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Chapter One

Introduction

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The hydrogen fuel cell has received extensive attention in the scientific community and the public at large since about 1990. The first experimental fuel cell was developed in the nineteenth century, and a 6 kW alkaline fuel cell in conjunction with a battery bank was used to power a small car as early as 1966, but it would not be until major improvements in power density were made in the 1990's that major car companies took serious interest in fuel cells.[1] Although the technology is currently quite expensive, fuel cells offer significant benefits including high overall efficiency, quiet operation due to few moving parts, and good efficiency over a wide range of operating points. Predicted cost reductions mean that in the near future, fuel cells could power everything from homes to vehicles to cell phones.

Although extensive research has been done into fuel cells for stationary power and for automobiles, and some research has been done for portable power applications like soldier power and devices like telephones and computers, virtually no work has been done in the field of small vehicles requiring under 10 kW of power.[2] This is an interesting option for small vehicles because the market – and governments – are beginning to put a high value on options offering low or zero emissions. Moreover, the challenge of putting fuel cells in scooters is an interesting technical problem because, due to weight and cost restrictions, power systems in these vehicles cannot be as complex as those found in cars. Yet, there is a high value on clean power. Subsystems like air compressors, reformers, and hydrogen storage tanks are all reduced in size and complexity, so production is made easier. On the other hand, efficiencies do not remain constant at small size so performance in this type of application will be poorer than in automobile fuel cell power systems.

The purpose of this study is to examine a particular application of fuel cell technology: the electric scooter. Scooters are small two-wheeled vehicles that can carry one or two people. They are unlike motorcycles in that they are ridden in a seated position with feet forward on a platform. Although in North America they are most associated with 1950's Vespas and the mod scene of later decades, these small and cheap vehicles remain a major mode of transportation in Asia and Europe today.

(Note that the distinction between "scooters" and "motorcycles" is not always made in the literature, especially by Asian researchers. Here it is assumed that "motorcycles" refers to scooters; this assumption is almost certain when it comes to vehicles less than 50 cc in displacement.)

Figure 1.1 A Scooter

Honda CUV-ES electric scooter[3]

Due to their small size and low price point, scooters have traditionally been powered by high power density two-stroke internal combustion engines, (although some of the larger models use four-stroke engines). Two-stroke engines produce a great deal of pollution and are an object of concern in many Asian countries.

Severe pollution from two-stroke engines is a significant driver for cleaner technology. Thus, the target market for this study is the Asian urban commuter, since scooter use is so heavy in many Asian cities, and air pollution is a major problem in the crowded cities of the Far East. Specifically, Taiwan (i.e. the Republic of China) is a prime example, with twenty million people sharing an area the size of Vancouver Island with ten million scooters. Compared to the battery-powered scooters currently being promoted by the Taiwan government, fuel cell engines offer the advantages of extended range and quick refueling.

Some countries in Europe, like Italy, also have extensive scooter populations and might also be able to afford expensive new technology more readily. Poorer countries like China and India are facing dramatic growth rates in two-stroke vehicle population as rickshaws and bicycles are being replaced, and low-powered but clean scooters would be a major step in providing mobility without compromising urban air quality.

Five chapters comprise the thesis.

The first outlines the pollution situation, includes a description of the two-stroke engine's pollution characteristics, and outlines Taiwan air pollution policy. A possible method for valuing reductions in air pollution is presented.

The second chapter discusses electric scooters and battery power for them. Hybrid vehicles and peaking power batteries are explained. The new zinc-air batteries, with their excellent energy storage densities, are examined as some scooter researchers and manufacturers are carefully looking at them for second generation zero emission scooters.

The third chapter describes in detail the engineering issues and science behind fuel cell technology and hydrogen storage. Both advantages and disadvantages of this type of power are examined. Hydrogen storage in the form of metal hydrides, and a proton exchange membrane fuel cell running at low temperatures, are chosen for the reasons of ease of manufacture and operation, low cost, and minimal volume.

The fourth chapter is the simulation and conceptual design core of the thesis. It explains the physical vehicle simulation used to simulate vehicle power requirements during typical urban driving. Using the specifications produced by the driving simulation, a fuel cell power system is designed. The fuel cell components are selected along with the hydrogen storage subsystem. The possibility of "hybridizing" the system by using a battery energy storage system is treated; this idea offers possible energy savings from regenerative braking and reduces the maximum size of the fuel cell, reducing cost. The performance of such a vehicle is examined in terms of technical performance metrics: total weight, fuel economy. (Note that this thesis did not involve construction of a physical prototype construction; the interested reader is referred to Appendix G for more information on that topic.)

The final chapter describes how these scooters might be brought to market. How much would a prototype cost? Could a fully-developed scooter be competitive with electric or two-stroke scooters? How would fuel costs compare to battery-powered scooters and gasoline-powered scooters? Infrastructure issues are briefly discussed. With the cost information finishing off the body the study, a final summary is presented that recapitulates the findings.

1.1 Transportation Background

1.1.1 Why Taiwan?

There are approximately 100 million motorcycles in the world. The greatest numbers are concentrated in Asia, and it is here that alternative scooters could have a major impact. Some illustrative countries are listed below:

Table 1.1. Motorcycle populations in selected countries, 1993

Country	Motorcycles	% of total vehicles	Country	Motorcycles	% of total vehicles
Argentina	882,000	15.5%	Switzerland	834,900	20.7%
Brazil	1,371,800	9.6%	Spain	2,655,900	17.1%
Canada	434,200	7.0%	UK	913,600	3.6%
Chile	37,120	3.9%			
Mexico	661,230	7.8%	Bangladesh	119,790	50.0%
Peru	86,940	12.4%	China	3,047,520	41.2%
USA (1991)	6,830,000	3.7%	Hong Kong	17,100	5.0%
Venezuela	580,920	25.3%	India	7,666,640	69.6%
			Indonesia	5,890,760	74.6%
Austria	601,160	14.9%	Japan	18,451,300	26.0%
Belgium	131,670	3.2%	Korea	1,066,800	34.4%
France	3,661,450	12.6%	Malaysia	2,460,640	59.0%
Germany	2,427,480	7.3%	Pakistan	627,170	48.8%
Italy	7,938,420	23.8%	Philippines	281,530	27.2%
Norway	202,860	9.5%	Taiwan (1991)	9,232,889	73.4%
Portugal	51,500	2.9%	Thailand	6,343,558	66.1%

Data from Weaver and Chan [4]

Numbers of scooters in use are high in Asia, and growth rates are also high. The People's Republic of China, for instance, had 500,000 motorcycles in 1980, and 10 million in 1994 - an annualized growth rate of 24%, faster than the 15-20% of Chinese urban vehicles in general.[5] India had an average annual growth rate of 16% for two-wheeled vehicles from 1981 to 1998.[6]

Worldwide scooter production is estimated at 17 million per year.[7] In 1994, Taiwan's motorcycle industry included 418 assemblers and manufacturers of parts and 16,000 employees. Revenues totaled $2.4 billion that year while total domestic production reached $3.2 billion (all figures US dollars unless otherwise noted.) [8]

As one of the "Five Tigers", Taiwan experienced rapid growth in the latter half of this century and became a manufacturing power; its vast foreign reserves helped it weather the Asian economic problems of the summer of 1998. Average household income in 1995 was $36,470 for an average household size (1996) of 3.6; transportation costs were estimated at $4,000 per year, behind household expenditures for food; rent, fuel, and power; and education.[9] Household income is fairly large compared to Taiwan's poorer neighbours, so adoption here is (i) easier than elsewhere and (ii) may ease development of advanced scooters elsewhere.

(In 1998, the U.S. dollar was equal to approximately 30 New Taiwan Dollars).

