

Zero emission passenger vehicles in tyhhe United States, anticipating future automobile industry trends based on stakeholder interview analysis

By

THOMAS M. GERMAN

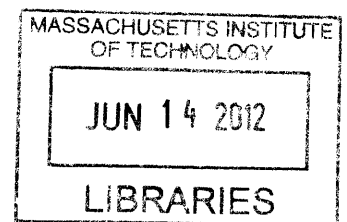
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
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Submitted to MIT Sloan School of Management
On May 11, 2012 in Partial Fulfillment of the
Requirements for the Degree of Master of Business Administration

Abstract

My personal interest in automobile evolution is the primary motivation for this thesis. My engineering education and a fifteen year career in professional automobile racing were also inspired by personal passion for automobile development. This thesis was an opportunity to apply technical and business knowledge to an emerging industry challenge.

Large, complex, interconnected problems are difficult to comprehend and challenging to solve. Today, the global automobile industry is facing such a problem. Global transportation sector greenhouse gas (GHG) emissions are increasing and the technology to mitigate this increasing threat is not penetrating the consumer market. The thesis objective is to determine how zero emission vehicle adoption may change the Automobile Industry structure in the next fifteen years.

Both interviews and literature sources provide the data for this thesis. Sixteen interviews were conducted across five stakeholder groups: automobile industry, government, petroleum industry, utility industry, and academia. The conclusions aggregate interviews, literature sources, and my analysis.

The cumulative data suggests transportation sector emissions are a threat to environmental stability. However, significant zero emission vehicle adoption is not expected in the next fifteen years. U.S. CAFE standards, as well as, emission standards in other countries are expected to improve new vehicle fuel efficiency. In China, local pollution problems may inspire zero emission vehicle adoption. But, these incremental improvements are not expected to mitigate the increase in transportation GHG emissions driven by population growth and industrialization.

Finally, four concepts are presented to accelerate zero emission vehicle development and adoption. Utilizing existing technology, retiring older technology, modular vehicle architecture, and competition driven development may contribute to faster development and increased adoption. Ultimately, faster development may lead to the better value proposition needed to inspire adoption.

Thesis Supervisor: John Van Maanen
Title: Erwin H. Schell Professor of Management
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Chapter 1 Background

Context and Personal Motivation for this Study

My personal interest in automobile evolution is the primary motivation for this thesis. My engineering education and a fifteen year career in professional automobile racing were also inspired by personal passion for automobile development. This thesis was an opportunity to apply technical and business knowledge to an emerging industry challenge.

My objective in this thesis is to provide insight into how zero emission vehicle adoption may potentially impact the automobile industry over the next fifteen years. Zero emission was selected for two reasons. First, zero emission vehicles may produce the most disruptive change to the automobile industry in my lifetime. Second, the zero emissions goal is a good catalyst for technology, market, and environmental conversations. The timeframe was limited to fifteen years to focus the work on the realities of today. If an automotive technology is available today, it will take five years to reach production and at least ten years to become a significant percentage of the automobile fleet. Consequently, predicting the impact of today's technology on the vehicle fleet in fifteen years is feasible.

Nothing endures but change (Heraclitus, 480 BC). We generate ideas, technologies advance, and societies grow. But, this cycle often produces unexpected results. When challenged with unintended consequences, government and industry respond. The government responds with policy and industry responds with invention, innovation, and growth. Nineteenth century urban transportation demonstrates this cycle.

In the late 1800s, when urban population and wealth were increasing and the horse was the dominate transportation mode, unintended consequences overwhelmed London and New York. “Vacant lots across America were piled high with manure; in New York these sometimes rose to forty and even sixty feet” (Morris, 2007). The challenges were not limited to excrement. With roughly 200,000 horses in New York City; urine, flies, congestion, carcasses, and traffic accidents plagued the city.

The Government worked on policy. “In 1898, delegates from across the globe gathered in New York City for the world’s first international urban planning conference. One topic dominated the discussion. It was not housing, land use, economic development, or infrastructure. The delegates were driven to desperation by horse manure.” (Morris, 2007).

Industry responded with the automobile, a 100 year old invention. Automobile emissions were easier to manage, it took less space, and innovation yielded superior utility. Growth was fast, between 1900 and 1920, “the U.S. automobile fleet increased at almost 40% per year” (Schafer, Heywood, Jacoby, & Waitz, 2009). “During the 1930s the automobile became the most important mode of transportation, two decades before the construction of the interstate highway system” (Schafer, Heywood, Jacoby, & Waitz, 2009).

Today, world population and standards of living are increasing which inspires personal transportation adoption. After 100 years of innovation and growth, we are faced with new unintended consequences: traffic congestion, pollution, global climate change, and energy

security. Just as widespread horse utilization challenged our cities in 1900, widespread automobile adoption is challenging twenty first century cities.

Problem Statement

Large, complex, interconnected problems are difficult to comprehend and challenging to solve. Today, the global automobile industry is facing such a problem. Global transportation sector greenhouse gas (GHG) emissions are increasing and it is challenging to determine if the current mitigation efforts will stabilize their impact on the climate.

Population Growth

In 2011, the world population reached 7 billion. If the future growth rate is similar to the past decade, 10 billion people will inhabit the earth by 2050. Between 2000 and 2010, the developing world population increased by 726 million. In contrast, the developed world population increased by just 47 million, fifteen times slower (United Nations, 2011).

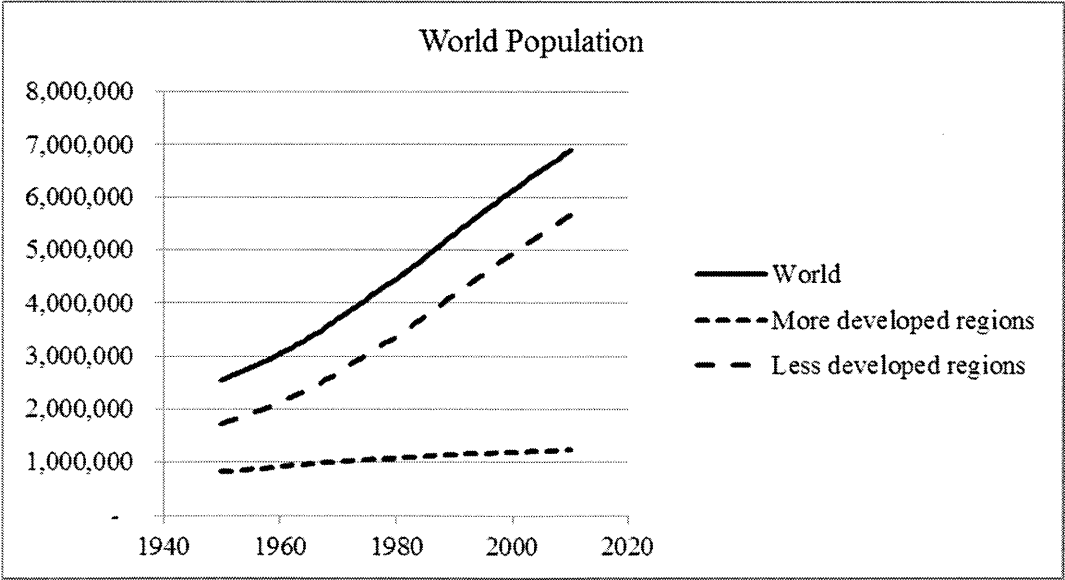


Figure 1: World population growth from 1950 to 2010. (United Nations, 2011)

In 2010 less developed regions made up 82% (5.6 million of 8.6 million) of the world population (United Nations, 2011). Considering the low vehicle ownership and increasing GDP/capita, the less developed world has the potential to produce the most dramatic automobile market growth in the history of the automobile.

Automobile Adoption

Today, for much of the industrialized world the automobile is part of everyday life. In the United States significant adoption occurred in the early 1900s. In Western Europe, widespread adoption started after the Second World War. Today, adoption has stabilized, in most of the industrialized countries “the vehicle market has essentially become a replacement market” (Schafer, Heywood, Jacoby, & Waitz, 2009). The majority of future automobile adoption will come from the developing world.

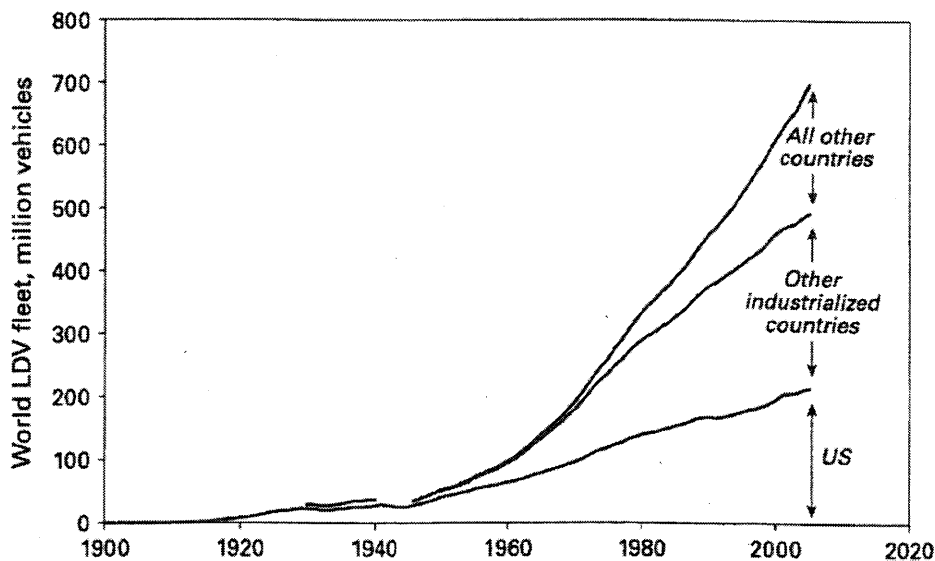


Figure 2: Vehicle adoption 1900 to 2005. (Schafer, Heywood, Jacoby, & Waitz, 2009)

In the U.S. adoption of low emission (hybrid) vehicles has been slow. Toyota introduced the Prius in model year 2000. By 2011 cumulative sales reached one million. Hybrid sales peaked

at 352,000 in 2007 and have declined to 274,000 in 2010 (Alternative Fuels and Advanced Vehicle Data Center, US DOE, 2011). In 2011, approximately 9.5 million light duty vehicles were sold in the U.S.; low emission vehicles were just 3%.

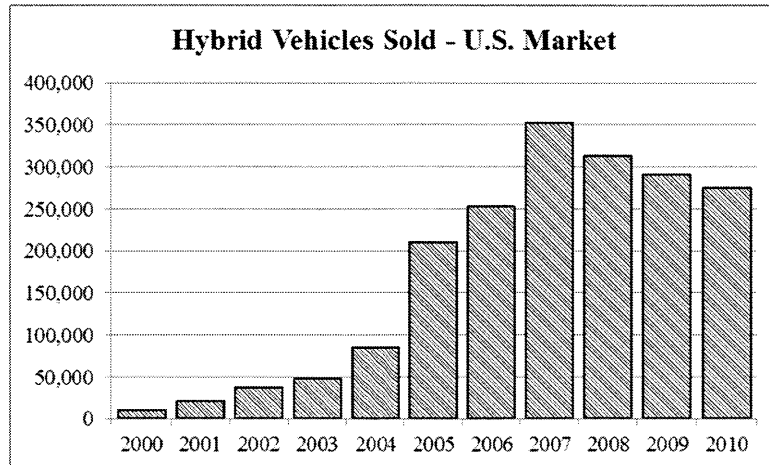


Figure 3: US Hybrid vehicle sales 2000 to 2010. (Alternative Fuels and Advanced Vehicle Data Center, US DOE, 2011)

In the U.S. market, initial market data suggests the adoption of new battery electric vehicle (Nissan Leaf) and extended range vehicles (Chevy Volt) is slightly slower than the Toyota Prius 12 years ago.

