Impacts of Passenger Vehicle Fuel Economy on a Global Scale

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Internal combustion engines (ICEs) have been the primary power source for transportation, heavy equipment, and many other applications for over a century. Despite widespread use and their many benefits, ICEs are also responsible for significant environmental damage. Particularly in terms of global warming. This paper aims to answer the question, "What steps can be taken to improve the fuel economy of current and future ICE powered passenger vehicles as well as reduce their overall environmental footprint?" In order to answer this question an engineering design matrix will be used in order to evaluate potential solutions and rank them. Their ranks will be based around multiple weighted categories such as ease of implementation, government involvement, or its potential as an equitable solution. Utilitarian Ethics is a framework generally based around the concept of "greatest good for the greatest number". In order to fairly address this issue, which has broad impacts on our society as a whole, Utilitarian Ethics was chosen as a lens for this papers analysis of how cleaner passenger vehicle technologies can be encouraged more equitably.

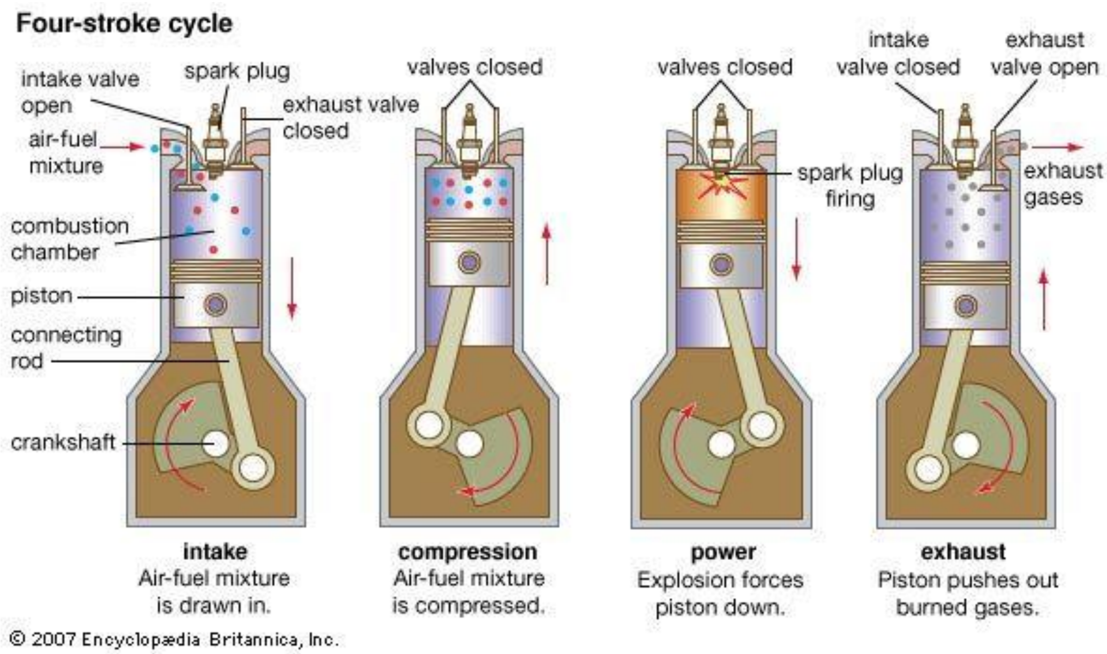
Background

To begin, an internal combustion engine is one where the fuel and air are mixed within the cylinder/s of the engine and then ignited (Proctor, 2022). The most common form is the piston engine, which is what is in the vast majority of automobiles today. The piston engine was developed off of a series of inventions, the earliest of which being the rotary crank mechanism found in saw mills connected to a water wheel in the Byzantine empire around 500 AD (Cook, 2016).

The first mainstream reciprocating engines were steam engines, which were replaced by both diesel and petrol engines for reliability and efficiency reasons (Peterson, 2014). A modern internal combustion engine works via the combustion cycle, which consists of four stages; intake, compression, combustion, and exhaust.