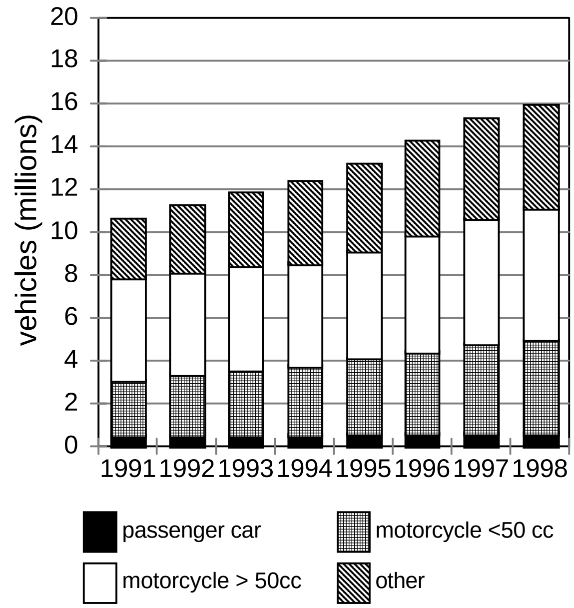
Air pollution is a major problem on this 400-km long island with an area of 35,873 km^2. Industry, diesel-powered vehicles, and the omnipresent two-wheeled, two-stroke scooters all contribute to the extremely dirty air. In 1997, the overall population was 21.7 million and the population density was 601 persons per square kilometer. In the same year, the city of Taipei's population density was 9560 persons per square kilometer while the second largest city, Kaohsiung, had a population density of 9350 persons per square kilometer. Urban centres with population over 1 million contained 67.8% of Taiwan's population.[10]

Taiwan is focused on here, because of the high fraction of scooters in its vehicle fleet, its poor air quality, and because it is one of the top six producers of scooters in the world. Being wealthier than many of the other countries with high scooter densities, Taiwan can afford to spend money on novel vehicle designs; on the other hand, it should be noted that any improved scooters that were developed would be of great benefit in reducing high air pollution levels in other developing countries.

1.1.2 Taiwan vehicle fleet

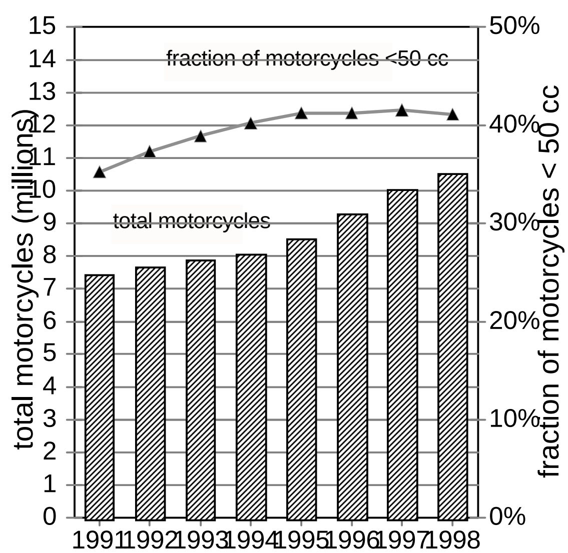
Taiwan's transportation split is interesting. Historically, the lack of an automotive industry in the critical growth period meant that people rapidly adopted scooters and then did not switch to automobiles as they became more wealthy. The crowded cities, warm weather, dense population and limited land continue to make scooters popular. Car use is increasing, but scooters have the advantage of being able to swarm through the congested car traffic in cities. This explains the over ten million scooters currently in Taiwan, of which approximately 60% are low-power scooters under 50 cc (cubic centimeters) in cylinder displacement.[11] The largest cylinder size (i.e. most powerful engine) allowed in Taiwanese scooters is 150 cc. Especially high-polluting two-stroke vehicles made up 40% of all vehicles in Taipei in 1996.[12]

Figure 1.2. Taiwan vehicle mix 1991-1998



Data from the Monthly Bulletin of Statistics of the Republic of China, February 1999.[13]

Figure 1.3. Scooter distribution in Taiwan 1991-1998



Data from the Monthly Bulletin of Statistics of the Republic of China, February 1999.[14]

The fraction of two-stroke scooters appears to have peaked, due to the cleaner and more powerful four-stroke scooters becoming cheaper and pollution standards becoming tighter.

A large number of vehicles are concentrated in the largest city, Taipei. According to the city's Department of Budget, Accounting, and Statistics, the Taipei motor vehicle population was approximately 1,532,000 in 1997, with 660,000 automobiles and 870,000 motorcycles.[15] Total Taipei vehicle density was 0.25 automobiles and 0.34 motorcycles per person, and the annual motorcycle growth rate was 7.3% between 1987 and 1997.

The 1991 percentage of motor vehicle air pollution that was produced by motorcycles and scooters was reported at: carbon monoxide, 37.7%; total hydrocarbons, 60.8%; nitrogen oxides, 2.9%. At this time, 73.4% of vehicles were motorcycles and scooters.[16] So the total amount of pollution contributed by motorcycles is less than their fraction of the vehicle population. Is their reputation for pollution undeserved, then?

Vehicle-mile-traveled (VMT) data for Taipei (1987) show the rest of the story. While more trips are made by scooters than by private car, the average car trip is farther and consequently more total miles are traveled by car. Scooters produce more pollution *per mile* than other vehicles:

Table 1.2. VMT data for Taipei, 1987

mode	% of trips	average length	fraction of total VMT
city bus	39%	6.5 km	38.1%
motorcycle	20%	7.8 km	23.5%
walking	17%	1.4 km	3.6%
private car	14%	13.5 km	28.4%
bicycle	6%	2.3 km	2.1%
taxi	3%	7.0 km	3.2%
train	1%	7.4 km	1.1%

Data from Price and Probert[17]

Although scooters only make up about 25% of VMT (when considering only engine-powered vehicles), they produce 38% of the carbon monoxide and 61% of the total hydrocarbons.

1.1.3 Taiwan Energy

Taiwan has virtually no energy resources of its own and imports the vast majority of its fuel. Its primary energy consumption is over 50% oil, approximately 25% coal, 10% nuclear, 5% natural gas, and under 5% hydroelectricity. In 1997, 3 million tons of LNG were imported (mainly from Indonesia), and the government expects to expand natural gas use to 13 million tons by 2010 and 16 million by 2020.[18] Oil is imported almost entirely from the Middle East, but coal is used for electric power generation, with imports mainly coming from Australia (35%), Indonesia (21%), South Africa (17%), and mainland China (15%).[19]

The US Energy Information Agency summarized the electric production situation as follows:

> At the end of 1997, Taipower [the government utility monopoly] operated 57 power plants (35 hydropower, 19 thermal, 3 nuclear) with total capacity of 23,763 megawatts (MW) (32% coal-fired, 23% oil-fired, 22% nuclear, 18% hydro, 5% gas-fired). In addition, cogenerators had 2,356 MW of capacity in place, which they used to generate about 10% of Taiwan's total electric power in 1996.[20]

Eight more coal-fired plants are to be built by 2001, with two nuclear reactors totaling 2.7 GW to be added at the Lungmen facility in Yenliao by 2004.

In terms of pollution, electricity is produced by relatively polluting coal plants, although this can be improved with different coals and power plants with advanced cleanup technology. For reasons of national security caused by the island’s extreme dependence on a possibly unstable oil supply, energy efficiency is a major focus of the Taiwan government. This is an added incentive to move away from gasoline powered scooters or at least to improve fuel economy.

1.2. Air Pollution

Why are these two-stroke scooters so polluting, and what can be done about it?

1.2.1. The internal combustion engine

After an initial flowering of radically different ideas and concepts, including electric vehicles, cars since the nineteenth century have almost universally burned gasoline and run on the *four-stroke Otto cycle*. The majority use spark plugs for ignition. However, the *two-stroke Otto cycle* is still widely used for applications like lawnmowers, outboard motors, and scooters, where simplicity, low cost, and high power per weight are more important than fuel efficiency or minimized air pollution. However, as more and more attention is paid to emissions, these two-stroke cycle engines (heretofore abbreviated “two-stroke engines”) are becoming less and less acceptable.