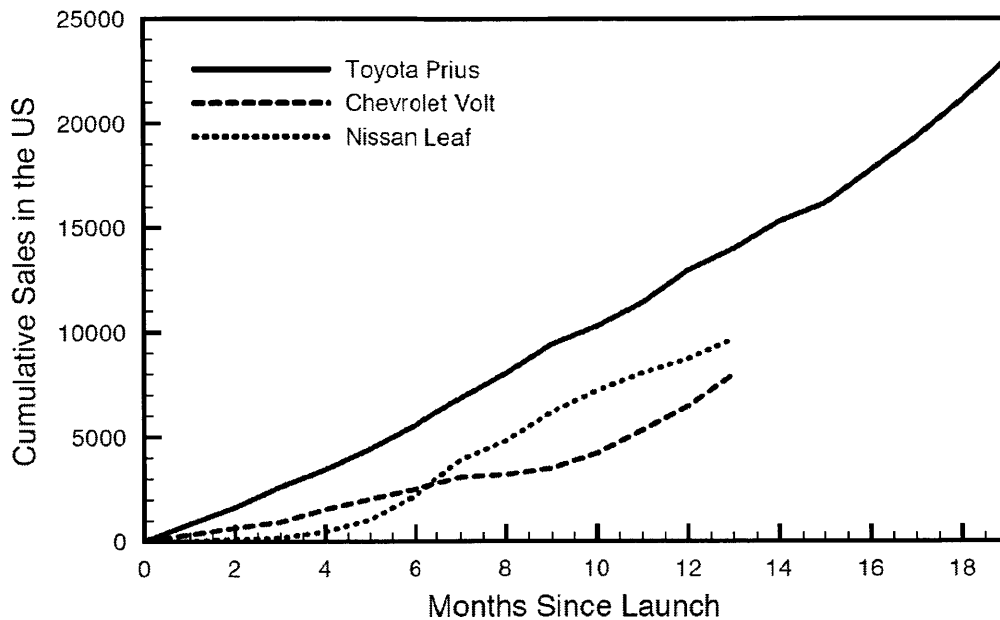


Figure 4: Recent hybrid vehicles sales: months since launch (Keith, 2012)

Zero and low emission passenger vehicle adoption is even slower in China, “5,655 electric vehicles and 2,713 hybrid vehicles were sold in 2011”. Zero and low emission vehicles represent 0.1% “of 14.5 million cars in 2011” (RushLane, 2011). With different utility requirements, the China story is much more complex than the passenger vehicle adoption suggests. Cost and immense congestion in China’s megacities inspire electric bicycle adoption. Representing over 90% of the world market, Chinese electric bicycle sales are “expected to reach 28 million vehicles this year” (Pike Research, 2012).

Today there are over one billion vehicles in the world. “By 2020, more than two billion vehicles will populate the world” (Sperling & Gordon, 2009). In the developed world, where the adoption rates are the lowest, the most advanced GHG technology is slowly penetrating the existing fleet. In the developing world, where the majority of people do not have access to personal transportation, vehicle adoption rates are the highest. In these regions, new vehicles

utilize less expensive and less effective GHG technology. Markets with the greatest size and growth potential are using and adopting passenger vehicles which do not utilize the latest GHG emissions technologies.

World GHG Emissions

Carbon dioxide (CO₂) is the primary GHG emission which contributes to climate change. When regions of the world industrialize, CO₂ emissions substantially increase. Since different parts of the world are in different stages of industrialization, CO₂ emissions trends are vastly different throughout the world.

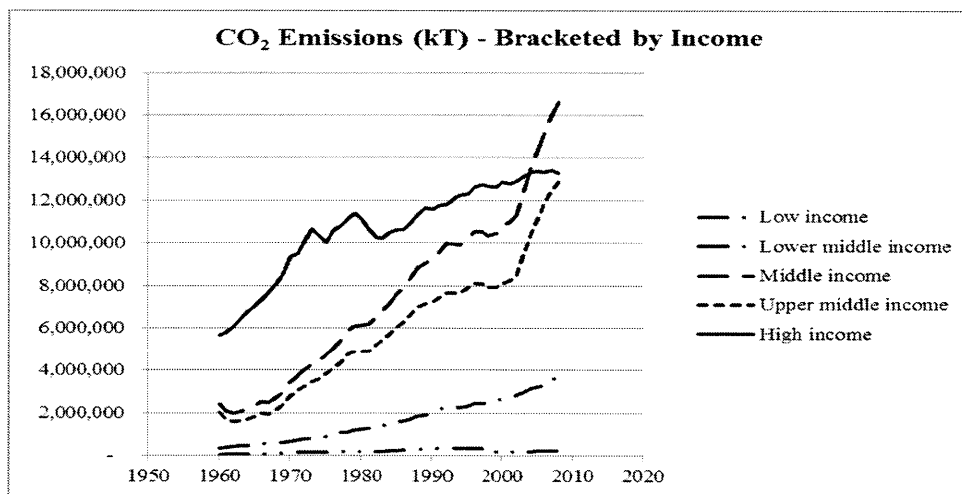


Figure 5: CO₂ emissions based on income (World Bank, 2012)

In 2005, CO₂ emissions from middle income countries exceeded emissions from the high income countries. Within the next couple years, CO₂ emissions from upper middle income countries will also exceed emissions from the high income countries. Population and vehicle adoption in

middle and upper middle income countries are increasing at unprecedented rates, as a result GHG emissions are increasing without bound.

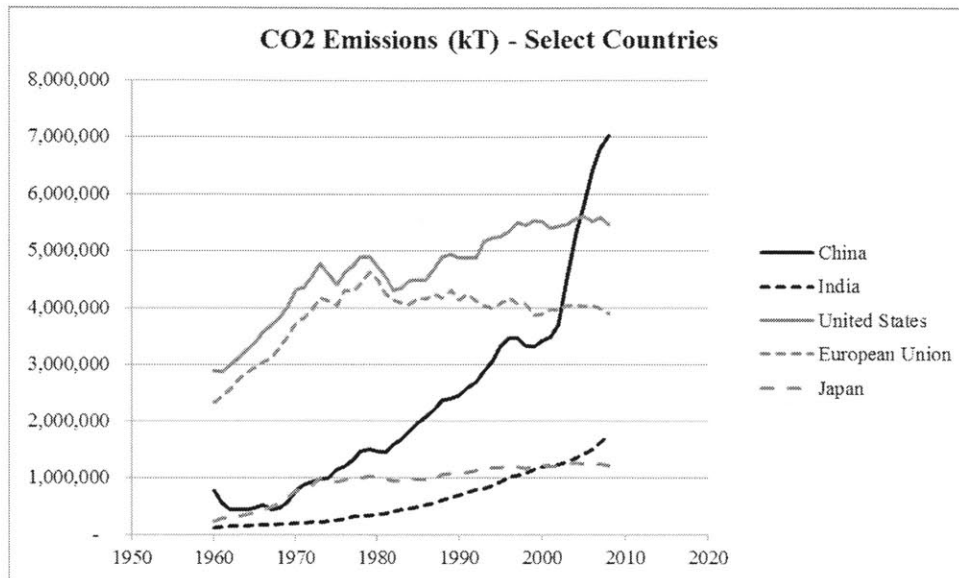


Figure 6: CO₂ Emissions from select countries (World Bank, 2012)

In 2005, China surpassed the U.S. and became the world's largest producer of CO₂ emissions. Given the population difference between China and the U.S. higher emissions are expected for similar levels of industrialization. As other middle and upper middle income countries are able to grow and industrialize, GHG emissions will increase.

Transportation GHG Emissions

Internal combustion emissions can be separated into two categories, emissions which contribute to local pollution (smog) and emissions which contribute to global GHGs. In the past 40 years, the U.S., Japanese and European automotive industries have substantially reduced vehicle emissions which contribute to local pollution. In mature automobile markets, local pollution

from the transportation sector has been mitigated and will continue to decrease over time. This is not true in immature markets where local pollution emissions are an increasing concern. In the past 10 years, governments and the automotive industry have started efforts to reduce GHG emissions. Global transportation is a large, complex, interconnected system which takes a long time to change. Consequently, the impact of GHG mitigation efforts is difficult to access.

Electricity generation, transportation, industrial manufacturing are the three largest GHG emission sources. The transportation sector is a major contributor to global GHGs, accounting for “approximately 23% of the world’s CO₂ emissions” (Schafer, Heywood, Jacoby, & Waitz, 2009) and in the US, the subcategory of “light-duty vehicles (LDVs) are responsible for 17.5% of carbon dioxide (CO₂)” (MIT Energy Initiative, 2010). The distribution of CO₂ emissions from fossil fuel combustion in the US and Europe are show below.

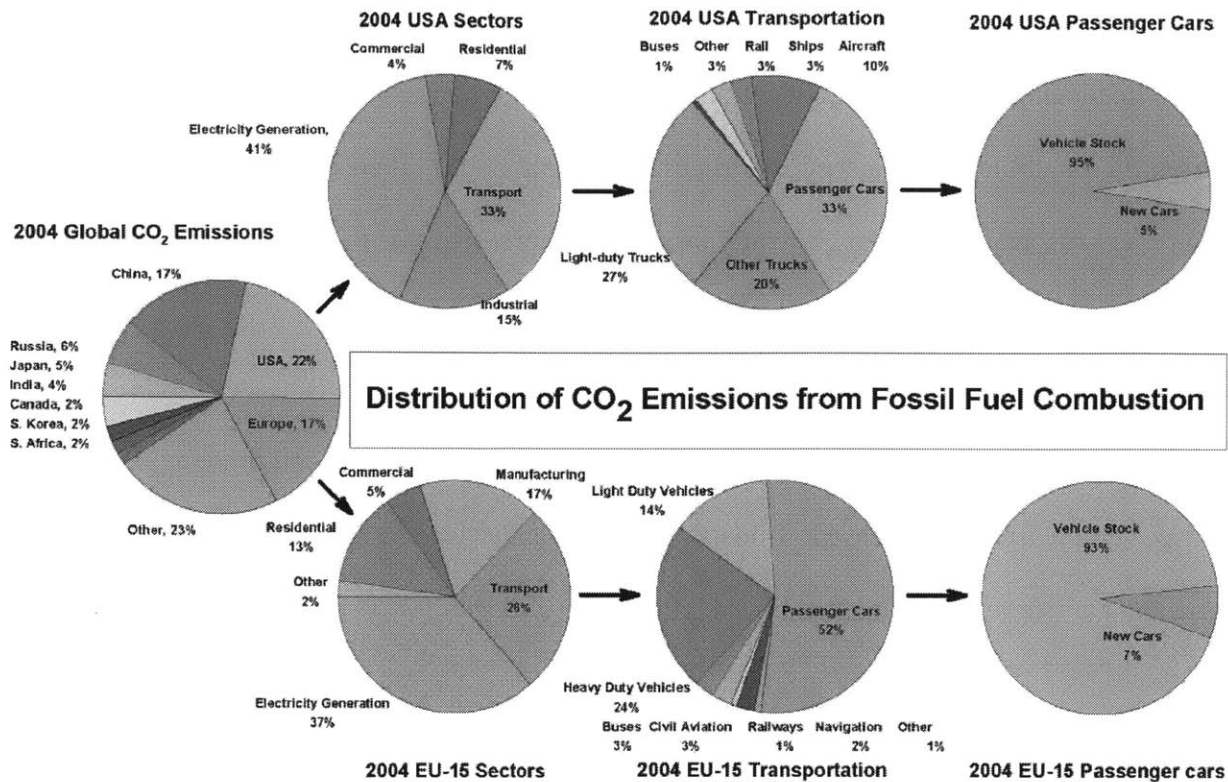


Figure 7: CO₂ emissions in the U.S. and Europe (Wallington, Sullivan, & Hurley, 2008)

In the US, 5% of CO₂ emissions are from the new vehicles and 95% are from the existing vehicle stock. In Europe the ratio is similar, 7% new vehicles to 93% existing vehicles. This distribution is an important factor limiting the rate GHG mitigation. New technology must first penetrate the new vehicle market and then new vehicle sales will slowly replace the existing vehicle fleet.

Automotive Industry Rate of Change

In order to mitigate GHG emissions and reduce petroleum dependency, new vehicle technologies must be conceived, developed, produced, and adopted. Updating the global vehicle is a slow process. First, new technologies must be developed for large scale production. It typically takes take five years to develop a technology from concept to production. Second, it takes about 20

years for the new technology to penetrate the new vehicle production. Finally, to reach sufficient vehicle fleet penetration to impact the transportation sector emissions will take another 10 to 15 years (MIT Laboratory for Energy and the Environment, 2005). If cost effective zero emission technology was available today, it would take at least three decades to significantly penetrate the global vehicle fleet and start reducing transportation GHG emissions.

The rate of change is slowing down. As vehicles become more reliable and more expensive the average vehicle life has increased. Consistently increasing since 1970, the U.S. average passenger car life reached a record high 11.1 years in 2011.