Figure 1

Combustion Cycle



The cycle is controlled with a reciprocating camshaft which is linked to the crankshaft in order to ensure proper engine timing. This camshaft controls the intake and exhaust valves that govern the combustion cycle. During the intake stage, air is pulled into the combustion chamber and a fuel injector fires, spraying fuel into the airstream just before it enters the chamber allowing it to swirl and mix more fully. The valves then slam shut as the piston begins to compress the mixture. The piston then approaches top dead center (TDC) and the spark plug fires igniting the compressed, fuel air mixture which causes it to detonate within the cylinder. This detonation forces the head of the piston down, turning the crankshaft which can then be used as a source of power (Cook, 2016).

Thermal efficiency is defined as the relationship between total energy contained within the fuel and the amount of energy generated by the engine (Bagolione, 2007). Reciprocating steam engines were only around 1-10% efficient, and while ICEs were a substantial improvement with modern ICEs being capable of nearly 50% thermal efficiency, modern passenger vehicles are only capable of achieving around 20-35% thermal efficiency (Proctor, 2022). This is because a vast majority of the fuel's energy is lost to radiant heat, friction, and other systems necessary to keep the engine running such as the cooling system or oil system.

Research Topic's Environmental Significance

The impacts of global warming, including rising sea levels, more frequent and severe weather events, and changes in ecosystems are already being felt around the world. Global warming is the long-term increase in the Earth's average surface temperature, primarily caused by greenhouse gas emissions, which trap heat from the sun much like a greenhouse (EPA, 2023). This gradual increase in global temperatures results in polar ice caps thawing which not only causes habitat loss for arctic creatures, but also results in higher sea levels which can mean flooding in coastal areas is more frequent (WHO, 2021). Similarly, global warming can have drastic impacts on atmospheric and oceanic circulation patterns which in more frequent storms (NASA, 2022). Particularly, global warming disrupts the jet stream, a high-altitude band of winds which guides global weather systems. This can result in prolonged heat waves, droughts, and heavy rainfall events, essentially making the weather severe and rapidly changing.

Pollution can have harmful effects on human health, ecosystems, and our natural environment. Pollution refers to the release of harmful substances or contaminants into the air, water, or soil, typically as a result of human activities. Air pollution can cause respiratory diseases and other health problems, particularly in urban areas where concentrations of pollutants can be high (Kioumourtzoglou, 2016). Similarly, water pollution can cause illnesses in humans and damage the extremely important ecosystems. A clear example of this is the Deepwater Horizon oil spill, which was considered to be the largest marine oil spill in the history of the petroleum industry. It was estimated that 210 million gallons of oil were discharged into the Gulf of Mexico. Reports came after that nearly 50% of shrimp and other fish were mutated or malformed, which unfortunately caused cascading issues throughout the ecosystem as these fish are consumed by larger animals. BP eventually plead guilty to 11 counts of manslaughter along with numerous negligence and environmental damage charges, which resulted in them paying well over 65 billion dollars in fines (EPA, 2022).

The reason these environmental events are important is because they are both heavily linked to the auto industry. CO2 and carbon monoxide are both considered greenhouse gases and passenger vehicles accounted for 41% of all carbon dioxide emissions generated in 2020. This of course means passenger vehicles play a key role in the fight against global warming. Roughly 50% of a typical barrel of crude oil is refined into gasoline, with another 30% being refined into diesel fuel (Wisconsin, 2020). ICE powered vehicles are the largest consumers of gasoline, meaning that passenger vehicle technology can be indirectly linked to the deepwater horizon incident. If there were less demand for oil, it is unlikely that the spill would've occurred. This is all to say that ICEs and particularly their role in passenger vehicles are a critical factor in many of the major environmental issues we face today.