Why are two-stroke engines so polluting, and what can be done to improve them? The answer will be clear after a brief tour through the workings of a four-stroke car internal combustion engine.

1.2.1.1 The four-stroke spark-ignition cycle

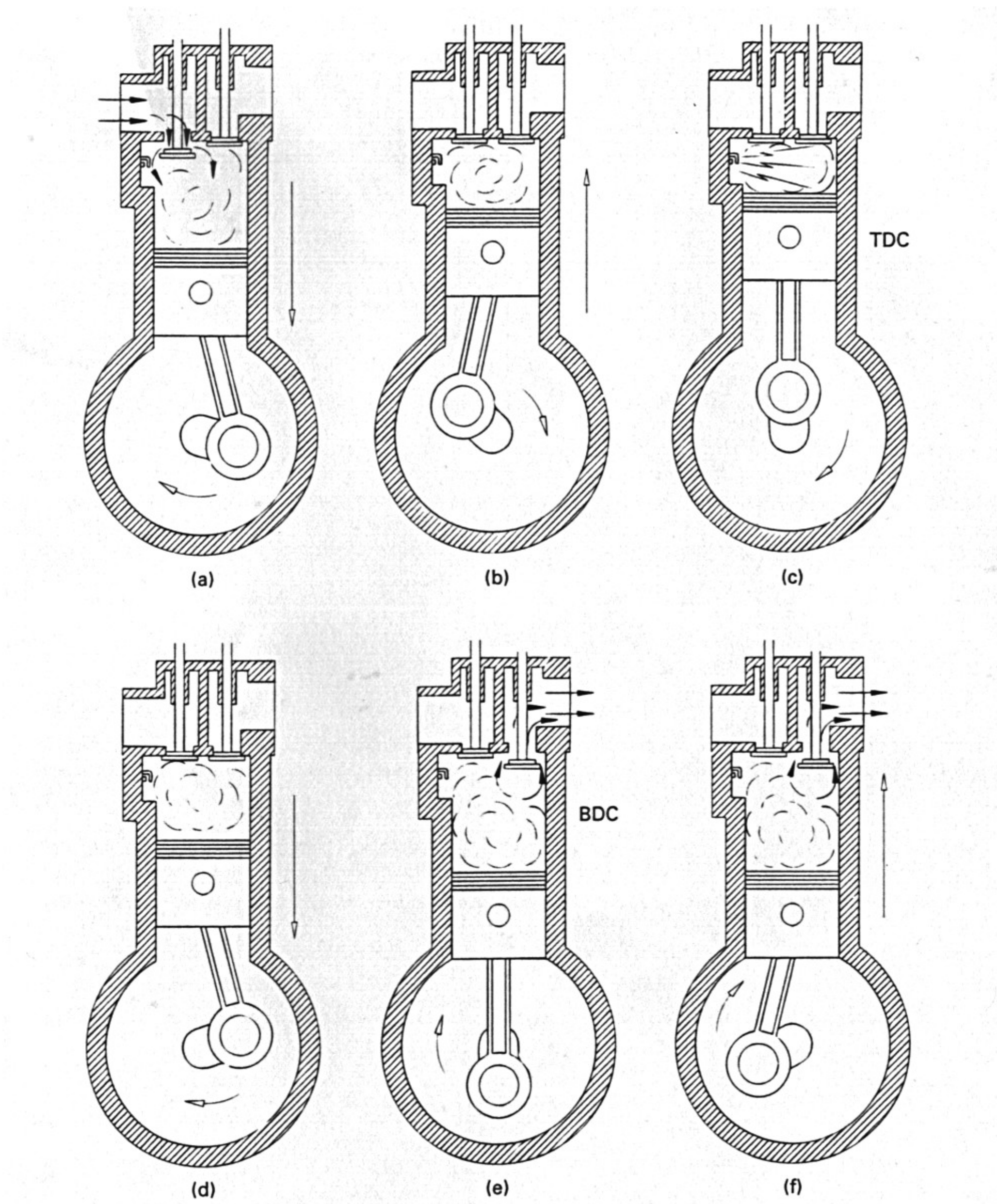
The typical car contains four to eight cylinders which are connected by pistons to a crankshaft. Each cylinder is stopped at one end by a movable piston; the other end is closed but contains valves to allow air, fuel, and exhaust gases to enter and exit. The space in the cylinder is called the combustion chamber, and its volume is determined by the position of the piston head as it slides up and down the chamber.

The process by which combustion turns the crankshaft (and, through the transmission, the axles and the wheels) is relatively straightforward. A “charge” of fuel and air is sucked into the combustion chamber by a downwards motion of the piston, compressed by an upwards thrust of the piston, and then ignited by a spark plug; the resulting expanding gases drive the piston towards the crankshaft; and the hinge at the end of the piston transforms the piston's linear motion to rotational motion, turning the crankshaft and providing power. The crankshaft rotates, bringing the piston back up, the combustion product gases are squeezed out, and a fresh batch of air/fuel is drawn down into the combustion chamber. Since there are multiple cylinders firing at different points in the turning of the crankshaft, the motor remains in fairly steady rotation. A flywheel smooths out any remaining irregularities.

In reality the situation is more complicated, with auxiliary systems. In a four-stroke spark-ignition engine with carburetor, the fuel is first thoroughly pre-mixed with the air prior to intake in the carburetor before it is introduced to the combustion chamber. The alternative is fuel injection, where the fuel is sprayed by a controlled injector either into the compressed air stream at the inlet tract (just before the inlet valve opens), or directly into the combustion chamber. The former is more common. These both require high-pressure injection, and the fuel also has less time to vaporize before being burned.

Note that in diesel (compression-ignition) engines, the fuel is injected into high-pressure air toward the end of the compression stroke.

Figure 1.4 Four-stroke cycle



The four-stroke cycle moves from (a) the intake stroke to (b) compression stroke (c) ignition and combustion (d) power stroke (e) exhaust valve opens (f) exhaust stroke. The diagram is from Pulkrabek.[21]

The four strokes are:

Intake / Induction stroke. The piston draws down from the closed position (TDC, or “Top Dead Center”) to BDC (“Bottom Dead Center”), and the intake valves are opened. A fresh charge of the pre-mixed air/fuel mixture is sucked into the chamber.

Compression stroke. At approximately BDC, the intake valves close. The turning of the crankshaft then begins to push the piston back up, compressing and heating up the air/fuel mix. Once the piston reaches approximately TDC, the spark plug fires, igniting the mixture. (If the heat causes the mixture to ignite before the spark plug fires, premature and unstable ignition occurs: “engine knock”). As the air/fuel mix burns, it releases heat and is transformed into combustion products: carbon dioxide, water, and various other compounds. The pressure and temperature increase dramatically.

Expansion / Power stroke. The piston is pushed downwards by the expanding gases and this push provides the power to rotate the crankshaft. At the end of the power stroke, the exhaust valve located at the top of the cylinder opens. The phenomenon known as “exhaust blowdown” begins: the gases in the combustion chamber, still at a higher pressure than the external atmosphere, escape out the exhaust valve.