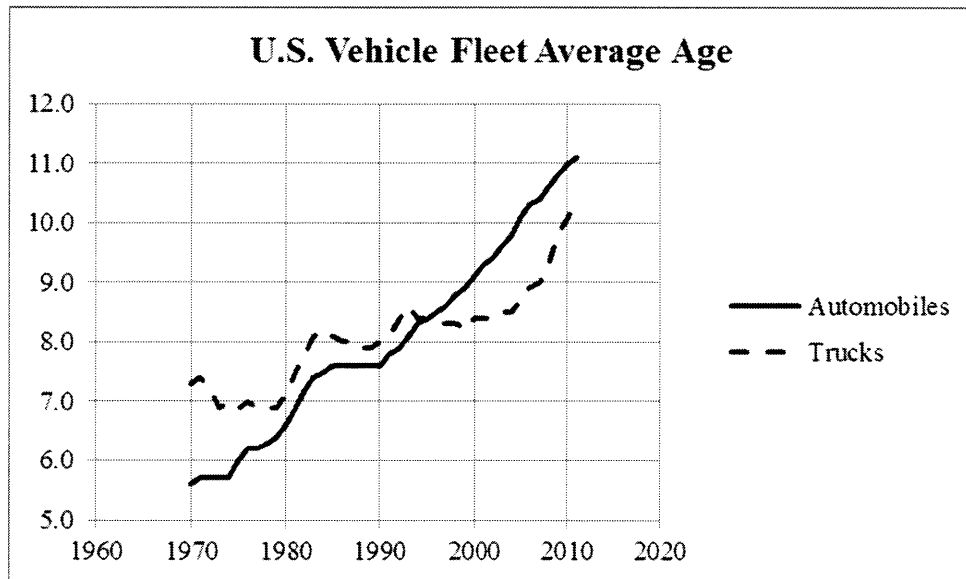


Figure 8: U.S. average vehicle age 1970 to 2010 (FHWA US DOT, 2011), (Polk, 2012)

Projecting this trend forward, the average vehicle in 2030 will have been produced in 2015. Accounting for the five year development time between concept and production, the average 2030 vehicle on the road will use 2010 technology.

As stated before, the world population is increasing, demand for personal transportation is increasing, and transportation section GHG emissions are rapidly rising. Due to the size and complexity of the transportation sector, efforts to mitigate GHG emissions take decades to produce a significant impact. Given the ever increasing demand for personal transportation, will the pressure to mitigate GHG emissions have a significant impact on the automobile industry structure? How will the automotive industry structure change to respond to growing environmental concerns?

Automobile Industry History

Over the past century, competitive advantage shifts have defined automotive industry leaders. Ford Motor Company dominated the market after introducing mass production. Customer segmentation helped create the competitive advantage which pushed GM to the dominate position. In recent years, Toyota's lean production system has created the advantage necessary to become the world automotive leader.

In the early days of the industry, automobiles were manufactured using "craft production" techniques. Each vehicle was unique and built to a specific customer's order. "Coach Builders" would custom build and fit each component, consequently, production was slow and expensive limiting the potential automobile market size.

Henry Ford revolutionized the industry by introducing mass production. By reducing cost, Ford made the automobile affordable to the masses, making Ford the global leader in automobile sales. "In 1914, Ford produced 308,162 cars, more than all other automakers combined" (Ford

Motor Company, 2012). Since mass production was easy to understand and implement, Ford's competitive advantage was short lived.

In the late 1920's, product diversity and customer credit enabled GM to surpass Ford as the world's largest automobile manufacturer. Under Alfred P. Sloan's guidance, GM segmented the market and offered different vehicles for different customers. In 1916, GMAC was created to enable customers to pay for their automobile over time. An evolutionary shift from Ford's mass production to GM's customer focused financing and vehicle selection allowed GM to remain the world's largest automobile manufacture for almost 90 years.

In 2008, Toyota surpassed GM as the world's largest automobile manufacturer (Marr, 2009). "Lean production" methods are widely credited for Toyota's rise to the top spot. Lean production is much more than a production method; it is a system which permeates every aspect of the firm. Lean production principles are evident from the supply chain, product engineering, manufacturing, to the customer, including interaction between supply chain elements. Toyota pioneered lean production after WWII and after 60 years of evolution and growth is now the world's largest automobile manufacturer (Womack, Jones, & Roos, 2007).

Each time a new manufacturer became the world's largest, their source of competitive advantage became more sophisticated. Competitors quickly identified mass production as the source of Ford's competitive advantage. The market segmentation and customer financing GM utilized to build competitive advantage was more sophisticated than mass production. Consequently, it took longer for competitors to understand and replicate. Toyota's lean production advantage is

another step in the increased sophistication of competitive advantage. To understand lean production millions of dollars and thousands of hours were dedicated to industry and academic studies around the world. One of the largest and most comprehensive studies was the International Motor Vehicle Program (IMVP) at MIT. With five million dollars from thirty six organizations, the IMVP spent five years studying lean production (Womack, Jones, & Roos, 2007). To date, Toyota's lean production competitive advantage is the most sophisticated and consequently the most difficult to reproduce. As the automobile industry matured, competitive advantage has become more difficult to create and identify.

Automobile Industry Today

The global automobile industry is a combination of centralized and regional structures. The combination of local consumer expectations, regional regulations, and manufacturing considerations results in a different value chain than other global manufacturing industries. Timothy Sturgeon of the MIT Industrial Performance Center defines four distinct value chain features of the automobile industry (Sturgeon, Memedovic, Biesebroeck, & Geroffi, 2009):

1. *“Extremely concentrated firm structure”*. “Eleven lead firms from three countries, Japan Germany and the USA, dominate production in the main markets”.
2. *“Final vehicle assembly, and by extension, parts production, has largely been kept close the end markets”*. Firms tend to build vehicles in the same regions vehicles are sold.
3. *“Strong regional-scale patterns of integration”*. Political, technical, and economic factors drive regional integration.
4. *“Few fully generic parts or subsystems”*. Models from the same firm use a limited number of common components and subsystems. Almost no components or subsystems

are built to industry standards and used by multiple firms in multiple models. A single supplier will design and manufacture multiple unique components with the same function for different firms, vehicle models, and geographic regions.

The global automotive industry is massive. In 2012, worldwide sales of passenger cars and light trucks are forecast to exceed 60 billion vehicles (ScotiaBank Global Economic Research, 2012). The global fleet of one billion vehicles supports fuel, maintenance, replacement part, insurance, and repair industries. The combination of massive size, geographic dispersion, networked support industries, and minimal industry standards have created an industry which takes decades to deliver notable change.

Transactions dominate the demand side (consumer) of the automobile value chain. Vehicle purchases, maintenance and fuel are all transactions. Zipcar, Better Place, and car share firms are offering alternative business models for vehicle and fuel transactions but, to date, have only inspired local appeal.

Industry Demand Evolution

Personal transportation demand is rapidly evolving. Consumer preferences, regional performance and cost expectations are challenging traditional demand assumptions. World demand is increasing but market segments are dramatically changing.

In the U.S., the American love affair with the car is losing momentum with the younger generation. In 1978, 50% of 16 year olds had a driver’s license by 2010 less than 29% had driver’s licenses (NHTS, 2012).

Table 1: U.S. drivers’ license recipients by age 1978, 1995, and 2010 (NHTS, 2012)

	1978	1995	2010
16	50.0%	43.1%	28.7%
17	75.0%	62.6%	47.1%
18	86.0%	73.1%	62.2%
19	92.0%	75.9%	71.1%

As shown below, this trend is evident in 16, 17, 18, and 19 year olds. In the media, anecdotal explanations offered to explain this cultural shift include: competing interests, social media, more stringent regulations, and increased cost (Neff, 2010).

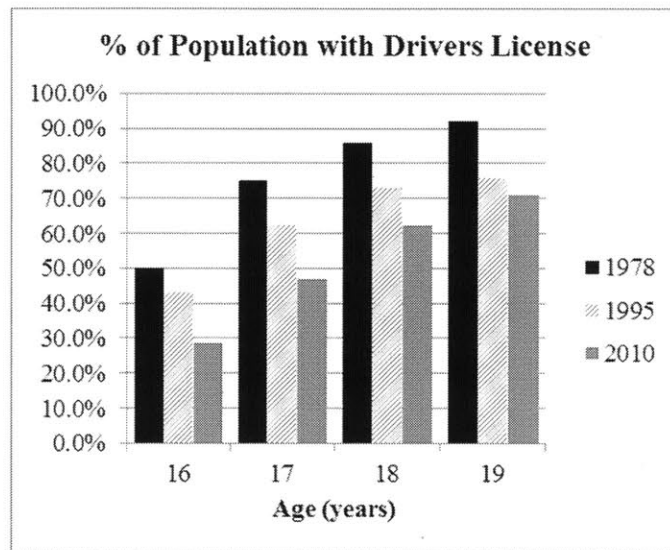


Figure 8: U.S. drivers’ license recipients by age (NHTS, 2012)

In the developing world, consumers have different needs and expectations. China is the largest and fastest growing automobile market but Chinese consumers simply cannot afford the same vehicles sold in the U.S. and Europe. Vehicle functional requirements are also different in the

developing world. The majority of the developing world population growth is in congested urban areas. Contemporary automobile architecture is based on the once dominate U.S. market. Many of the cost criteria and functional specifications are not relevant in developing world markets.

Across the world, governments are changing their environmental expectations. The U.S. Government has raised corporate average fuel economy (CAFE) standards, offered consumers low emission vehicle purchase incentives, created a \$25 billion Advanced Technology Vehicle Manufacturing Incentive, and increased grant funding for electric vehicle components (World Bank, 2011). European governments have also increased adoption incentives while raising emission and efficiency requirements. In 2011, the Chinese New Energy Vehicles program has grown to 25 cities and latest estimates suggest the China program will be supported by RMB 100 billion (15.8 billion USD) in government investments (World Bank, 2011). Similar to the developed world objectives, China's program aims to reduce CO₂ emissions, promote energy security, reduce urban pollution, and develop the domestic (Chinese) automobile industry.

Today, zero emission and hybrid vehicles cost more than vehicles with internal combustion engines. Zero emission vehicle technology is immature and the vehicles are designed to accept both internal combustion and electric drivetrains. This compromised drivetrain increases electric vehicle costs. Even with regulators offering subsidies consumer adoption of currently available zero emission vehicles is slow. Few consumers are willing to pay a premium for environmental performance.

Zero Emission Vehicle Architecture

The drive train in a zero emission vehicle is completely different than a traditional internal combustion engine vehicle. The figure below illustrates the traditional internal combustion engine drivetrain, a parallel hybrid drive train, a series hybrid drivetrain, and a zero emission drive train.

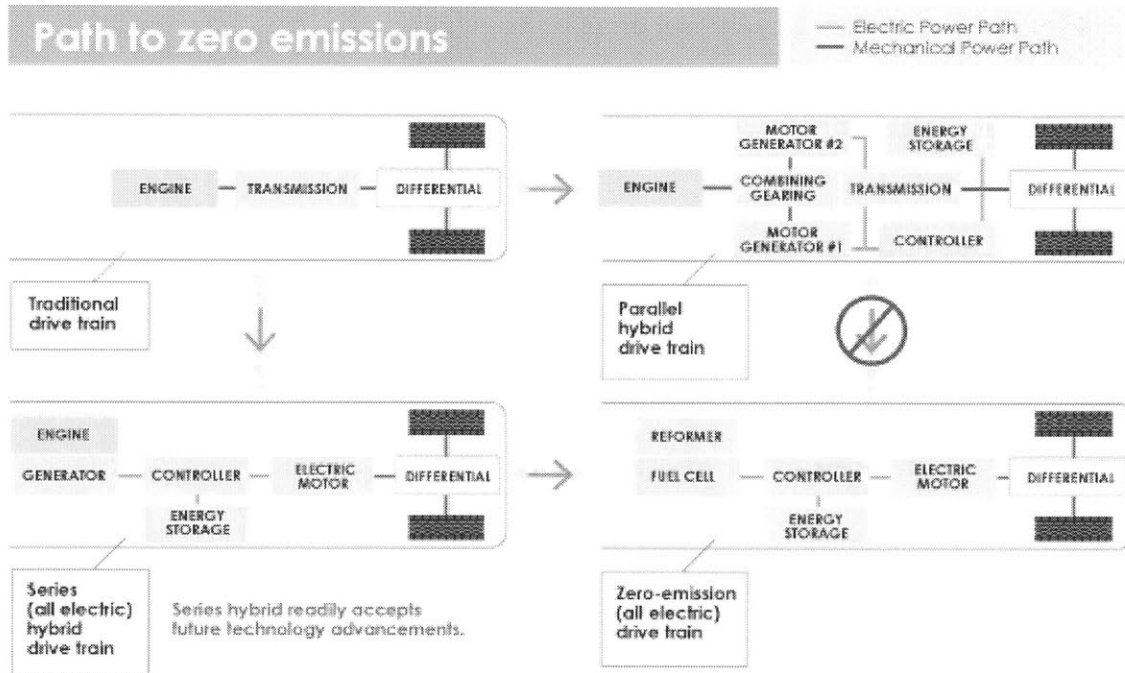


Figure 9: Vehicle architecture schematics (Hybridrive.com, 2012)

Traditional internal combustion engine vehicles (ICEV) appear simple in the schematic but in reality have thousands of components and multiple complex subsystems. Both the engine and transmissions are complex, highly evolved machines.

