO_2.

Moreover, Using hydrogen as a fuel raises a number of safety and liability concerns. Chief among these are the explosiveness of hydrogen, the need to store it at exceptionally high pressures, and its affinity for migration through metals that can lead to embrittlement and fracture.

B. Recommendations

There are far simpler, less expensive, and more effective ways to reduce carbon dioxide emissions. People and businesses already have strong incentives to conserve energy, and competitive electricity markets and real-time pricing of electricity will strengthen those incentives. Gasoline cars are increasingly efficient and targeting gross polluting vehicles on the road today will greatly reduce auto emissions.[18] None of these alternatives requires constructing a hydrogen generation and distribution infrastructure, a massive and expensive undertaking.

If reducing atmospheric carbon dioxide emissions is the goal, there are other ways besides using hydrogen to power cars.

One benefit of making cars run on hydrogen is that much of the carbon dioxide can be generated centrally (in reforming plants), and can therefore be collected and disposed of. Sequestration is the process by which carbon dioxide leaving a reforming plant can be compressed and pumped into underground or ocean reservoirs for long-term storage. It is at least theoretically possible to remove atmospheric carbon dioxide in this way for long periods.[15] Assuming that sequestration can be done in a cost-effective way, this will significantly improve the picture for hydrogen fuel cell cars. Sequestration of carbon dioxide is estimated to dramatically reduce CO_2 emissions from large central sources (power plants, hydrogen plants).[16] The cost incurred for a combined-cycle power generation plant using sequestration is a reduction in efficiency from 55 percent to 45 percent and a 70 percent increase in electricity generation costs. Similar efficiency decreases are to be expected for introducing sequestration to hydrogen generation facilities. The science behind sequestration is still new, and the costs are not well understood, but the possibility exists at least in theory that CO_2 can be removed from the atmosphere and stored in reservoirs for long periods. Sequestration therefore becomes an economic choice.

In the end, it all boils down to a question of cost. Using hydrogen as a fuel to power cars will be more expensive than using gasoline. Its impact on the environment will be limited, if even measurable. Many people already complain routinely about the high price of gasoline. How much extra are these same consumers willing to pay in an attempt to minimally reduce atmospheric carbon dioxide?

While the effort to identify and advance new energy sources and create domestic energy independence are noble goals, it remains unclear how hydrogen can fit in this picture or whether its net impacts would even be positive. While the idea of applauding hydrogen fuel as a cutting-edge technology is harmless (and may, in fact, stimulate private sector investment), until clear economic calculations and choices are made about how much the public is willing to pay for marginal reductions in CO_2, policymakers should look cautiously at hydrogen. It is clearly no panacea.

Appendix

Table 16: Abbreviations Used

Term	Definition
Electrolysis	Hydrogen generation via electrolysis
FC- naphtha	Liquid fuel cell vehicle
FC- H_2	Hydrogen fuel cell vehicle
Gas cogen	Gas-fired Combined Cycle Turbine Electric Generator
Gas single	Gas-fired Single stage Turbine Electric Generator
Hydro	Hydroelectric electricity generator
ICE	Internal Combustion Engine
LPG	Liquefied Petroleum Gas (50% C3 / 50% C4)
On-board	Vehicle has hydrogen reformer generator on-board
PEM	Proton Exchange Membrane- type of fuel cell
Sequestration	Long-term underground CO_2 storage
SMR	Steam methane hydrogen reformer
SMR- CH_4	Hydrogen reformer- CH_4 feed
SR- LPG	Hydrogen reformer- LPG feed

About the Author

William Korchinski is a chemical engineer who has spent his career working worldwide in the oil refining and chemical industries. His primary focuses include the development and deployment of rigorous process simulation technology, the design and installation of real-time multivariable controls, and economic studies related to the process industries. Mr. Korchinski has applied his extensive background in statistical analysis and mathematical solution techniques in working for a number of corporations and consulting firms. He has worked at over 50 industrial sites throughout the world and has developed a dozen commercial technologies. Currently he runs his own business, Advanced Industrial Modeling, Inc, in Santa Barbara, California.

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Endnotes

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