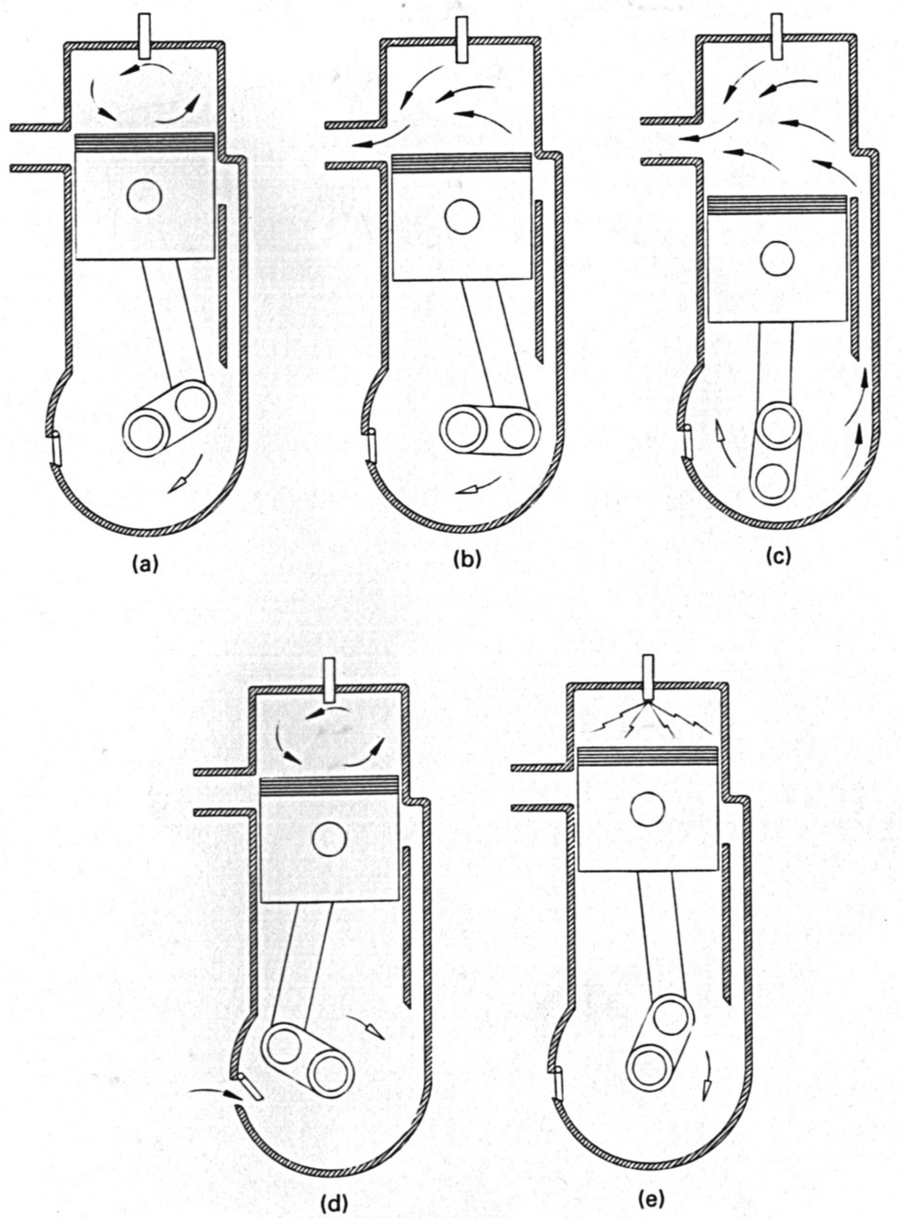
Exhaust stroke. However, some gases remain after the pressure in the combustion chamber has dropped to atmospheric. The next stroke is an upwards motion; the piston moves from BDC to TDC, pushing out the remaining gas. The exhaust valve closes at the end of this stroke, and the cycle begins again.

Note that the valves open once per cycle, but each cycle consists of two strokes. Thus, lobes on a camshaft are needed to regulate this action. Lubrication is by oil pumped up from an oil sump at the bottom of the crankcase.

1.2.1.2 The two-stroke cycle

The key mechanical difference between the two-stroke cycle and the four-stroke cycle is that the two-stroke engine draws air/fuel in at the same time as it pushes out exhaust. However, it is this seemingly minor difference that produces all the major disadvantages and advantages: higher power, lower complexity, and increased hydrocarbon emissions.

Figure 1.5 Two-stroke cycle



Here, (a) is the power stroke, (b) is exhaust blowdown, (c) is cylinder scavenging, (d) is the compression stroke and combustion occurs at (e). The diagram is from Pulkrabek.[22]

Expansion / Power stroke. In the two-stroke engine, as in the four-stroke engine, the expanding combustion products force the piston down to provide the power. Pressure and temperature start to decrease from their maximum values. As the piston moves downwards - but before it reaches BDC - exhaust blowdown is begun. This is done by opening an exhaust valve at the cylinder head or by having the descending piston uncover ports at the sides of the cylinder, allowing the gases to escape.

Intake / Scavenging stroke As the pressure drops and atmospheric pressure is nearly reached inside the cylinder, intake slots at the side of the cylinder are uncovered and pressurized air/fuel is allowed to enter the cylinder. This mix pushes out remaining exhaust gases and fills the cylinder - a process known as "scavenging." The piston descends to BDC and switches direction. On its way up, the piston quickly covers the intake port and exhaust ports (or, exhaust valves are closed with a separate mechanism). With all valves/ports closed, the piston finishes compressing the air/fuel as it moves back up to TDC. A spark plug fires as the piston reaches TDC, ignition occurs, and the cycle repeats

Note that in the two-stroke cycle, the air/fuel mixture must enter under pressure, in order to force out the exhaust gases. This is done in one of two ways: with a supercharger (compressor) that compresses the air/fuel before it enters the cylinder, or more commonly, by redesigning the crankcase so that it acts as a compressor during the power stroke (in other words, as the piston descends, it turns the crankshaft *and* compresses the air in the crankcase) This crankcase compression replaced earlier designs which used blowers to push in the air/fuel mixture.

In the case of crankcase compression, the crankcase is no longer filled with lubricating oil as it is with four-stroke engines, since it needs to hold the air as well. In practice, what this means is that lubricating oil must be mixed with the fuel in a predetermined proportion; when the carburetor introduces the oil/fuel/air mix into the crankcase, the gasoline vaporizes and the oil turns into a mist of liquid droplets. These droplets lubricate the crankshaft, piston pin, and cylinder walls, while the gasoline is compressed with air and eventually enters the cylinder. However, much of the oil that enters the cylinder is burned along with the fuel, and produces severe emissions problems. Small oil particulates may form. Finally, the oil also reduces the efficiency of the fuel combustion, because it is heavier and less reactive and thus does not completely burn.

1.2.1.3 Advantages and disadvantages

Due to the fact that both intake and exhaust valves are open at some point during the two-stroke cycle, it is possible for as much as 20-40% of the air/fuel to flow directly out of the cylinder.[23] This "short-circuiting" produces the blue smoke characteristic of unburned hydrocarbons, and reduces fuel economy. (Using direct fuel injection rather than carburetion can reduce this effect because air/fuel injection timing is better controlled, but this technology is only now beginning to be adopted for two-stroke engines, as environmental standards tighten and the extra cost thus becomes both bearable and necessary). Short-circuiting is an especially serious problem at high power, where the engine is turning at high rpm and there is very little time per stroke for scavenging to take place. The durability of two-stroke engines is also less than that of four-stroke engines.[24]

Incomplete combustion of the fuel is also a problem, especially at low loads. The residual gas left in the cylinder after scavenging increases if blowdown is too weak, and this high-heat capacity gas reduces flame temperatures. The result is unstable combustion, especially at the fringes of the fuel cloud where the mixture is lean, and the flame is extinguished before all the fuel is burned. The air/fuel mixture is kept rich to avoid this problem.[25,26] (A "lean" air/fuel mix has more air than is necessary for complete combustion; a "rich" mix, less)

On the other hand, a major advantage of two-stroke engines is that they offer far higher power per weight and per volume. Various components (oil pumps, distributor drives, valves) may be omitted because valves are replaced by ports, and because oil is included in the fuel. But most importantly, the two-stroke engine has a power stroke twice as frequent (per revolution) as the four-stroke engine of the same cylinder displacement, resulting in almost double the specific power. Related to this is the fact that the camshaft and relating mechanical timing devices required in a four-stroke engine are not needed. The high power density and simple construction make two-stroke engines attractive for scooters, outboard motors, and power tools like chainsaws and hedge trimmers.

Absolute maximum thermal efficiency is on the order of 14% for a typical 1 kW two-stroke engine, up to 21% for a modified lean-burn two-stroke engine.[27]

The size of scooter studied here is the 50 cc scooter - or rather, electric scooters with power and performance comparable to two-stroke internal combustion engine scooters with cylinder volumes of 50 cc. This translates to a gross power output of about 5 kW. Low-end 50 cc scooters are sold for approximately $1,000 in Taiwan.