Parallel hybrid drive trains represent the majority of “hybrid” vehicles offered today. The original Toyota Prius has a parallel hybrid drive train. These are a traditional internal combustion drive train integrated with an electric drive train. All the necessary components to move the

vehicle are duplicated. There are two energy storage units, a tank for gasoline or diesel fuel and a battery to store electrical energy. There are two systems to convert energy-to-motive-force. The traditional system; an internal combustion engine, transmission, and differential, and the electric drive system; the electric motor and controller. Additional components are required to integrate the two systems. Based on this complexity, it is not feasible for a parallel hybrid drive train to be less expensive than a traditional drive train.

Series hybrid drive trains have not reached the U.S. automobile market. Extended range electric vehicles (EREV) are in intuitive name used to describe series hybrid vehicle architecture. The 2012 Chevy Volt is marketed as an EREV but, is actually a parallel hybrid. The Volt gasoline drivetrain adds power to the electric driveline under certain operating conditions. The series hybrid configuration eliminates the majority of integration complexity required in a parallel hybrid and also does not require a transmission. They combine an electric drive system with an internal combustion generator system to extend the useful range.

All electric drive trains are the simplest configuration. The primary components include: an energy storage unit, a controller (the electronics), and a motor to converts power to motive force. Energy storage technology is commonly cited as the limitation of all electric drive trains. Energy storage from batteries is expensive and heavy; fuel cell technologies are lighter but more expensive and also face infrastructure and supply chain challenges. The Nissan Leaf and the Tesla are examples of battery electric vehicles (BEV) sold today. With the exception of test fleets, fuel cell vehicles (FCV) have not reached consumers.

* * * *

Chapter 1 explained my thesis motivations and highlighted significant challenges facing the automobile industry. Industrialization and population are increasing vehicle adoption and consequently, GHG emissions. The automobile industry size and complexity make change difficult. New automobile technologies take thirty to fifty years to make a difference (MIT Laboratory for Energy and the Environment, 2005). The rate at which GHG emissions are increasing compared to the time for new vehicles technology to make a difference, increase climate change concerns.

Zero emission vehicle technology is available to mitigate the growing emission challenge. The adoption of this technology has been slow and limited. A literature survey and stakeholder interviews were conducted to gain insight into how zero emission vehicle adoption may impact the automobile industry. Chapter 2 will describe detail the interview process.

Chapter 2 Thesis Overview

Methodology

Both interviews and literature sources provide the data for this thesis. Interviews were conducted across five stakeholder groups. Literature sources included books, academic journals and reports, government databases and reports, internet and print media. Chapter Three summarizes the interviews. Chapter Four aggregates interviews, literature sources, and the author's analysis and conclusions.

Selection of Interview Candidates

Interview candidates were selected to represent diverse zero emission vehicle stakeholders. Interviews were secured with representatives from government, automotive industry, energy industry, petroleum industry, and academia stakeholders. Due to the size and complexity of acquiring and analyzing consumer responses, they are not represented as a stakeholder group.

Internet searches were used to generate an initial interview candidate list. Two media lists of zero emission vehicle “influential stakeholders” were found. First, the *Automotive News* published an Electrifying 100 list.

“In the past couple of years, it became clear that this wave of interest in vehicle electrification would differ from past industry forays into alternative propulsion. It was going to be broader and more sustained. Hybrids had spread through automakers' lineups. But more dramatically, new car companies were springing up to create battery-powered electric vehicles. That's why, late last year; we decided to take a closer look at the key players

driving vehicle electrification. You're looking at the result, the Electrifying 100” (Automotive News, 2011).

Second, in a November 2011 *Forbes* article, former CIA director and author of *The Crisis in Energy Policy (2011)* John Deutch identified: seven people who in his words, “have most influenced world energy developments and are thinking about the most important energy issues facing our world” (Forbes.com, 2011) Eight interview requests were made and five interviews were generated, three of which were the people listed in the Automotive News Electrifying 100 and two were recommendations.

The initial candidate list was expanding by searching the MIT “Infinite Connection” database for alumni employed by stakeholder corporations. Next, MIT academics were added to the candidate list based on MIT News articles and MIT Energy Initiative publications relating to zero emission vehicles and components. Personal network contacts were leveraged to fill in stakeholder gaps in the candidate list. Finally, at the conclusion of each interview, the interviewee was asked if they knew anyone who would make a good interview candidate. Several offered introductions which yielded interviews. Thirty five interview requests were made by letter or email and sixteen interviews were completed. Practical considerations guided which interviews were conducted in person and which were conducted by phone.

Of the sixteen interviews completed, four represented the automobile industry, two represented the U.S. government, four represented utility industry, two represented the petroleum industry, and four represented academia (two from engineering and two from business).

Interview Format

Interviews began with a brief author biography and a concise thesis description. Interviewees were asked to respond to five questions. Occasionally, follow up questions or clarifications were required to provoke responses consistent with the original question. The interviewer's opinions or previous interviewees' responses were not disclosed or discussed during the question portion of the interview.

In most cases, general low and or zero emission vehicle discussions followed the question portion of the interview. The extended conversations offered useful insights and often provided an opportunity for the interviewee to articulate an overall zero emission vehicle position.

Interview Questions

Thesis Question: How will zero emission vehicle adoption change the Automobile Industry structure in the next 15 years (by 2026)?

Interview questions:

1. Are transportation sector emissions a threat to environmental stability?
2. Who or what will inspire zero emission vehicle adoption?
3. Who will supply zero emission vehicle solutions?
4. What technologies will be utilized by zero emission vehicles?
5. How will consumers source energy?

The interview questions and time frame were chosen to promote broad, reasonable conversation. The questions were used to guide the interview, not constrain the interview. For example, interviewees were not discouraged from discussing hybrid (low emission) vehicles or the fifty year potential of hydrogen fuel cells but, as the next question was posed, the conversation, at least temporarily, was reset to 'zero emission vehicles in the next fifteen years'.

The questions were intentionally open ended, technology neutral, and constrained to zero emissions. The open ended nature promoted discussion and explanation. Although the questions were technology neutral, the zero emission and fifteen year constraints focused the discussion on a limited number of technologies.

Questions were structured to allow a one word or single sentence response. The intention was not to encourage brief responses but to insure the questions were clearly articulated.

The scope of the questions was intended to cover environmental, technology, and value chain aspects of the automotive industry.

- Question 1 was intended to elicit responses ranging from a simple yes or no to a time qualified yes (for example: "Yes, they will be significant in thirty years").
- Question 2 was intended to promote discussion of market driven and policy driven approaches.
- Question 3 was a supply chain and an incumbent-versus-new-entrant question.
- Question 4 was intended to encourage discussion of technology tradeoffs.

- Question 5 was meant to promote contrasts between electricity, hydrogen, battery exchange, and other potential energy sources.

In hindsight, a question designed to address the supply chain retail side would have added value.

Interview Response Processing

During each interview, I took handwritten notes detailing the responses and conversation. As best I could, the responses were written in the interviewees own words. Immediately after the interview, I recorded the responses and conversation notes in Microsoft Word. Audio recordings were not used.

Three steps were used to summarize the interview responses. First, tables were created to provide an overview of stakeholder group responses. Table 2 provides an example and Table 3 is the legend.

Table 2: Example interview analysis table

Response	Stakeholder 1	Stakeholder 2
Batteries		
Unknown		
Hydrogen		

Table 3: Interview table legend

The majority	
About half	
A minority	
No one	

A written summary of the stakeholder responses follows the tabular summary. The summary is anonymous and comments are not attributed to a specific interviewee. Second, a collective interview synopsis was written. Third, responses across stakeholder groups were characterized as “collective knowledge” or “dissenting opinions”.

Chapter 3 Interview Summary and Analysis

Question 1

Are transportation sector emissions a threat to environmental stability?

Table 4: Question 1 summary

Response	Stakeholder				
	Automotive Industry	Petroleum Industry	Electric Utility	Government	Academia
Yes. They are a threat					
No commitment					
No. They are not a threat					

All but one interviewee stated transportation sector emissions are a threat to environmental stability. Most supported their opinion with statements to the effect ‘I am not a climate expert, but the majority of scientist believe the trend of increased GHG emissions is a problem’. Four interviewees were more specific and noted transportation sector GHG emission must decrease to achieve the target 450 ppm CO₂ equivalent. No one spoke to the severity or the timetable of the threat.

Seven interviewees discussed the distinction between emissions which contribute to local pollution and emissions with contribute to greenhouse gasses (GHG emissions). All who distinguished between local pollution and GHG emission offered a similar synopsis: ‘Over the past thirty years, the U.S., Japan, and Europe have made significant reductions in local pollution. Although, continued improvement is expected, mitigation efforts from automakers, fuel

suppliers, and governments have been successful. Local pollution in the emerging countries and GHG emissions throughout the world are a more challenging problem.’

According to respondents, local pollution in emerging countries faces two challenges:

Availability of high quality fuel and the cost of technology. A consistent supply of high quality fuel is not available in most emerging countries, improved standards and supply upgrades are required. Second, low emission (local pollution) vehicle technology and high quality fuels add cost. Since local pollution externalities are not part of emerging market transportation costs, market forces have not encouraged adoption of these more expensive technologies.

GHG emission reduction challenges highlighted by interviewees include: Change will take time; multiple solutions are required, intelligent solutions are needed, leadership is necessary, and coordination is critical. Although each of these comments came from a different interviewee, the aggregate highlights the complexity of this challenge.

Question 2
Who or what will inspire zero emission vehicle adoption?

Table 5: Question 2 summary

Response	Stakeholder				
	Automotive Industry	Petroleum Industry	Electric Utility	Government	Academia
Consumer market forces					
A combination of market and regulatory forces					
Government regulation					

Five interviewees first addressed this question with a disclaimer. War, disruption of the oil supply, a major environmental event, and gasoline price shocks were all cited as external factors that could abruptly accelerate zero emission vehicle adoption. Independent of external shocks, responses varied across and within stakeholder groups. Eight interviewees felt strongly that market forces must inspire adoption. Five interviewees indicated regulation would be necessary to overcome market failures and a weak value proposition. Three cited a combination of market forces and regulation would inspire adoption. One response accurately stated governments do not have sufficient budget to subsidize the market share required to impact GHG emissions.

The market forces group message was clear: vehicles must increase consumer value or they would not be adopted. In one fashion or another, all interviewees said vehicle utility must improve. Second and third generation vehicle cost reductions were highlighted by a two interviewees. Four interviewees suggested that improving consumer ‘perceived value’ might be as important, if not more so, than cost reduction or utility improvements.

A gap between perceived customer value and actual customer value was highlighted by a two interviewees. They emphasized the better driving experience an electric drive vehicle delivers; less vibration, less noise, smoother acceleration, no light throttle hesitation, and no loss in acceleration due to shifts. Convenience was another unrealized benefit. Battery electric vehicles do not require traveling to the gas station and waiting, the majority of recharging was done at home. Consequently, the consumer never waits while the vehicle is being recharged (refueled). This group felt most consumers are unaware of these benefits. They said consumers are too concerned with by range anxiety. Consumer perceptions were a consistent theme among the market inspired adoption group.

The stakeholders, who suggested a combination of market forces and government regulations will drive adoption, felt the market would not be dominated by a single technology. A portfolio of technologies and regulations will support unique market segments.