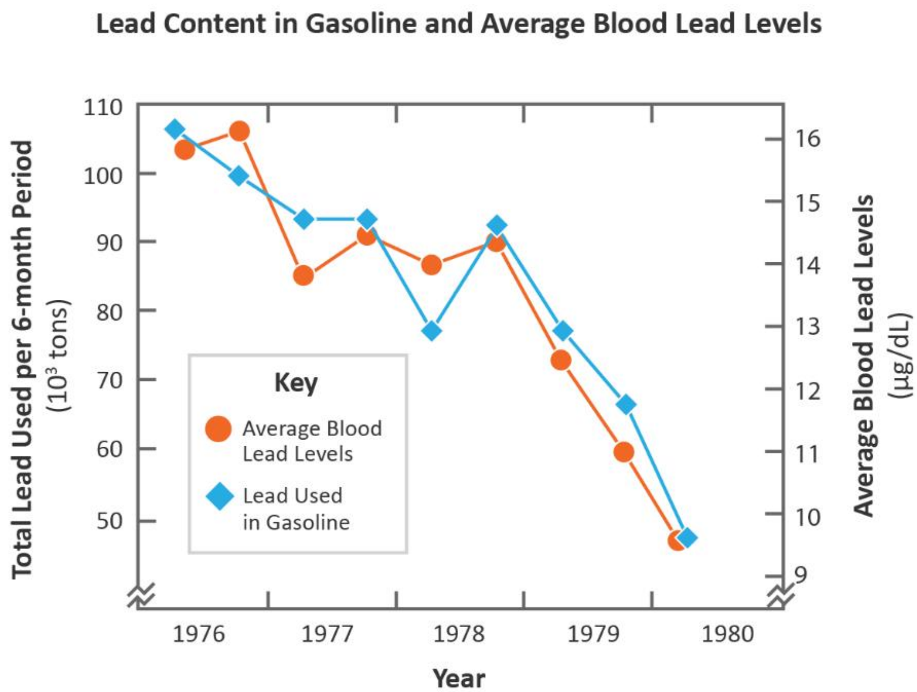
Successes in Pollution Reduction

There have been a few key examples of strategies and technologies implemented into the automotive industry which have been widely regarded as successes in reducing automobile's environmental impact. These will be discussed in order to gain insight into which features of the technology, or regulation made them viable for application in the industry.

The first change to cover is the phasing out of leaded gasoline. Leaded gasoline was invented in 1921 by Thomas Midgley. The purpose of his fuel additive was to help stabilize the combustion process as well as improve overall fuel economy. Tetraethyllead, the compound added to gasoline to make leaded gasoline, acts as an octane booster, which allows engine compression to be raised significantly (Edelstein, 2021). Higher engine compression increases the overall efficiency of the engine, allowing it to use less fuel. When the fuel was burnt, the lead in the gasoline spread into the air causing substantial damage, particularly in cities. Lead is one of the most well-known neurotoxins, due in part to its impacts to the environment as a fuel additive (Edelstein, 2021). However, lead poisoning has many other important effects such as intellectual disability, memory problems, seizures, comas, and infertility to name a few. In a study conducted by Aaron Reuben and colleagues, it was found that more than half of the US population had clinically concerning levels of lead in their blood as children, resulting in a wide variety of health effects, one of the most staggering being that its responsible for the loss of well over 800 million IQ points in the children born and raised during the era of leaded gasoline.

Figure 2

Leaded Gasoline's impact on American Blood lead levels.



The EPA was formed with the Clean Air Act in 1970. This act required a 90 percent reduction in emissions from new automobiles by 1975 (EPA, 2023). This seems to have set a standard in emissions regulations. Rather than requiring certain technologies be implemented, such as the use of unleaded gasoline, the EPA regulates the emissions output of the cars. As far as the regulations are concerned, as long as the emissions are reduced to the standard they deem acceptable, they do not care what path the auto industry takes to get there. Leaded gasoline was the standard for fifty-four years before the EPA decided to phase it out in 1975 (EPA, 2022). It was not phased out for the numerous health effects described earlier, but rather because leaded gasoline was prone to clogging catalytic converters, a technology which will be discussed later. What's concerning with these styles of regulations is that leaded gas was still being sold in the United States until 1996, when it was finally banned outright. Despite knowing the dangers of leaded gasoline for at least 20 years, the EPA was unable or otherwise unwilling to outright ban it, allowing it to do untold damage to American citizens (Edelstein, 2021). To be fair to the newly formed EPA's efforts, there were extreme lobbying efforts and fear tactics used by the automotive and oil industry in order to prevent the phasing out of leaded gasoline (Melosi, 2010). Which is likely why their preferred method rather than outright banning a technology or hazard is to phase it out. It's much easier to slowly reduce the amount of leaded gasoline being sold and encourage other technologies rather than put a halt on it right away with no other solutions being proposed. Phased in regulations have been largely successful, but slow, in achieving the goals of the EPA.