1.2.2 Pollutants

The major vehicle pollutants are carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM) and various hydrocarbons (HC). Combustion also produces carbon dioxide, a greenhouse gas. Two-stroke engines produce significant amounts of unburned hydrocarbons, atomized lubricating oil, and CO due to their design, but little NO_x

Carbon monoxide is generally a product of incomplete combustion, and is frequently found in rich mixtures. Carbon monoxide binds with hemoglobin in the blood, reducing the blood's capacity to carry oxygen. This can result in heart strain and pulmonary problems.

NO_x is a collective name for nitrogen oxide (NO) and nitrogen dioxide (NO_2). Its production is largely thermally controlled in the combustion process from nitrogen in the air, which reacts with oxygen at high temperatures to form NO_2 and NO. NO_x tends to peak at an air-fuel ratio approximately 1.1 times stoichiometric, where there is excess oxygen.[28] The low NO_x output characteristic of two-stroke engines is due to the lower temperature and pressure at the same speed and torque as matching four-stroke engines.[29] The lower pressure of a two-stroke engine is the result of the higher stroke frequency and thus lesser need for high pressure to provide power. The lower temperature is partially the result of the richer mix being off-stoichiometric and thus being farther from the temperature peak and reduced in oxygen, and partially due to "exhaust gas recycling" where the incompletely exhausted combustion products, with their high heat capacity, keep down the temperature in the cylinder.

NO_x combines with moisture to produce acid rain, and increases the risk of respiratory disease and causes pulmonary and respiratory problems. NO_x and volatile organic compounds are also precursors for photochemically-produced ozone (smog), which is an irritant that affects the eyes, upper respiratory tract, and causes asthma and headaches.

Hydrocarbon emissions from two-stroke engines mainly result from the "short-circuit" passage of unburned fuel straight through the cylinder to the exhaust previously described.[30] Hydrocarbons in the atmosphere react photochemically to produce smog, and this is a major problem. Also, certain hydrocarbons are directly toxic to the human body.

Particulate matter consists of fine solid particles (often soot or agglomerated hydrocarbons), or liquid droplets. TSP ("total suspended particulates") is a measure of particulates smaller than 70 µm in diameter, while PM_{10} is a category for particles less than 10 µm. PM can lodge in the lungs and act as an irritant or cause cancer. (Recent medical and policy attention has turned to $PM_{2.5}$, an even finer classification of particulates). PM emissions from tailpipes are often measured by proxy, using the opacity of the exhaust. Black smoke is associated with soot, and blue, gray, or white smoke with condensed hydrocarbons from lubricating oil or incomplete fuel combustion. In two-stroke engines, lubricating oil is mixed with fuel at a ratio of about 1:40 by volume, and these more viscous lubricating oils tend to pass through the engine unburnt and condense as particulates.[31]

Finally, note that a major source of emissions is evaporative emissions. This can account for as much as 30%-40% of total volatile organic compound mobile source emissions.[32] Sources include losses during refueling, direct evaporation from the tank as it heats up and expands in the morning, and "hot soak" losses: those due to the engine continuing to heat up parts of the fuel system even when the vehicle is shut off.

1.2.3 Vehicle emissions standards and the reality

Vehicle emissions standards are the instrument by which vehicular air pollution has been traditionally addressed; these maximum emissions are measured using well-documented procedures generally involving placing the vehicle on a rolling-drum dynamometer, and accelerating/decelerating the vehicle through a "driving cycle" of prescribed velocities over a certain time period. This simulates the effects of different power levels on pollution production. Total pollutants are collected in a bag, separated and weighed, and divided by total distance "traveled" to give a pollution rating in terms of grams per kilometer.

Listed below are data showing Taiwan's increasingly strict emissions policy, compared with U. S. motorcycle and automobile standards. Data is from the Weaver and Chan study and an ROC-EPA document titled "Emission Standards of Air Pollutants for Transportation Vehicles".[33,34]

The "test procedure" column describes the driving cycle used for the vehicle; the ECE-40 (Economic Commission for Europe) test driving cycle and the American Federal Test Procedure are different driving patterns used for testing motorcycle emissions. The two velocity *vs.* time traces are plotted and described in greater detail in section 4.3.

Table 1.3 A comparison of vehicle emissions standards

motorcycle standard and driving cycle	**year**	**test procedure**	**THC (g/km)**	**CO (g/km)**	**NO_x (g/km)**
Taiwan "first stage"	1988	ECE-40	5.5*	8.8	*
Taiwan "second stage"	1991	ECE-40	3.0*	4.5	*
Taiwan "third stage"	1998	ECE-40	2.0*	3.5	*
Taiwan "third stage" special low emission motorcycles	1999	ECE-40	0.58*	1.08	*
Taiwan fourth stage (proposed) two-stroke motorcycles	2003	ECE-40 (cold test)	1.0*	7.0	*
Taiwan fourth stage (proposed) four-stroke motorcycles,	2003	ECE-40 (cold test)	2.0*	7.0	*
California motorcycles <280 cc	1988	Modified FTP	1.0	12.0	–
US motorcycles, all types	1980	Modified FTP	5.0	12.0	–
US automobiles (Clean Air Act Amendment)	1990	FTP	0.16†	2.11	0.25

Notes follow on next page.

* Taiwan standards asterisked are for THC + NO_x *combined*.

† Before 1990, the standards were for total hydrocarbons; since the 1990 Clean Air Act Amendment, the figure of 0.16 grams/km is for non-methane hydrocarbons (NMHC). A more aggressive driving cycle

will be introduced for the 2000 model year, as part of the Supplemental Federal Test Procedure.

Note that the fourth-stage standards require a different procedure in that the engine is started from cold conditions; this is supposed to produce 2.5 times as many pollutants as the equivalent “warm test”, so what appears to be a loosening of the standards is in fact a move towards stricter requirements.

Particulate matter emissions from motorcycles are not regulated anywhere, although Taiwan does require a maximum smoke opacity of 15%, which is often considered a crude proxy for total particulate matter.[35]

As the data below show, when tested in the lab under the same ECE-40 test driving cycle, emissions from actual in-service motorcycles tend to be higher than the current (“third stage”) standards of 2.0 g/km from THC and NO_x and 1.1 g/km of CO. For example, a two-stroke 50 cc scooter without benefit of catalyst produces 3.8 g/km of THC and NO_x, and 7.5 g/km of CO. Data for four-stroke scooters, catalyst-equipped scooters, and an automobile are also provided for comparison:

Table 1.4 Data on motorcycle emissions: four-strokes and catalysts

model or standard	model year	test cycle	THC (g/km)	CO (g/km)	NO_X (g/km)	fuel econ (mpg)
50 cc Sanyang 2-stroke motorcycle, no catalyst	1995	ECE-40	3.8	7.5	0.007	91-95
50 cc Sanyang 2-stroke motorcycle, oxidation catalyst	1995	ECE-40	2.1	2.9	0.000	91-99
125 cc Sanyang 4-stroke motorcycle, no catalyst	1992	ECE-40	0.64	4.0	0.19	85-88
Ford automobile, 3-way catalyst, fuel injection	1991	FTP	0.12	1.3	0.14	26-33

Source: mean results of National Taiwan University study on scooter and car emissions[36] The low NOx readings are due to several test producing readings "below the analyzer's detection limit"

The evidence shows that two-stroke motorcycles produce very high quantities of hydrocarbons, and low NO_x. The ECE-40 driving cycle is a simplified test pattern not intended to mimic road driving, and modeling results done by Taiwan's Environmental Protection Agency shown below in Table 1.4 using the more representative Taiwan Motorcycle Driving Cycle strongly suggest that real world emissions factors are higher by as much as a factor of ten: 13.7 g/km of THC and NO_x and 29.2 g/km of CO.