The regulation group responses were comparatively short. An 'uncompetitive consumer value proposition' seemed to be the underlying assumption but, it was not explicitly stated. Most did not comment on regulation strategies. The minority who discussed strategies had two options. Government stakeholders discussed recent US CAFE regulations and one interviewee discussed gasoline taxes, highlighting the low gasoline price in the US relative to the rest of the world.

Most if not all stakeholders agreed that the current value proposition is not strong enough to inspire zero emission vehicle adoption. Some suggested adoption would come from market forces and others suggested regulations. Overall, responses were weighted toward market inspired adoption.

Question 3
Who will supply zero emission vehicle solutions?

Table 6: Question 3 summary

Response	Stakeholder				
	Automotive Industry	Petroleum Industry	Electric Utility	Government	Academia
Automobile Industry					
New Entrants					
Combination of New and Existing Firms					

An automotive industry stakeholder stated “American capitalism will source solutions from everywhere.” Another said this is ‘the standard disruptive innovation question: Will today’s incumbents survive a disruptive change?’ Almost all interviewees stated that the current automobile manufactures were uniquely qualified to meet the significant challenge of producing vehicles at scale which meet highly evolved customer expectations and regulations. Response variations seemed to be based on the interviewees’ interpretation of the question. Some interpreted the question as to who would supply vehicles, other interpreted the questions as to who would supply the technology, and a few respondents answered both questions.

Most discussed changes and new entrants to the supply chain. Most also said the current automakers would supply vehicles. The dominate response was a combination of new and existing firms would supply zero emissions vehicle solutions. No one stated existing vehicle manufactures would be replaced by new entrants.

Question 4

What technologies will be utilized by zero emission vehicles?

Table 7: Question 4 summary

Response	Stakeholder				
	Automotive Industry	Petroleum Industry	Electric Utility	Government	Academia
Electric Drive, Battery Storage					
Electric Drive, Hydrogen Fuel Cell Storage					
Not enough information to predict at this time					

When this question was posed, a number of interviewees requested clarification on “zero emissions”. Tank-to-wheels zero emission technologies was the intent of the question. Based on this constraint, responses focused on electric drive vehicles with energy storage in either batteries or hydrogen fuel cells. Five interviewees also discussed the zero emission aspect of plug-in hybrids (PHEV); vehicles offered today have “full electric” operating range of 15 to 45 miles. Since the eighty percent of U.S. trips are less than 20 miles, these vehicles will operate in a zero emissions mode the majority of the time (NHTS, 2009).

Table 8: U.S. personal vehicle travel distances segmented by trip distance (NHTS, 2009)

Miles	Share of Vehicle Trips	
	All Trips	To Work
< 6 miles	61.7%	42.9%
6 - 10 miles	13.6%	17.0%
11 - 15 miles	8.7%	14.1%
16 - 20 miles	4.8%	8.3%
21 - 30 miles	4.9%	9.4%
> 30 miles	5.0%	7.3%

Interviewees also emphasized the importance of including well-to-tank emissions (emissions generated by the production and distribution). Each of these detours added value to the interview. A level of uncertainty was expressed by every respondent, some focused on technology uncertainty, others focused on the uncertainty of which solution will dominate, and a few discussed the time-frame uncertainty.

Cost, energy density, and recharge rates were all highlighted as battery uncertainties. There was a consensus that battery technology would incrementally improve and costs would fall. But the magnitude and timing of improvements is uncertain. Four interviewees indicated battery electric vehicles (BEV) fit certain market segments better than others. Generally, densely populated urban areas were considered a good fit for BEVs. In at least six interviews, BEV was the assumed solution and hydrogen commentary had to be prompted. The future of hydrogen was raised in every interview since much of the literature highlights it as the long term fuel the world will eventually adopt. Almost all interviewees felt the fifteen year timeframe I imposed virtually eliminated widespread adoption of hydrogen as a viable option.

The uncertainties associated with hydrogen mentioned by respondents included production cost and storage costs. Most responses indicated the cost of storage both on and off the vehicle needed to significantly decline to make fuel cell vehicles (FCV) a realistic mainstream option. Six interviewees also expressed uncertainty on what hydrogen production methods would prevail and some noted that certain methods had significant well-to-tank GHG emissions.

One interviewee emphasized that significant GHG emission reductions will not come from zero emission technologies in the near future (15 years). Reductions he felt will come from improved, hence, higher internal combustion efficiency. Three interviewees emphasized vehicle weight reduction to reduce GHG emissions. Three interviewees advocated vehicle connectivity and new ownership business models as important contributors to emissions reductions.

Question 5
How will consumers source energy?

Table 9: Question 5 summary

Response	Stakeholder				
	Automotive Industry	Petroleum Industry	Electric Utility	Government	Academia
Dedicated distribution stations					
Personal residence and work					
Multiples sources					

Initial responses were based on what technologies the interviewee forecast would be utilized by consumers. When hydrogen was the favored technology, “dedicated distribution stations” was the response. When battery technology was preferred, the response was “multiple energy sources”. Four interviewees specifically commented that hydrogen production and electricity generation would utilize multiple sources and processes. They also said economic and regional factors would determine the preferred sources and processes.

“Personal residence and work” was a response option since several interviewees contrasted home, work, and public options for BEV recharging in the near term. Although a subset of “multiple sources”, this detailed response stressed the significance of existing infrastructure. Interviewees indicated the majority of infrastructure was ‘now in place to support home and workplace charging’ but ‘the business model for public charging was challenging’.

Consequently, even though the electricity may be produced from multiple energy sources the respondents felt home and work would ultimately be the primary consumer sources. Four

interviewees highlighted the convenience aspects of recharging. Recharging, they said, is a very different experience than refueling. If home and workplace charging is available, travel to a unique location to source energy is not necessary and, unlike petroleum refueling, the consumer does not need to wait while their vehicle is recharged. This convenience was cited as part of the “BEV value proposition”.

Economic value, source diversity, and regional factors were consistent themes in each interview. Many respondents felt that consumers will migrate toward the most valuable energy sources. Although most agreed there is not yet a clear technology winner, very few respondents included hydrogen as a competitor. When interviewees did discuss hydrogen, responses highlighted infrastructure and production challenges. Regional infrastructure growth was suggested by one interviewee as the model for FCV adoption. Collectively interviewees suggested energy would be sourced based on consumer economic value and regional factors would influence the available supply and consumer demand.

Stakeholder Alignment

Interview responses illustrate two types of stakeholder alignment. First, members of a stakeholder group provided similar responses to the questions. Second, different stakeholder groups collectively provided similar responses to multiple questions.

Across stakeholders

In two of five questions, responses across stakeholders were aligned. The majority of stakeholders in every group indicated transportation sector emissions were a threat to environmental stability. Most stakeholders in all groups agreed that customers would source

energy from multiple sources. This alignment is significant relative to hydrogen powered vehicles. One member of the automobile industry group indicated hydrogen power vehicles would be utilized by zero emission vehicles and, consequently, said that energy would be sourced from “dedicated distribution stations”. All other responses favored zero emission technologies other than hydrogen and multiple energy sources.

Except the automobile industry, stakeholder groups agreed zero emission vehicle solutions would be supplied by a combination of new and existing firms. The divergence observed in the automobile industry group was likely due to semantic differences. The question asked who will supply zero emission vehicle solutions. The wording was not intended to differentiate between entire vehicles and components. A couple of responses from the automobile industry focused on the final vehicle and mass markets, these responses indicated zero emission vehicle solutions would come from the existing automobile industry. Considering niche markets and the industry supply chain, all stakeholders agreed solutions would come from a combination of new and existing firms.

On two of the five questions, stakeholder groups did not agree. The most distinct difference was the difference between regulation and market forces. The majority of responses indicated market forces would inspire adoption but about 20% of the respondents indicated government regulation would inspire zero emission vehicle adoption. The question of whom or what will inspire adoption evoked the clearest responses. Three respondents indicated a combination of market and regulator forces would inspire adoption but most had a clear point of view. Stakeholder groups did not agree on what technologies would be utilized by zero emission vehicles.

Differences seem to be based more on uncertainty than a difference of opinion. Some stakeholder groups favored BEVs and others indicated there was not enough information to predict a favored technology at this time. The disagreement among stakeholders on adoption inspiration and technology highlights opportunity for technological and business model innovation.

In sum, stakeholder groups agree there is a need to improve transportation sector emissions. They do not agree on which zero emission technology will be utilized or what will inspire consumer adoption.

Within a stakeholder groups

Five questions and five stakeholder groups yield twenty five responses where stakeholders within a group may or may not be aligned. Responses within a stakeholder group were aligned twenty one times, only four responses showed divergence within a group.

Within the petroleum and utility industry stakeholder groups, responses were not aligned with respect to the source of inspiration for zero emission vehicle adoption. These industries represent the most heavily regulated stakeholder groups. Responses covered the entire spectrum, some favored consumer market forces, others indicated government regulations would inspire adoption, and some indicated adoption would be inspired by a combination of consumer and regulation forces.

Within the automotive industry stakeholder group, some responses indicated zero emission vehicle solutions would come from within the industry others conceded solutions would also come from new entrants. Within the petroleum industry stakeholder group, some responses indicated battery storage would be the primary technology utilized in zero emission vehicles, others indicated there was not enough information to predict a technology at this time.

Overall, twenty one of twenty five responses were consistent within the stakeholder groups. Of the four responses that diverged, two were based on uncertainty. Responses to the age old “market versus regulation” question were the only source of distinct variation within a stakeholder group. Alignment within the stakeholder groups was high.

Common collective knowledge

The process I use to label information “common collective knowledge” has three steps. First, consistent concepts from the majority of interviews are identified. Second, I create a statement summarizing each concept. Finally, every statement must pass the following criteria: in my opinion, none of the interviewees would disagree with the statement. Based on this process, the following statements are considered to be “common collective knowledge”.

- Transportation sector emissions are a threat to environmental stability.
 - In developing and emerging economies, transportation sector emissions are important to mitigating local pollution and global GHG emissions.
 - In developed markets, transportation sector emissions are important to mitigating global GHG emissions.

- The value proposition offered by zero emission vehicle technology today will not inspire market penetration significant enough to forestall an increase in GHG emissions from the global transportation sector.
- The consumer vehicle market is competitive and complex. Current automobile manufactures have unique knowledge and capabilities. It is unlikely zero emission vehicle adoption will displace existing automobile manufacturers.
- The automobile industry supply chain will change. Some firms will evolve, new entrants will replace others. Overall, the supply chain will experience a more significant disruption than the automobile manufacturers.

Common gaps in collective knowledge

“Common gaps in collective knowledge” are intended to identify areas where the conclusions are either uncertain or unknown. The following statements represent common gaps in collective knowledge:

- The future of zero emission vehicle technology is uncertain. The vehicle value propositions will depend on technology advances that may or may not occur in the future.
- The time required for hydrogen to become a consumer vehicle energy source is unknown. Although it is technically possible for hydrogen to power zero emissions vehicles, the cost associated with technology and infrastructure to make hydrogen an economically competitive solution are uncertain or unknown.

It was not an interview questions but almost every interviewee discussed at least one alternative business model. Topics ranged from energy supply to vehicle ownership. Existing business models with unknown futures were mentioned and business models that do not exist were mentioned. A common gap in collective knowledge is:

- Starting in the 1920s, vehicle financing helped shape to automobile market and, in the 1990s; vehicle leasing influenced the new and used vehicle markets. It is uncertain and unknown how business models inspired by zero emission vehicles will shape the consumer vehicle market.

Divergent opinions

Distinct differences in opinion are labeled “divergent opinions”. Almost every response had an assumed or explicit qualifying time frame. This time dependency influences responses. For example, the question of hydrogen becoming economically viable in five years will provoke a different response than if hydrogen will become economically viable in twenty five years. This section separates opinions that are different because interviewees have different timing assumptions from opinions that will not change over time. Divergent opinions represent a qualitative difference in opinion between at least two interviewees that is not expected to change over time. Two divergent opinions emerged from the interviews.

The first is the obvious (and timeless) “regulation versus market” debate. Although all interviewees would agree regulatory and market forces make a positive contribution to society, there is a distinct difference between those who presume regulations are necessary and those who

presume regulations lead to inefficient outcomes. My observation is that, regulation and market related responses tend to have a strong emotional component. All other responses tended to have a mechanical bias built on pertinent knowledge and fact.