Regulating to Innovate

Another method used to reduce tailpipe emissions was simply to require it. As astounding as that sounds strict regulations, particularly on carbon monoxide and nitrogen oxide emissions, led to the widespread adoption of the catalytic converter (Palucka, 2023). A catalytic converter takes harmful emissions such as carbon monoxide or unburned hydrocarbons and converts them into a less harmful emission like carbon dioxide in the case of a two-way catalytic converter. One of the major downsides however, was that they require the use of unleaded fuel as lead would quickly destroy the converter as mentioned previously (EPA, 2022). The EPAs regulations were so strict that they essentially mandated the use of catalytic converters in new vehicles in order to meet emissions standards, which had the byproduct of discouraging the sale of leaded gasoline. Since 1975, nearly every passenger vehicle sold in the US has come with a catalytic converter installed in order to meet rising emissions standards. Another benefit to catalytic converters as a technology was their relatively small impact on the performance of the vehicles. While early models did have small impacts on peak horsepower numbers, overall there are very minor drawbacks to the addition of a catalytic converter to a car (Melosi, 2010). This made their near requirement in all new cars sold in the US a much easier pill for the public and for automakers to swallow. However, even with this, automakers were given five years of notice before regulations actually came into effect in 1975 making progress still somewhat slow.

Similarly, exhaust gas recirculation (EGR) valves were developed in order to meet rising emissions standards in 1972. EGR valves were developed to specifically reduce nitrogen oxide emissions. The technology works by redirecting some of the engines exhaust gases back through the intake tract. This reduces the amount of oxygen available in the combustion chamber which in turn reduces peak cylinder temperature (Baglione, 2007). Nitrogen oxide is primarily produced by high temperature mixtures of nitrogen and oxygen, and so by reducing cylinder charge temperature nitrogen oxide production is limited. Exhaust gas recirculation can also be useful for improving fuel economy, which it does by reducing the loss of thermal energy within the combustion chamber surface, while also reducing throttle losses. While not specifically required by the EPA, EGR valves, like catalytic converters were essentially required in order to meet the emissions standards set by the EPA (EPA, 2023). Another example of regulating to innovate as an emissions reduction strategy.

Direct Regulatory Action

California lawmaking takes a much more direct route than the EPA. California is well known for having the first required vehicle emissions controls device, which was the positive crankcase ventilation system or PCV. A PCV addresses an issue with internal combustion engines. As they operate they create “blowby” which is positive pressure escaping past the piston and typically into the oil pan or engine body where it’s not supposed to be. This pressure either builds up until it causes some seal to fail and releases into the atmosphere, or more sophisticated automakers would install a tube venting these gases directly out of the engine's body and into the atmosphere in order to prevent any seals from failing. PCV systems redirect these blowby gases back into the intake stream where they can be recirculated and more completely combusted (Gardner, 2023).

The adoption of these systems is particularly important because with the EPA's style of regulation it would have been nearly impossible to force their use in new passenger vehicles. At the time, the EPA primarily measured tailpipe emissions from the vehicles, detecting blowby emissions leaking out from nearly anywhere on the engine block itself would've been quite difficult to measure and enforce with their methods. As mentioned previously, the EPA preferred to set a standard for automakers to meet, but with no way of measuring these blowby gases, it is not possible to set a standard. To solve this, California simply required the use of the technology in all cars sold in the state of California (Cook, 2016). While direct and to the point there was also the effect that automakers installed this technology on all their production cars rather than make changes so individual cars would be legal in California. While this can be a good thing, it also means that the state with the strictest laws tends to set the standard for the rest of the United States, particularly when that state has as large of a consumer base as California. As a result of this national environmental laws are actually somewhat lackluster and instead just focus on overall pollution reduction goals such as a reduction of 10% overall in x number of years (EPA, 2022). Most other federal laws to keep up with pollution control are based around preventing the removal and tampering with emissions controls systems (EPA, 2022). This simplifies things because emissions laws do not have to go through a national level allowing quicker development of environmental regulation by proxy through California. However, this also means that a substantial number of automotive emissions laws are still optional to manufacturers should they decide that its simply not worth it anymore to sell in the state of California, or if California has any major reversal on regulations, overhaul, state collapse, etc, there are very few if any national laws requiring specific technologies be implemented on passenger vehicles.