Table 1.5 Simulated emissions from more realistic driving cycle

model or standard	model year	test cycle	THC (g/km)	CO (g/km)	NO_X (g/km)	fuel econ (mpg)
2- stroke motorcycle, modeled using MOBILE-5	1996	TMDC	13.2	29.2	0.51	n/a
4- stroke motorcycle, modeled using MOBILE-5	1996	TMDC	5.4	26.8	0.51	n/a

Source: Republic of China Environmental Protection Agency vehicle simulation [37] The THC figure includes evaporative and resting losses in addition to exhaust.

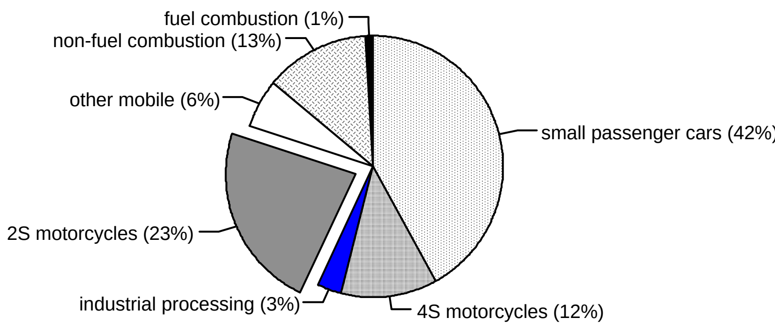
Due to the high-power spikes of the TMDC, more pollution is generated than during the ECE-40 cycle test.

1.2.4. Air pollution sources in Taiwan

Taiwan has an average population density higher than virtually all other developed countries, and more importantly, one of the largest average motor vehicle densities in the world at 425 per square kilometer in 1997.[38] This vehicle density is double that of Japan, four times that of Germany, and eighty times that of the USA.[39] It should be noted that the central mountain range of Taiwan is thinly populated, meaning that the relevant densities are even higher in the urbanized coastal areas.

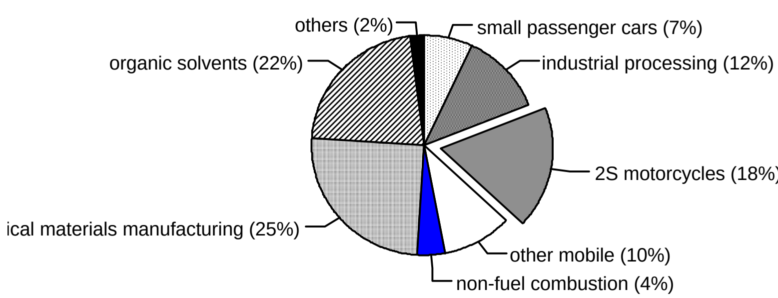
In terms of emission of pollution, a study done at ITRI (the Industrial Technology Research Institute – a Taiwanese national laboratory for applied research) reported that, in 1994, the majority of carbon monoxide is emitted by vehicles, while two-stroke motorcycles specifically are a major producer of hydrocarbons. The figures below are total emissions for 1994.

Figure 1.6 Carbon monoxide emissions by source



The total mass of CO emitted was 2.05 x 10^6 tonnes in 1994. Data from the Mechanical Industry Research Laboratories, Industrial Technology Research Institute, Taiwan[40]

Figure 1.7 Hydrocarbon emissions by source



The total mass of THC - total hydrocarbons - emitted was 1.11 x 10^6 tonnes in 1994. Data from the Mechanical Industry Research Laboratories, Industrial Technology Research Institute, Taiwan.[41]

Two-stroke scooters produce 28% of carbon monoxide emissions, and 51% of hydrocarbon emissions. The relative unimportance emissions from power plants (included under either "nonfuel combustion" or "other") from this data is a little surprising.

Air conditions are poor. One yardstick of pollution, the Pollution Standards Index (PSI) common to many countries, illustrates this point. PSI, an artificial measure used to provide a single level of "pollution", is the maximum of the indices for five different pollutants: CO, ozone, NO_2, SO_2, and PM_{10}. These indices are segmented linear functions of concentration, as shown below. (Note that the original units of ppm and ppb were homogenized to $\mu g/m^3$).

Table 1.6 PSI subindex pollutants in Taiwan

PSI value of subindex	**24-hr PM_{10}**	**24-hr SO_2**	**8-hr CO**	**1-hr O_3**	**1-hr NO_2**
50	50	90	5600	130	n/s
100	150	400	11250	260	n/s
200	350	860	18750	430	1230
300	420	1710	37500	860	2460
400	500	2290	50000	1070	3290
500	600	2860	62500	1290	4110

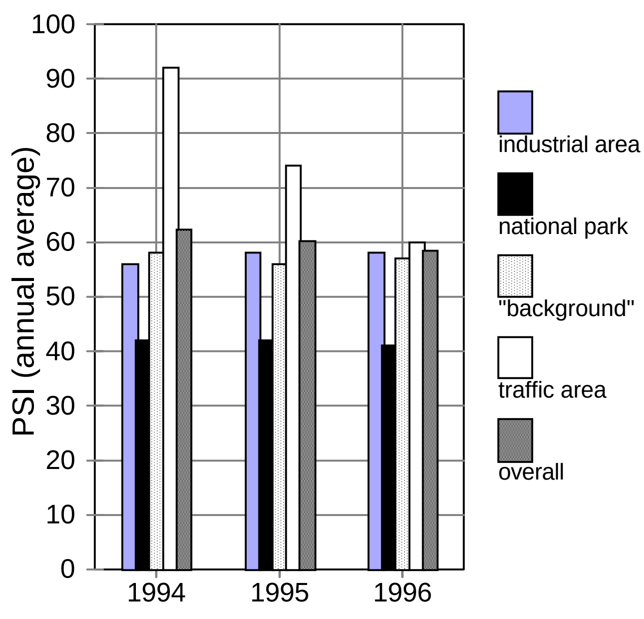
n/s: no standard for short-term; the index merely measures exceedances in this case. Data is from the Republic of China EPA's web site[42]

Thus, an unhealthy condition (PSI>100) takes place when any of the five concentrations exceeds the "100" subindex value. For example, if the average PM10 concentration over 24 hours is higher than 150 $\mu g/m^3$, *or* if the average SO_2 concentration over 24 hours is higher than 400 $\mu g/m^3$, then the PSI itself is greater than 100. The same holds true for carbon monoxide, ozone, and NO_2.

The number of PSI exceedance days for each year from 1987 to 1991 was over 15% but for the years 1995-1997, this had reduced to 6%.[43,44] This is still three times higher in Taiwan than in many other countries.[45] As a comparison, some urban Southern California counties had years in which over 20% of days had PSI > 100 (data for years since 1993), but these were the extreme cases. For 5,690 county-years between 1993 to 1998 for counties across the United States, *fully 99.2%* had less than 6% exceedances per year.[46] In fact, 83.5% of the county-years had less than 1% PSI exceedances. In other words, Taiwan's *overall* pollution rate of 6% exceedances per year was worse than all but 0.8% of American individual county readings.

In addition, the *average* level of pollution has been decreasing over time, as indicated by various subsets of the seventy-one monitoring stations scattered across Taiwan:

Figure 1.8 PSI in Taiwan, 1994-1996



Data is from the Taiwan Environmental Protection Agency.[47]

1.2.5 Cleaner combustion technology

There are numerous options for reducing vehicle emissions. Over the years, four-stroke engines have received much more research attention than two-stroke engines, due to the overwhelming number of automobiles in the world, and this is part of the reason automobile technologies like catalysts and fuel injection have not been adapted for the two-stroke market. The most important reason, however, is that most of the pollution cleanup technologies add weight and cost, eroding the original benefits of two-stroke engines.