The second divergent opinion is the feasibility hydrogen powered zero emission vehicles. Given a reasonable amount of time, there is a difference of opinion on whether or not hydrogen will become a viable option for vehicles. One respondent said hydrogen will be viable sooner than most think.

* * * *

Chapter Three summarized and analyzed the information collected during stakeholder interviews. Relevant to the zero emissions vehicle adoption and the automobile industry, three themes emerged from the interviews. First, infrastructure is critical. Existing infrastructure will support initial BEV adoption but new infrastructure is necessary to support FCV vehicles. Second, an attractive value proposition must exist and be understood by consumers. Third, timing is uncertain.

Chapter Four will aggregate interviews, literature sources, my analysis and conclusions. This final chapter will culminate with my forecast on how zero emission vehicle adoption will change the Automobile Industry structure in the next fifteen years.

Chapter 4 Summary and Conclusions

The automotive industry is large, complex, and interconnected. For over 100 years, the unique combination of centralized and regional structures has insulated the automotive industry from major disruptions. The few structural changes which have occurred in the industry took decades to unfold. Consequently, predicting how zero emission vehicle adoption will change the industry structure is difficult and requires a long time horizon. This chapter will focus on trends identified in the literature and interviewees. For reasons identified in Chapter Two, the timeframe is limited to the next fifteen years.

Question 1

Are transportation sector emissions a threat to environmental stability?

Transportation sector emissions are significant to the environment. Both local pollutants and GHG emissions are important. As noted, local pollution in developed economies has been successfully mitigated but it is a growing problem in emerging and developing markets. In contrast, GHG emissions are a challenge for the entire world. Developed markets contribute more GHG emissions per capita whereas emerging and developing markets contribute more total GHG emissions.

In the emerging and developing markets, transportation sector local pollution is an increasing problem. Dramatic population growth coupled with industrialization is accelerating personal transportation adoption. Although fuel and vehicle technologies are available to mitigate local pollution higher costs limit adoption. Developed markets faced a similar dilemma in the 1970s and 1980s, after decades of urban growth, local pollution

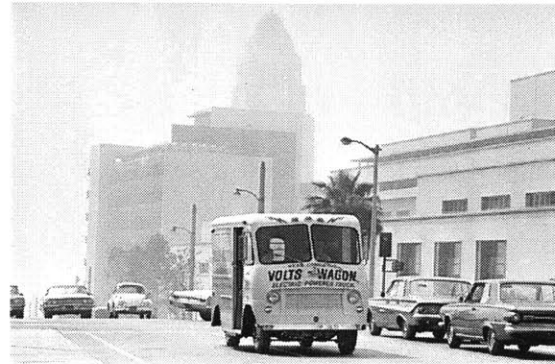


Figure 10: 1967 Los Angeles smog (Los Angeles Times Local, 2011)

(smog) plagued cities. The picture from the 1967 Los Angeles Times shows city hall obscured by smog providing a vivid reminder of the problem. The visibility of smog helped inspire the market forces and government regulations which ultimately reduced local pollution. In developed markets, smog visibility seemingly inspired government regulation and market forces to mitigate local pollution. This may occur in developing markets as well. For example, recent media reports illustrate what may be a trend: “newspapers across China have been scrutinizing heavy smog” (BBC News China, 2011). Although local pollution will increase in the short-term, smog visibility inspires both market forces and government regulations to reach to the problem.

Transportation sector GHG emissions are a challenge for the entire world. Population and industrialization in less developed regions are increasing. This combination increases vehicle adoption and consequently GHG emissions. In the last ten years, as noted in Chapter One, CO₂ emissions in the upper middle income and middle income countries have increased over 50% (World Bank, 2012).

Significant obstacles to mitigating GHG emissions include the understanding and acceptance of their impact. It is easy to see local pollution and consequently acknowledge the challenge. The effect of GHG emissions is difficult to comprehend, human beings cannot perceive climate change, and the causal relationship between GHG emission and climate change is not intuitive. Consequently, widespread acceptance of GHG emission driven climate change requires significant time, faith in science, and a belief in the scientific method. Since this challenge is “invisible”, inspiring market forces and government regulations is challenging.

This concept of “invisible” GHG emissions was evident in every interview. Most interviewees qualified their response with statements to the effect ‘I am not a climate expert, but the majority of scientist believe the trend of increased GHG emissions is a problem’. No one described climate change using firsthand knowledge or experience. The timing of the GHG emission threat was also absent from interviews. It is not clear to all interviewed when GHG emissions will pose a significant threat to environmental stability or if current levels of GHG emission are in fact a grave threat to environmental stability.

Question 2

Who or what will inspire zero emission vehicle adoption?

It is not clear when or if significant zero emission vehicle adoption will occur. Market forces and government regulation will perhaps combine to inspire adoption but it is difficult to predict if and when the magnitude of adoption will be large enough to make a significant impact on transportation sector GHG emissions. Technology is simultaneously advancing for both zero emission and internal combustion vehicles. Based on current adoption rate and the size of the world vehicle fleet, zero emission vehicles will not significantly reduce transportation sector GHG emissions in the next fifteen years.

Regulations

In the US, three types of government regulation are in place to help with zero emission vehicle adoption. The gas tax provides an incentive for consumers to purchase more efficient vehicles. The Corporate Average Fuel Economy (CAFE) standards encourage automobile manufactures to produce more efficient vehicles. And, the Fuel Efficient Vehicle Tax Credits subsidize fuel efficient vehicle consumer costs. However, the impact of these regulations is not expected make a significant impact on global GHG emissions.

Gas taxes are not expected to drive zero emission vehicle adoptions. First, in the U.S., popular support for increasing gas taxes does not exist. Many politicians consider a significant increase to the gas tax “political suicide”. Second, low energy prices are seen to contribute to global competitiveness so there is little initiative for nations to increase gas taxes. Finally, higher

gasoline taxes in Europe have inspired smaller, higher efficiency internal combustion vehicles but they have not inspired zero emission vehicle adoption.

In 1978, the first CAFE standards were established. These standards have been praised for improving vehicle efficiency: “CAFE standards were effective in increasing new car and truck fuel economy by 70 percent between 1975 and 1988. In 2000 alone, CAFE standards saved American consumers \$92 billion, reduced oil use by 60 billion gallons of gasoline, and kept 720 million tons of global warming pollution out of our atmosphere” (Union of Concerned Scientist, 2007). In 2011, new CAFE standards were established thru 2025. The 1985 27.5 mpg target, established in 1978, remained constant until 2011. From 1985 to 2000 the reported passenger car fuel economy did not significantly improve. From 2000 to 2010 the reported passenger car fuel economy improved 19% without any pressure from CAFE regulations. (NHTS, 2012) The 2011 CAFE standards are intended to increase the passenger car fuel economy 104% in 15 years, from 27.5 mpg in 2010 to 55.0 mpg in 2025 (NHTS, 2012).

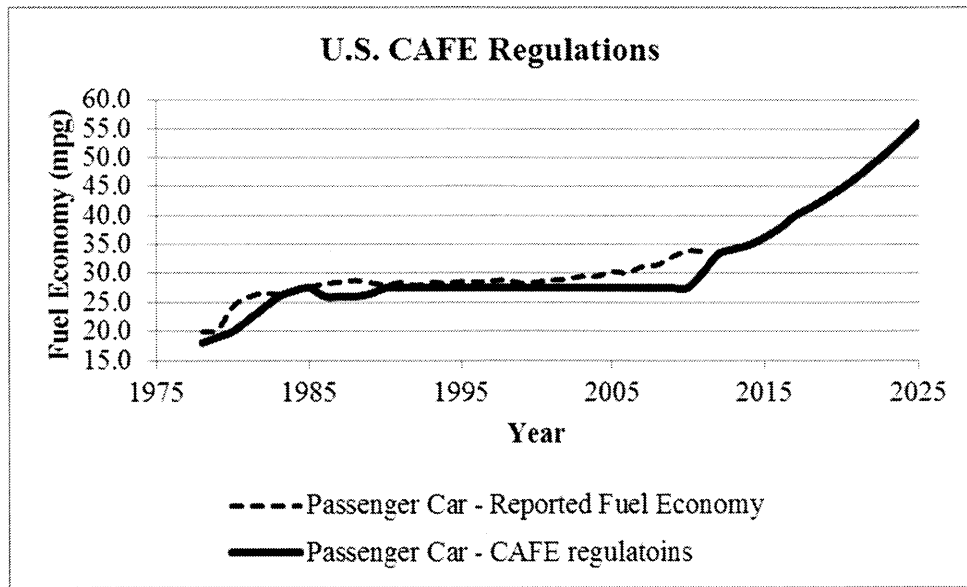


Figure 11: U.S. CAFE standards and performance (NHTS, 2012)

The CAFE regulations are expected to increase the fuel efficiency and of new vehicles. The higher efficiency vehicles will be a combination of internal combustion, hybrid (low emissions), and zero emission vehicles. Since, vehicles are developed for regional markets; the global effect of U.S. CAFE regulations is likely to be minimal.

Nor is it likely that demand subsidies (tax credits, etc.) will inspire significant zero emission vehicle adoption. As discussed by one of the academic researchers interviewed, government financial incentives are not feasible to support significant adoptions. Consider the following: In the US, 13.2 million passenger vehicles were sold in 2011 (Automotive News, 2012). If 25% of vehicles sold received a \$7500 tax credit, the cost would be \$25 billion dollars. This would represent 40% of the Federal Government 2011 ground transportation \$62 billion budget (USGovernmentSpending.com, 2012).

Market forces

Historically, market forces have been the primary drivers of major transportation technology shifts. In the early 1900s, the automobile was more expensive than the horse but offered higher utility (consumers preferred the “automobile value proposition”). Early air travel adoption followed a similar trend. Flying was faster but more expensive than automobile travel. Preferred value propositions inspired early automotive and air transportation adoption.

At this time, the “zero emission vehicle value proposition” is not strong enough to inspire mass adoption. The cost premium must be reduced or the perceived utility of the vehicle must increase for significant consumer adoption to occur. Both interviews and the current literature suggest cost reductions in the next fifteen years will come from gradual iterative development, not from technological breakthroughs. Significant barriers to zero emission cost reduction involve compromises made to the vehicle architecture. The 2012 Nissan Leaf is the first electric vehicle specifically designed for a mass market. Other zero emission vehicles are a compromise between hybrid and internal combustion vehicle architecture or targeted at a niche market. The simplicity of zero emission vehicle architecture will likely yield cost reductions as hybrid and internal combustion compromises are eliminated but, this will take time.

Adoption rates are also a function of perceived utility. Consumers suffer from “range anxiety” (i.e. they are concerned they will not be able to source energy during their travels). Adoption is limited by the lack of infrastructure to support refueling (recharging). Without widespread infrastructure and fast charging technology, the utility and consequently the value of zero emission vehicles is substantially diminished.

But there are some market segments emerging where zero emission vehicles offer superior value propositions. Fleets are sensitive to fuel costs and battery electric vehicles (BEV) fuel costs are significantly lower than petroleum. With known driving routes, centralized refueling, and in many cases urban utilization zero emission vehicle value propositions are attractive for certain fleet applications.

Although zero emission vehicles may be attractive to certain market segments and regulations may inspire limited or initial adoption, mass adoption requires a better value proposition relative to internal combustion engines. Infrastructure is part of vehicle utility and consequently part of the value proposition.

Question 3

Who will supply zero emission vehicle solutions?

In the next fifteen years, zero emission vehicle solutions will be supplied by combination of existing automobile industry firms and new entrants. The current automotive manufactures are uniquely qualified to meet the significant challenge of producing vehicles at scale to meet highly evolved customer expectations and government regulations. Notable disruptions to the existing supply chain are, however, to be expected.

In the next fifteen years, existing automobile manufactures will likely supply mass produced zero emission vehicles. A combination of new entrants and existing manufactures will supply low volume niche market segments. The number of specialized market segments will increase based on vehicle use patterns. Fleet vehicles such as taxis, light duty service trucks, and urban delivery vehicles represent new entrant opportunities. Lower volume and unique specifications make fleets attractive to new entrants and less attractive to consumer market suppliers.

Significant zero emission vehicle adoption will likely disrupt the automobile industry supply chain. Zero emission vehicles use different components and systems than existing internal combustion vehicles. Some existing suppliers will adapt and develop new competencies. New entrants will replace existing suppliers who fail to adapt. As new technologies emerge for zero emission vehicles, increased technology collaboration between incumbents is expected.