Incentivization of Greener Technologies

The final emission control strategy to cover from the government is the incentivization of cleaner technologies. Rather than outright banning old technologies, or mandating the use of a specific new technology, the government uses rebates in order to encourage consumers and auto manufacturers to adopt new technologies which are better for the environment. An excellent example of this was the use of tax credits to help spur the development of hybrid electric vehicles as well as other efficient fuel sources such as diesel and natural gas. The U.S Energy Policy Act of 2005 established a tax credit of up to 3,400 dollars towards the purchase of new hybrid vehicles. These credits were only available for the first 60,000 models sold per auto manufacturer in order to encourage development. This was used in order to offset the high costs associated with hybrid electric vehicles. In essence a hybrid electric vehicle is still a regular passenger vehicle car but with an entire electrical powertrain system added on, which of course increases the cost at the consumer for these vehicles. This credit made more expensive, but more environmentally friendly, vehicles more attainable to the public. One of the downsides to this is that only those who are purchasing new vehicles are eligible for this tax credit. This means that higher income households who are more likely to purchase a new car are more likely to benefit from these tax credits resulting in an inequitable distribution of taxpayer money.

The Current Passenger Vehicle Landscape

In order to make an assessment on what the best method for reducing passenger vehicle emissions would be, first the current landscape of the automobile industry must be taken into account in order to tailor the solution to the current environment. The average age of cars on the road in the U.S in 2021 was 12.1 years, and is projected to continue to increase (Hedges, 2022). This means that Americans are holding onto cars longer than ever, which may make emission controls efforts at the vehicle sale side slow down. Instead, regulatory action, or incentivization for new technologies to be implemented into old vehicles may be more suited to the changing car market.

These efforts could have a more direct impact, allowing legislation to make changes more quickly. Many technologies like the aforementioned EGR, and PCV systems can be fairly easily adapted into older cars provided there is incentive to do so. This can even be taken further with more expensive and advanced technologies such as hybrid powertrains which improve fuel economy. This helps the consumer and the general public by having them money on fuel, and reducing the amount of fuel burned when using the car.

Strategies for Improved Sustainability

Through the analysis conducted through this paper, a few key strategies for reducing passenger vehicle emissions can be identified. Overarchingly they are;

- Incentivization of new technologies on new vehicles sold
- Immediate regulatory action on new vehicles sold
- Phased in emissions standards on new vehicles sold
- Incentivization of new technologies on existing passenger vehicles

These strategies will be evaluated through the use of an Engineering design matrix, with categories chosen and weighted based on utilitarian ethics.

Research Methodology

Categories will be given a score of 1-5 in order to rank each solution. Totals will be tallied at the end with different weights given to different categories based upon the STS framework used to analyze the solutions. Categories will be given a positive or negative score depending on if a high value is correlated with a good result or a bad result. Categories used to score the different solutions are as follows:

- Cost (-)
  - Cost to both the taxpayer and the consumer
- Level of Government Oversight (-)
  - Degree to which government involvement is necessary, regulatory action is the government forcing a change and would have a high score in this category
- Ease of implementation (+)
  - Difficulty in passing regulation or getting the solution started
- Equity (+)
  - Equality of solution, making sure that people of all income, race, gender, etc are all fairly impacted by the solution
- Environmental impact (+)
  - Degree of importance of the regulation to preventing environmental damage. Solutions which reduce few tailpipe emissions score low in this category.
- Speed of environmental impact (+)
  - How quickly the solution can be implemented, as well as how quickly it will make a difference to the environment.