1.2.5.1 Exhaust gas recirculation

EGR is mainly used in automobiles to reduce NO_x production, but it is discussed here mainly to explain why two-stroke scooters produce low levels of that particular pollutant. Exhaust gas recirculation causes some of the burned gases to combine with the incoming air/fuel. This lowers the engine temperature because the relatively large heat capacity of triatomic species like CO_2 and H_2O in the recirculated exhaust gas dilute the contents and steal heat from the combustion process, and this means less NO_x production. In fact, due to the nature of two-stroke engines (with the incoming charge partially mixing with the outgoing gases), some EGR occurs automatically. EGR has the disadvantage of slowing combustion rate and thus making stable combustion more difficult; there is increased possibility of unburnt hydrocarbon emissions.[48]

1.2.5.2 Superchargers

Superchargers allow precompression of the air/fuel without requiring crankcase compression, and avoid mixing lubricating oil with the fuel, but add expense. Essentially, a supercharger is a compressor or blower that increases the pressure of the intake air. It may be powered off the crankshaft (thus parasitically consuming some of the developed power), electrically, or by a turbine driven by the exhaust gas flow in which case it is called a turbocharger.

1.2.5.3 Fuel injection

As alluded to earlier, with fuel injection systems only air is compressed in the crankcase, not an air/fuel mixture. The fuel spray is then injected at high pressure into the compressed air stream just before intake or directly into the combustion chamber; such a system allows more precise, electronic control of the air-to-fuel ratio than a carburetor. Orbital Engineering in Australia is one company trying to combine the high power density of two-stroke engines with the efficiency of direct fuel injection; the company also modifies the combustion chamber to improve emissions.

Fuel injection is estimated to reduce fuel consumption by 25-35% due to the more complete combustion, and to reduce unburned hydrocarbon emissions by 75-85% and carbon monoxide by 50% for the same reason.[49]

However, the pumping system required to maintain injection pressure reduces the power density advantage of two-stroke engines.[50] A Piaggio study estimates the pump power at 300 W at maximum speed of 8000 rpm, for a test 4 kW engine; this amounts to a 7.5% parasitic power loss.[51]

1.2.5.4 Catalysis of exhaust gases

Three-way catalysts like those found in typical automobile engines are composed of alloys of expensive metals like platinum and/or palladium with rhodium. Three-way catalysts are so named because they simultaneously oxidize hydrocarbons and CO, and reduce NO to nitrogen. A rich air/fuel ratio is needed for the NO_x reduction; this richer condition increases exhaust pollutants and partially offsets the benefit of catalysis. These systems require fairly precise stoichiometry and typically electronic control using oxygen sensors in the exhaust pipe is needed to maintain this ratio.

Oxidation catalysts, on the other hand, use metals like platinum and/or palladium to increase the rate of oxidation of exhaust molecules like CO and hydrocarbons; essentially, this is catalytic combustion. Catalysts are "poisoned" by lead in the fuel, and sulfur or phosphorous compounds that may be found in the lubricating oil; active sites are taken up by these compounds and the catalysts must be thermally or chemically treated to restore their function.

The high proportion of scavenged unburnt air/fuel in the exhaust gas is problematic for catalytic converters. On the one hand, the heat capacity of the hydrocarbons reduce the temperature of the exhaust, delaying catalyst activation. On the other hand, catalyst oxidation of the unburned A/F may increase temperature to *too* high a level, causing catalyst durability problems. The solution is sometimes to use two-stage catalysts, with the rate of catalysis controlled by admitting "secondary air"[52]

In the National Taiwan University experiment described in Table 1.4, an oxidation catalyst attached to a two-stroke motorcycle was found to reduce 45.4% of total hydrocarbons, and 61.2%

of CO; emissions for NO_x were already extremely low. (In comparison, the same study found that car three-way catalysts achieved reductions of 90.5% of total hydrocarbons, 88.0% of CO, and 94.2% of NO_x of automobile exhaust).

1.2.5.5 Replacement by four-stroke engines

The more and more stringent emissions standards have made switching to four-strokes an increasingly attractive option. In fact, a researcher at ITRI wrote that the announced year 2003 fourth-stage standards would be "too tough for 2 stroke [engines] to survive. This is an understanding between Taiwan EPA and motorcycle makers to phase out 2-strokes by that time."[53] This is an easy solution because it leverages well-understood existing technology. Drawbacks include greater vehicle weight and larger engine sizes, and of course more expensive engines. Advanced four-strokes would follow the advances made on the automobile side, with three-way catalysts, engine timing optimization for reduced emissions rather than specific power, etc.

1.2.5.6 Relative costs and benefits of various technologies

A Piaggio study also estimated the costs for various clean two-stroke technologies that they considered for new high-efficiency and low-emissions two stroke engines. The relative costs are reproduced below, along with estimates of air pollution reduction. Note that the base cost to manufacture a two-stroke scooter engine is approximately $150.[54]

Table 1.7 Cleanup technology, effects and prices

Type of engine	relative cost	THC reduction	CO reduction
Two-stroke standard	1.0	baseline	baseline
Fuel injection with external scavenge (separate blower to scavenge cylinder)	1.5-1.7	75% - 85%	50%
FAST ("Fully Atomized Stratified Turbulence") - mechanical control	1.2-1.4	68% - 76%	65% - 80%
FAST - electronic control	1.4-1.6	68% - 76%	65% - 80%
catalytic converter	1.7	45% - 80%	61 - 95%
Equivalent four-stroke	1.5-1.7	83%	47%

Sources: for catalyst cost, Felton.[55] For other costs, Piaggio study.[56] For reductions in pollution, National Taiwan University study[57], Piaggio study for direct injection with electronic-control pollution reductions assumed to be the same as mechanical-control reductions.[58]

Improvements that may seem simple, technologically speaking, actually add about 50% to the engine cost. On the other hand, the standard engines cost only about $150 to manufacture, so the difference in dollars is not great - perhaps $150 once manufacturing and markups are included.

So significant reductions are possible using relatively inexpensive improved combustion techniques, the easiest of which is a transition to only four-stroke vehicles. Are electric vehicles necessary, then? Or in other words, is it worth spending additional money on "zero-emission"vehicles to reduce emissions further?

1.2.6. Assessing the damage

The process of establishing - and quantifying - a causal link between scooter tailpipe emissions and health and environmental damages is a long one with many steps. In general, researchers have proceeded through the following stages:

1. Measurement of pollutant emissions by collecting tailpipe exhaust under various simulated driving cycles, as tested on a dynamometer.

2. Dispersion modeling, based on local wind patterns and atmospheric models, to proceed from pollution emitted per kilometer on the streets to ambient concentrations in the local environment.

3. Estimation of individual exposure to various pollutants by studying population distributions

4. Dose-response modeling of health effects resulting from exposure. Epidemiological studies are generally used to try to correlate incidences of high pollution with acute and chronic negative health effects, which are measured in terms of deaths (mortality) and loss of useful function (morbidity).

5. Estimates of the cost of health damages, either by calculating the value of lost work-days or by contingent-valuation surveys that aim to capture the value of health externalities.

Similar processes are applied to damage caused to buildings and other material objects. The literature contains little data quantifying specific Taiwan conditions, although studies have been done to estimate valuation of health episodes (i.e. the fifth step).

1.2.6.1 Reduction estimate

Also, a previous ITRI study estimated reductions in CO and THC levels in the air assuming current emission rates and increasing vehicle populations after 1991 (steps 1 and 2 of the cost-benefit analysis process enumerated above). The CALINE-4 line source and dispersion model was used to estimate ambient pollution concentrations near roads. Three situations were studied and the following results were obtained for the 1991-1996 time period:

Table 1.8 ITRI prediction of effects of scooter replacement on pollution

Scenario	***CO***	***HC***
Baseline: no change in scooter pollution levels	0%	0%
All motorcycles after 1991 meet second-stage standards	-17.4%	-5.8%
As above but with 20% of scooters replaced by electric	-24.8%	-12.2%
As above, but with 50% of scooters replaced by electric	-35.1%	-17.2%

Data from ITRI study [59]

These reductions are almost equal to the fractions of carbon monoxide and hydrocarbons emitted by scooters overall, but it should be kept in mind that these measurements are for roadside ambient concentrations, not overall emissions.