Incumbents will collaborate to mitigate emerging technology risks.

Zero emission vehicle architecture allows common components across vehicle platforms and vehicle manufactures. This modular vehicle architecture based on common components could significantly disrupt the current automotive manufacturers, reducing entry barriers and accelerating the rate of development. Although a module zero emission vehicle platform may eventually disrupt the automobile industry, the current zero emission value proposition is not yet adequate to inspire adoption.

Question 4

What technologies will be utilized by zero emission vehicles?

For the next fifteen years, vehicles using battery energy storage and electric drive (BEV) will dominate the zero emission vehicle segments. Well-to-wheels zero emissions has been demonstrated by three vehicle architectures: hydrogen internal combustion engines (hydrogen ICE), hydrogen fuel cells with electric drive (FCV), and battery energy storage with electric drive (BEV). Each technology has a different set of challenges.

Vehicle type	Energy Source	Energy Storage	Motion
Hydrogen ICE	Hydrogen	Fuel cell	Internal combustion engine with traditional driveline
FCV	Hydrogen	Fuel cell	Electric drive
BEV	Electricity	Battery	Electric drive

Figure 12: Zero emission vehicle architecture

Infrastructure is a challenge for all zero emission vehicle architectures. Infrastructure will play a critical role in determining which technologies are utilized and which are not utilized. Today, hydrogen infrastructure does not exist, whereas electricity infrastructure exists in industrialized nations. To support hydrogen zero emission vehicles, supply and distribution chains would have to be built. To support large scale BEV adoption, the existing electricity grid would require upgrades and additional capacity. The cost of each infrastructure option is difficult to estimate and the timing of each investment is different. An automotive industry interviewee suggested hydrogen infrastructure could follow of regional pattern of growth concurrent with regional

vehicle sales, distributing the cost over time. This concept also works for electricity infrastructure growth. The BEV infrastructure is better suited to incremental growth

The challenges associated with hydrogen included production cost, storage costs, and infrastructure deployment. Based on the uncertainty and conjecture surrounding hydrogen vehicles, Hydrogen ICE and FCV are not expected to have significant adoption in the next fifteen years.

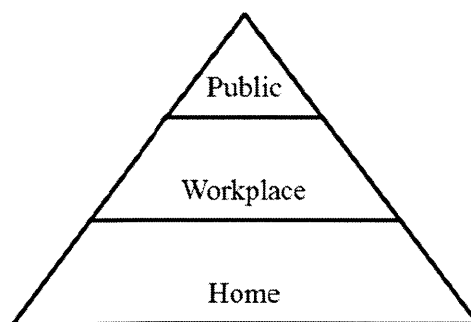
Cost, energy density, recharge rate, and infrastructure deployment are the main BEV challenges. Battery costs have significantly reduced in the past 10 years but remain prohibitively high. Future cost improvements are expected but the magnitude and timing are uncertain. Yet, for the next fifteen years, electric drive with battery energy storage (BEV) will be the primary technology used in zero emission vehicles.

Question 5

How will consumers source energy?

Cost, convenience, and availability will determine how consumers source energy. Since battery electric vehicles are the most likely zero emission vehicle to be utilized, the question becomes how will consumers source electricity? Consumers may source transportation electricity from existing infrastructure and from future infrastructure. Existing infrastructure options include home, work, and public charging. Since future infrastructure options only are bounded by imagination and theoretical physics. New infrastructure discussion in this section is limited to battery swaps, high power highway charging stations, and wireless charging.

A utility industry representative described existing infrastructure transportation electricity demand using the pyramid shown below. Home charging represents the majority of charging. Vehicles are usually parked overnight and electricity rates are lowest at night. Overnight home charging represents a low cost, convenient option.



Work charging is second highest demand option. In a few cases, employers are allowing employees to charge free. In other cases, the infrastructure costs are passed on to the employee. Various fee schedules are used to charge employees for transportation electricity, some are based

on the electricity used, and others are based on renting a parking spot with charging access.

Some employers attempt to recover the infrastructure cost, others do not. If significant adoption occurs, most firms will probably pass charging costs to the employees. Since rates are typically higher during working hours, workplace charging will be more expensive than home charging yet still a convenient option.

Public charging represents the lowest demand. Business model challenges are the primary reason utility companies do not expect public charging to represent a significant portion of transportation electricity demand. Whereas Level 1 charging (slowest charge rate, least expensive infrastructure) is sufficient for most home and workplace charging, Level 2 charging (faster and more expensive infrastructure) is needed for public charging. Vacancy is also a concern for public charging, hence business models often charge per hour parked, not on the electricity consumed. To recover the infrastructure and vacancy expenses, public charging rates tend to exceed gasoline expenses, effectively reducing the operating cost advantage of electric vehicles. Based on cost and convenience, consumers will source transportation first at home, second at work, and, when necessary, from public charging stations.

Future infrastructure options are represented by battery swapping, high power highway charging stations, and wireless charging. The Israeli firm, Better Place, is pioneering a battery swapping business model. In this mode, the company owns the battery and provides both public battery swapping stations and public charging stations. Consumer fees are based on energy and amortized battery costs. Business model details are not published but high battery utilization to reduce battery expenses and grid storage income are important profitability factors. My

interviews however revealed two significant strategic challenges facing Better Place. First, all vehicles must use a limited number of battery designs to make the model feasible. To date, battery size and shape is unique to the vehicle model. Second, automobile manufactures must supply vehicles without batteries and equipped to utilize Better Place battery standards.

Automobile manufactures consider the battery part of their “core competence”. To date, only the Renault-Thus, the Better Place model will be restricted to only a few segmented markets unless existing automobile manufactures change their current strategy or new manufacturing entrants appear.

High power highway charging stations are the likely alternative to battery swapping. Charging stations require less infrastructure investment and fewer common standards. As charging efficiency improves, dedicated high power – fast charge stations could add significant utility to the battery electric vehicle proposition. These stations will be necessary to inspire mass adoption of battery electric vehicles.

Wireless charging may eventually be available for zero emission vehicles. Energy may be available in the roadway, parking locations, or at home. In 2007, MIT researchers Soljačić, Joannopoulos, and Fisher demonstrated a magnetic resonance device which wirelessly powered a sixty watt light bulb (MIT Technology Review, 2008). Building on the this work, Stanford University researchers are working to “develop an all-electric highway that wirelessly charges cars and trucks as they cruise down the road” (Standford Report, 2012). The Stanford results were published in the journal Applied Physics Letters in November 2011 (Yu, Sandhu, Beiker, Sassoon, & Fan, 2011). Wireless may offer the most convenient solution for charging zero

emission vehicles but the infrastructure and standards required will take considerable time to develop and implement. Home wireless charging may become readily available in the next fifteen years but public wireless charging will take longer to develop and implement.

Based on convenience, cost, and availability consumers will source transportation electricity primarily at home and work. In some instances energy will be sourced public sources may include wireless and corded options. Public stationary sourcing may be supported by alternate business models, one interviewee suggested public charging at retail firms may become a source of differentiation. A “wireless highway” would require significant infrastructure investment and standards adoption. The time and investment required will set off a comparison between hydrogen and the “wireless highway”.

* * * *

The summary and conclusions presented in Chapter Four are disappointing. Both interviews and literature sources suggest transportation sector emissions are a threat to environmental stability. However, significant zero emission vehicle adoption is not expected in the next fifteen years. U.S. CAFE standards, as well as, emission standards in other developed countries are expected to improve new vehicle fuel efficiency. In China, local pollution problems may inspire zero emission vehicle adoption (passenger vehicles, scooters, and electric bicycles). But, these incremental improvements are not expected to mitigate the increase in GHG emissions from population growth and industrialization.

The current rate we are mitigating GHG emissions is too slow. Chapter Five will present suggestions and ideas to increase the rate of GHG emission mitigation. Several of the topics are existing ideas which have market presence, others are conceptual, and one is novel. Chapter Five will conclude with a short list of “future research” topics, representing gaps in knowledge or knowledge aggregation.

Chapter 5 Future Trends

This thesis started with a narrative of the transition from horses to automobiles in the early 1900s. After 100 years of growth, the world is faced with traffic congestion, pollution, global climate change, and energy security challenges. These are large, complex, interconnected problems that do not have known solutions.

This chapter will focus on concepts that may be part of a solution. Several of these concepts were mentioned by those interviewed, others are drawn from my own reflections on what I have learned through research and writing this thesis.

- First, we need to focus on existing technology. Utilizing existing technology can bring change to the market sooner.
- Second, we need to retire older technology. The global automobile fleet is expected to reach two billion cars by 2020 (Sperling & Gordon, 2009), the composition of this fleet is changed by new vehicles entering the fleet and older vehicles leaving the fleet.
- Third, common components across vehicle models and manufactures are needed and may decrease development time. Modular design could shorten the time-to-market for new vehicle technology.
- Finally, firms must continue working to reduce design cycle time. “Competition driven development” has the potential to dramatically reduce design cycle time thru leveraged investment and an increased number of contributors.

As evidenced by world GHG increase in the past decade and supported by the interviews, GHG emission mitigation technologies are not being adopted fast enough to prevent future

environmental concerns. Multiple solutions are needed to improve the existing vehicle fleet technology and accelerate innovation of new vehicle technology.

Utilize existing technology and infrastructure

Much of the literature and interview content focused technology advances. As discussed in Chapter One, new technologies take thirty to fifty years to make a significant impact on GHG emissions (MIT Laboratory for Energy and the Environment, 2005). The automobile industry's slow clockspeed makes solutions that utilize and develop existing technology attractive. Tesla Motors is an excellent illustration of this point. Tesla did not invent new BEV technology. Utilizing existing technology, within a single vehicle development cycle, Tesla demonstrated that existing technology could produce a high performance, long range BEV. The demonstration was compelling enough to evoke a response from General Motors. In the 2009 Los Angeles auto show keynote speech, Bob Lutz, GM Vice Chairman of Global Product Development, thanked Tesla Motors for "proving electric cars are viable". (Aziz, 2009). Utilizing existing BEV technology may increase the industry clockspeed and deliver value to the market sooner.

Utilization of existing infrastructure could increase zero emission vehicle adoption. Drivers demand convenient energy access, consequently, infrastructure expectations are adoption barriers. In fleet vehicle market segments, electricity infrastructure often already exists. Urban commercial vehicle travel routes start and finish from a single location, this central location usually has the necessary electricity infrastructure to support BEV charging stations. Home and work charging also utilize existing infrastructure. Business models that leverage existing infrastructure improve the "value proposition" and may increase zero emission vehicle adoption.

Retire older technology

The average age of the global vehicle fleet will is directly related to “GHG emissions per mile traveled”. Older vehicles tend to emit more GHGs per mile. Newer vehicles, utilizing state-of-the-art, technology emit fewer GHGs per mile. When older vehicles are retired and replaced with newer, lower emission, vehicles the aggregate GHG emissions per mile traveled decreases. One of the challenges with this concept is motivating consumers to retire older technology vehicles.

In June 2009, the CARS (commonly known as cash for clunkers) economic stimulus program was introduced to inspire new vehicle sales (Romer & Carroll, 2010). This program had the secondary effect of reducing GHG emissions. Using back of the envelope calculations, MIT Professor Christopher Knittel estimates the implied cost these GHG reductions were ten times the Congressional Budget Office estimates of the Waxman-Markey cap and trade program \$28 per ton estimates (Knittel, 2009). Designed as a stimulus program during the global financial crisis, CARS was not an economically efficient GHG reduction program. It does, however, provide valuable baseline data to analyze the financial and environmental impact of vehicle retirement programs.

Modular design

Due to size and complexity, changes to the automobile industry take significant time. MIT Professor Charles Fine defines the industry rate of evolution as “clockspeed”. Professor Fine’s research concludes the automobile industry “organizational clockspeed” as four to five times slower than the computer industry (Fine, 1998).

In his book *Clockspeed*, published in 1998, Professor Fine defines the concept of the “business double helix”. This concept illuminates how industry forces cycle firms between vertical/integrated and horizontal/modular structures (Fine, 1998). The high clockspeed computer industry is one of the best known examples of the business double helix cycle. Starting with a vertical/integrated structure, the computer industry evolved to a horizontal industry structure with modular product architecture during the 1980s and 1990s. Apple’s strength and the market penetration of portable computing would suggest aspects of the computer industry are returning to the vertical/integrated structure. In the computer industry, accelerated consumer adoption occurred with immature technology and modular product architecture.