Using Utilitarian ethics as a lens to analyze these solutions, a weighting of 1.5 will be given to Equity as well as Environmental impact. These categories are the most important for the greatest good for the most people, and should help weight the results in order to ensure the STS framework was followed within this analysis.

Results

Figure 3

Cost Benefit analysis using Utilitarian Ethics as a framework

	Incentivization of New Tech for New Vehicles	**Incentivization of New tech for Old vehicles**	**Phased in Emissions Standards**	**Immediate Regulatory Action**
Cost (-)	3	4	1	2
Level of Government Oversight (-)	2	2	1	4
Ease of Implementation (+)	4	3	5	1
Equity (+)	1	5	2	2
Environmental Impact (+)	4	4	3	3
Speed of Environmental Impact (+)	2	5	1	5
Weighted Total	8.5	15.5	11.5	7.5

These weighted results show that far and away the best solution using these categories as a scale is Incentivization of new technology to be implemented into old existing vehicles. This allows all people with cars a fair opportunity to receive improvements to their vehicles to reduce emissions and potentially improve fuel economy. Similarly, a tax credit or other similar incentive for installing emissions control systems on existing vehicles would have results substantially faster than waiting for the systems to trickle down through the market over time as the EPA has done in the past. It can be seen that immediate regulatory action is one of the least successful solutions available for solving this problem, however it is by far one of the fastest solutions allowing for rapid changes to be made should it become necessary.

Discussion

From the results above it can be found that the most equitable solution is the incentivization of the installation of new technologies on old passenger vehicles. Incentivizing rather than penalizing has the benefit of avoiding unfairly punishing lower income households who may not have had opportunities to pursue more environmentally friendly options when picking or using their passenger vehicle. Similarly, while nearly all of these solutions use taxpayer money in order to help reduce tailpipe emissions, this solution allows these monies to be distributed more evenly. With average new car prices getting to nearly 40,000 dollars it's clear to see how low income households would be virtually unaffected by tax breaks and incentives that go towards purchasing a brand new vehicle (Fischer, 2022). This of course means that tax credits given out to incentivize the use of cleaner vehicles primarily went to wealthier households.

Furthermore, the environmental impact of such a solution was found to be substantially higher as while only 2.86 million new cars are sold each year in the U.S, there are currently over 282 million passenger vehicles on the road in the United States as of 2021 (Tiseo, 2023). Legislation efforts targeting vehicles still in use would result in an impact on nearly 100 times as many cars as regulations imposed just on new vehicles sold. While the environmental impact is obviously important as a global concern with global warming, it is also an ethical concern as many global environmental disasters and effects disproportionately effect poorer at-risk communities (Failey, 2016).

A tax credit encouraging the installation of emissions controls devices on existing passenger vehicles however would likely cost a substantial amount due to the scale of vehicles impacted. However, many technologies that would be implemented have already been developed through emissions standards pushed by the EPA. This means that the innovation has already taken place, all that needs to happen is for these newer technologies to be installed on older vehicles, reducing cost substantially. The taxpayer would only be paying for the parts themselves and the installation, not the research and development costs.

Notably, other solutions such as immediate regulatory action were unfit for use, and is likely why this strategy is not used often in policymaking. This type of legislation results in far too much government control over the emissions development and reduces the potential for innovation within emissions control. Similarly, rapid regulatory actions are often passed directly onto the consumer rather than the auto manufacturer (Melosi, 2010). Making this solution less equitable and less applicable as a solution under the aforementioned STS framework.

Conclusion

In conclusion it was found that the best solution for reducing the tailpipe emissions of passenger vehicles was to encourage the installation of new environmentally friendly technologies onto existing passenger vehicles. This allows for more equitable distribution of environmental damage control resources, as well as more rapid implementation into the passenger vehicle landscape as the average age of passenger vehicles continues to grow in the United States. This question was answered using a Utilitarian ethics framework, giving additional weight to solutions which result in the greatest good for the largest number of people.

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