As presented in Chapter 2, the automobile industry is vertical and the product architecture is integral. Professor Fine presents three forces of disintegration which push toward horizontal and modular configuration (Fine, 1998). Today, the three forces of disintegration are evident in the low and zero emission automobile market segments:

1. “The relentless entry of niche competitors hoping to pick off discrete industry segments”
(p. 48)

The Renault-Nissan alliance is committed to the BEV market segment. It is targeting niche markets all over the world where the BEV value proposition is strong. Firms like Tesla and Fisker are attacking the high end BEV markets, existing and startup firms are targeting fleet market segments.

2. “The challenge of keeping ahead of the competition across the many dimensions of technology and markets required by an integral system” (p. 48)

Large automobile manufactures face significant challenges identifying which technologies and suppliers will emerge as the industry leaders. Battery technology is perhaps the best example. Competing technologies are emerging from across the globe. To identify and integrating superior technology is a massive task. An incorrect assessment could significantly damage a firms’ competitive position.

3. “The bureaucratic and organization rigidities that often settle upon large, established companies” (p. 49)

Five of the twenty five largest companies in the world are automobile manufactures. In 2011, fourteen automobile manufactures were listed on the Global 500 list. The annual revenue for these fourteen firms totaled \$1.4 trillion dollars (CNN Money, 2012). All global automobile manufactures face organization rigidities and bureaucracy.

All three forces of disintegration are apparent in the automobile industry today. Adopting a horizontal/modular structure may accelerate the development of zero emission vehicles. Increased development is expected to improve the value proposition and, ultimately, increase adoption.

Competition driven development

Competition driven development has the potential to accelerate zero emission vehicle development, decrease the technology risk to automobile manufactures, and increase zero emission vehicle consumer awareness and appeal. In simple terms, competition driven development has the potential for faster innovation with lower risk. It may also increase consumer demand.

In practice, different definitions are used to describe the innovation process. For this section standard dictionary definitions will be used (Encarta®, 2007).

- Innovation: The act or process of inventing or introducing something new
- Invention: The creation of something new
- Development: The process of changing and becoming larger, stronger, or more impressive, successful, or advanced, or of causing somebody or something to change in this way
- Research: Methodical investigation into a subject in order to discover facts, to establish or revise a theory, or to develop a plan of action based on the facts discovered
- Prototype: A first full-size functional model to be manufactured, e.g. of a car or a machine
- Testing: To try something out, e.g. by touching, operating, or experiencing it, in order to find out what it is like, how well it works, or what it feels like
- Design: Make a detailed plan of the form or structure of something, emphasizing features such as its appearance, convenience, and efficient functioning
- Production: The process of manufacturing a product for sale

As illustrated in the figure below, an innovation process starts with invention and ends with production. Development follows invention and spans four phases. An invention is researched then a prototype is made and tested. Finally, a consumer product is designed. This development process is cyclical and iterative. For example, five prototypes may be built and tested before the final design phase is initiated. Consumer adoption begins at after production starts.

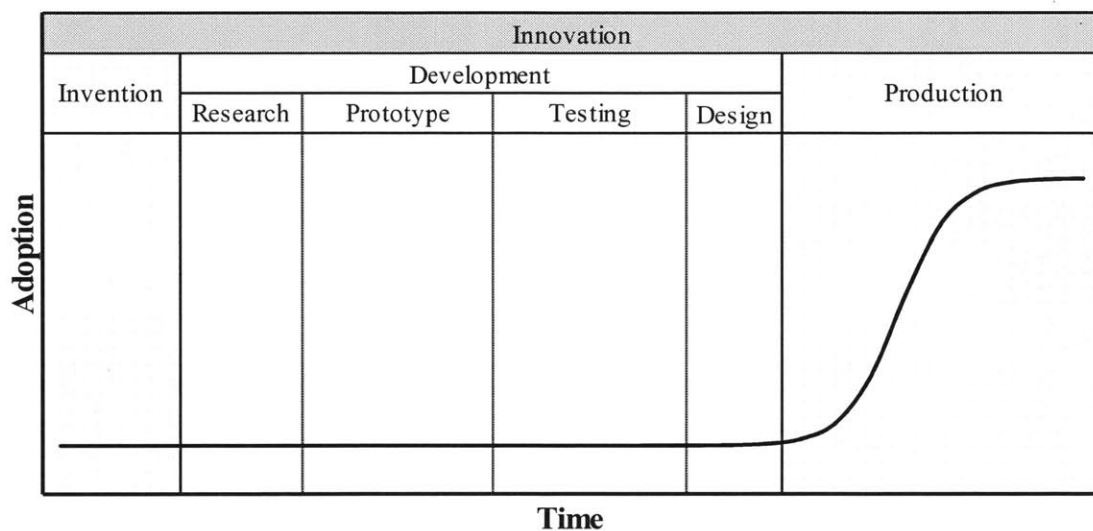


Figure 13: Innovation and market adoption process

Competition driven development focusses on building and testing prototypes. Multiple teams, referred to as “solvers” in prize literature, develop prototypes at regular intervals then compete to determine the best prototype. The net effect of repeated competitions is faster prototype and testing phases which decreases the time between invention and production. With less time in development, innovative products reach the market sooner.

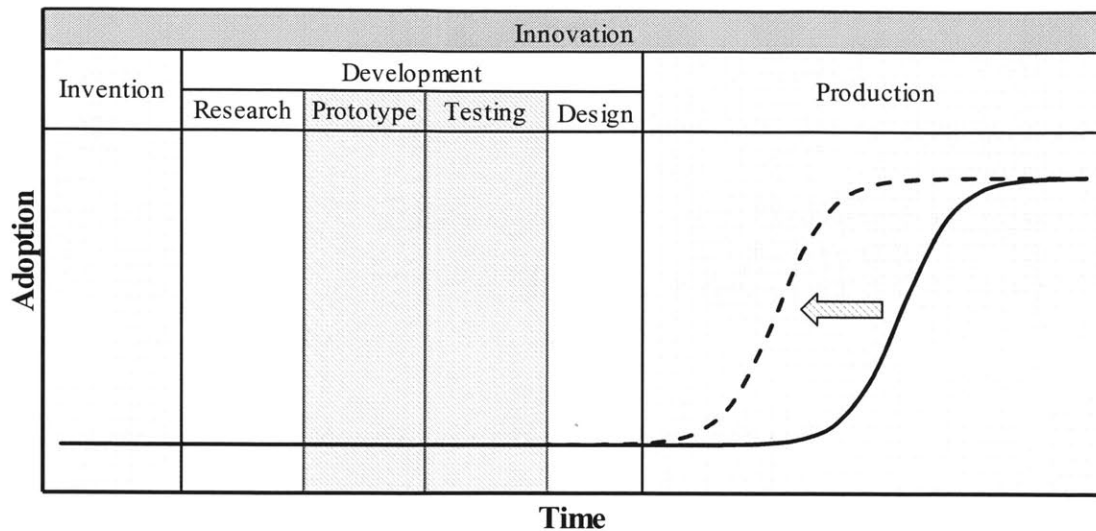


Figure 14: Innovation and market adoption with “competition driven development”

Competition driven development is not a new concept. The first American automobile race, held November 28, 1895 in Chicago, IL (The Library of Congress, 2012), allowed vehicles using gasoline, steam, or electricity. Final awards were based on general utility, speed, cost, economy, general appearance, and excellence of design (Anderson, 1954). A quarter century before the internal combustion engine became the dominate technology, competition between technologies was accelerating development and educating consumers. Perhaps more interesting, the nature of early competitions favored liquid fuel, the first American race was fifty four miles and the first Indianapolis 500 in 1911 was 500 miles. In the days leading up to the first American Race, competitors using electric vehicles emphasized they did not expect to finish “the race but, merely wished to prove that their machines were practicable for “normal” distance driving” (Anderson, 1954).

Faster innovation

Three sources of faster innovation are apparent in competition driven development. First, the innovation advantages of collaboration, convergence, inspiration, and refined goals. Second, the development shifts from series to parallel. Third, sponsorship leverage increases the available development resources.

In a February 2012 TED talk X Prize founder Peter Diamandis reflected on his X Prize experience, “Small teams driven by their passions with a clear focus can do extraordinary things. Things that large corporations and governments could only do in the past” (Diamandis, 2012). I agree with this statement and would add, small groups in repeated competitions offer distinct innovation advantages. Collaboration, convergence, inspiration, and refined goals are natural byproducts of repeated competitions.

Collaboration may be direct and indirect. An example of direct collaboration is two weaker competitors combining efforts to defeat a stronger competitor. Competitors may also choose to collaborate on operational items not critical to competition metrics.

Collaboration may also be indirect or inadvertent. Since the competition is repeated, competitors tend to build social networks with other competitors. These networks are conduits for indirect collaboration.

Teams make significant effort to study and observe their competition. If a particular solution or portion of a solution is superior, competitors will converge. After convergence, a larger effort is focused on the next iteration. This opportunity to learn

and converge on the “best” solutions does not exist when teams are isolated or the competition is not repeated.

Competitors know replicating the competition will only make them as good as their competitors, development is necessary to achieve the next competitive advantage. This “competitive inspiration” drives teams to improve. Both extrinsic and intrinsic motivations continuously push competitors to develop better solutions for the next competition.

Repeated competitions encourage competitors to refine goals. There is only one winner, all the other competitors must determine what changes are necessary to improve. The winner is also forced to refine their goals, without improvement the winning status will be lost. Winners know, or soon learn, that competitive advantage is temporary. These competitive pressures force teams to regularly evolve their strategic objectives.

These characteristics, of repeated competitions, increase the speed of innovation. By aligning the competition objectives with the market objectives, competition driven development can increase the speed of product innovation.

Entertainment based competitions attract competitors and sponsors. In repeated competitions, competitors operate in a collaborative-parallel structure. Competitors work in parallel isolation to advance their prototype then, during competition, they directly and indirectly collaborate. Faster innovation is achieved by both parallel development and

multiple competitors. Sponsorship is a key element of innovation advantage. Sponsors invest in competition for marketing and advertising benefit. Since competitive success increases marketing and advertising benefits (sponsor value), the technology development to support competition is funded by sponsorship. However, in most cases this sponsorship investment only yields advertising and marketing value. The technology developed is not relevant to most sponsors' core business. By aligning competition and market technology objectives, sponsorship will contribute to advancing market relevant technology.

Decrease risk

Competition can reduce both uncertainty and asymmetric information risks. It is difficult to predict if, or when, an emerging technology will satisfy market needs. Sourcing technology always carries asymmetric information risk. Multiple competitors, repeated competitions, clear success metrics, and transparent officiating reduce both risks. The risk reduction is not automatic, the regulations must be carefully designed to insure market needs are aligned with the competition objectives, the metrics accurately quantify objectives, and the competition is sufficiently transparent to minimize asymmetric information. Successfully executed, competitions can reduce new technology risks.

Higher awareness and appeal

Entertainment based competitions attract corporate sponsors. These sponsorships are based on awareness, appeal, and brand marketing benefits. The same channels can increase awareness and appeal of new technology. But, the awareness and appeal benefits of repeated competitions go beyond traditional advertising and marketing metrics, during competition a story is created. This story is communicated by the event

announcers, the television broadcasts, as well as, internet and print media outlets. Consequently, entertainment based competitions multiply exposure. The educational effect of storytelling and the entertainment based exposure can inspire consumer demand.

* * * *

Although, significant zero emission vehicle adoption is not expected in the next fifteen years four concepts were presented to increase the zero emission vehicle adoption. Utilizing existing technology, retiring older technology, and shifting to modular vehicle architecture may accelerate zero emission vehicle development. Ultimately, faster development leads to a better value proposition which is needed to inspire adoption.

Competition driven development has the potential for faster innovation with lower risk and increase consumer demand. Famed Indy driver and car builder Dan Gurney offers an analogy. "Racing is like warfare, it accelerates the evolution of ideas" (Popular Mechanics, 2011).

Future Research

The literature review, interview, and writing processes have identified three topics for future research. First, considering the global fleet size and transportation adoption rates, what level of vehicle GHG emissions are necessary to stabilize the transportation sector environmental impact? Second, could a modular vehicle architecture and horizontal industry structure improve the consumer value proposition of zero emission vehicles? Third, what are the key alignment factors for completion driven development to successfully accelerate product innovation?

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