It is not clear whether it is old, highly polluting scooters or a random sample of scooters that are being replaced with battery-powered scooters. However, the results clearly demonstrate how important scooter pollution reductions are in improving localized air quality; scooters clearly were predicted to produce *at least* 35% of roadside CO and 17% of roadside HC.

1.2.6.2 Externality damage estimate

A systematic study of the health and environmental benefits of reduced air pollution is not within the scope of this study. However, as a rough estimate of the benefits of cleaner air, the particulate ($PM_{2.5}$) pollution emitted by four-stroke scooters was calculated as if it were an automobile, but factored by the greater fuel economy of the scooter. Next, the externality cost of air pollutants was obtained from a recent study by Spadaro and Rabl.[60] They calculated the following externality costs of various vehicle air pollutants:

Table 1.9 Estimate of externality damages from air pollutants

Pollutant	***Euros / tonne***	***$ / gram***
Urban nitrate	1.6×10^4	$0.0200
Ozone from NOx	1.45×10^3	$0.0018
Fine particles ($PM_{2.5}$)	2.2×10^6	$2.75

Note: at the time the study was done (October 1998), 1 ecu was equal to 1.25 US dollars. The ecu has since been replaced by the euro.

The authors used a fine particulate ($PM_{2.5}$) emission rate of 0.75 grams for a 43.3 km Paris trip in a three-way-catalyst-equipped automobile, or 0.017 g/km. This is based on Heywood, which specifically quotes a figure of 0.020 g/km for particulates for a car running on unleaded fuel with no catalyst.[61] Using the authors' figure and their implied fuel economy of 9.14 km/L (21.5 mpg) gives an emission rate of 0.155 grams of fine particulates per liter of fuel. An equal emission rate was assumed for scooters running on the same four-stroke cycle as the automobiles. With a 100 mpg fuel economy (4.6 times better than the car), the per-kilometer emission rate is only 0.0037 g/km. Annual health costs for 12,000 km/y driving means annual health externalities of $120 per year per four-stroke scooter.

The figure of 0.51 g/km of NO_x from Table 1.5 for simulated urban scooter driving, when taken through similar calculations, yields externalities of $133 per year, for a total pollutant damage of $253 per year. Damages from other pollutants are not included.

The health cost is scaled by a factor proportional to the ratio of Taiwan GNP per capita to French GNP per capita, taken to the power of the elasticity of willingness to pay for health with respect to GNP:

$$\text{damage in Taiwan} = \text{damage in France x } \left(\frac{\text{Taiwan GNP per capita}}{\text{France GNP per capita}}\right)^{elasticity}$$

In 1998, French GNP per capita was $23,789 in 1997 US dollars, and the Taiwan GNP per capita was $13,819 in 1997 dollars.[62,63] The elasticity of willingness to pay with respect to income was estimated at 0.4 for Taiwan by an Alberini, Cropper, *et al*. study.[64] Note, however, that the original damages were obtained for a uniform distribution of population around emission sources, and a population density of 7500 persons per km^2 was used. Average density in Taipei is 1.27 times greater, for a final ratio of 1.022 for Taipei damages to Paris damages in terms of g/km.

Assuming a ten year vehicle lifetime and 10% discount rate means a final present value cost of emissions of $1,590. Spadaro and Rabl quote a very broad uncertainty in terms of a geometric mean standard deviation of 4.0, so that a 68% confidence level corresponds to $400 to $6,355. If elasticity is 1.0 rather than 0.4 (i.e. damage scales linearly with GNP), then the equivalent interval is $290 to $4,590.

This is a large amount and suggests that improvements in air quality would produce a significant benefit; a complete elimination of tailpipe emissions from the use of electric scooters could be a significant benefit over even four-stroke engines, the expected replacement for two-stroke engines. Of course, as the large geometric standard deviation suggests, this is only an attempt to broadly quantify the problem and is subject to the large uncertainties involved in any cost-benefit analysis.

1.2.7 Government policy approaches

Due to the problem of air pollution, several Asian governments have implemented measures to control two-stroke vehicles. For example, Thailand motorcycles have been restricted to 150 cc, "presumably ... to limit the maximum engine power, and thus the acceleration rates, top speed, and fuel consumption"[65]. In practice, the policy encourages use of *more* polluting two-stroke engines for their higher power at the same 150 cc displacement. Similarly, the city of Shanghai currently tightly restricts the supply of motorcycle licenses, although as previously discussed, all predictions point to vastly increasing Chinese vehicle usage. Taiwan's policy towards scooters, which is more advanced than virtually all of its neighbours, is discussed below.

1.2.7.1 Taiwan policy history: tighter emissions standards

Taiwan's 1991 ("second stage") standards were the strictest in the world, and essentially forced two-stroke motorcycles to be equipped with oxidation catalytic converters to meet these requirements. These catalytic converters cost approximately $80 for the manufacturer. To meet the 1991 standards, four-stroke motorcycles required modification to allow exhaust air injection (estimated cost $40-$60).[66]

Most Taiwanese motorcycle manufacturers depend on foreign (Japanese) parent companies for advanced technology, and catalytic converters are all imported. Naturally, Taiwanese manufacturers would like to produce them domestically.[67]

1.2.7.2 Later years: inspection and maintenance

In addition to tightening standards for new motorcycles and scooters, the Taiwanese government has acted to control emissions from highly polluting existing motorcycles. This is an effective method of cleaning up the worst offenders, which can account for the majority of the pollution. Originally, this consisted solely of roadside testing of emissions from randomly selected vehicles. Annual stationary emissions testing was begun in several counties. Testing was voluntary and there were no fines; incentive was provided by a system where drivers who brought in their vehicles for testing were given ballots to enter in a cash lottery.[68]

Later, a sticker system was implemented and as of 1998, motorcycle and scooter licenses can be revoked if the owner fails to bring in the vehicle for annual emissions testing. Vehicles that fail the test must be tuned up and brought in a month later for retesting; a second failure also means license revocation. By tackling the most errant vehicles, significant gains can be made; statistics report an average 48% reduction in CO emissions and 35% reduction in total hydrocarbons in offending vehicles after rechecking[69]. Currently, there are 456 inspection and maintenance (I&M) stations across the island, and approximately 400,000 scooters were inspected in 1996. Remote sensing is employed to measure CO and hydrocarbon emissions. [70]

1.2.7.3 Future direction: zero-emission vehicles

In 1991, ITRI researchers estimated that by 1996, up to 50% of scooters would have to be replaced by electric scooters to prevent continued degradation of air quality. This was in addition to the adoption of second stage emission standards and gradual replacement of the existing fleet by more advanced vehicles. No 50% replacement occurred, but a government policy was defined that required 2% of the scooter fleet to be zero-emission scooters by the year 2000.[71] This is almost as aggressive as California's clean air policy requiring zero emission automobiles, but whether either will succeed is uncertain.

The objective appears to be to convert small engine (50 cc) scooters to electric power, while keeping clean four-stroke engines for the larger (100 cc and up) scooters.[72] By 1997, there were approximately 300 electric scooters in use in Taiwan.[73] There is currently a $5,000 New Taiwan Dollar (USD $150) subsidy for each electric vehicle purchased.

This "Electric Motorcycle Development Action Plan" will be funded by the government at a cost of NTD $3.8 billion (USD $115 million) from 1999 to 2002. This money is to go to research funding and subsidizes for electric scooter purchases. Details of the plan are listed below.

Table 1.10 Electric Motorcycle Development Action Plan

Year	***Number of electric vehicles to be sold***	***Notes***
1999	10,000	Republic of China EPA to select specially designated locations for initial promotion The Kwang Yang Motor Co. (Kymco) plans to begin mass production in March, 1999 5% of annual motorcycle sales by manufacturers producing more than 50,000 motorcycles per year must meet special "low emission motorcycle" standards (see Table 1.3)
2000	40,000	Electric motorcycle sales required to comprise 2% of all motorcycle sales
2001	80,000	Electric motorcycle operating environment [recharging infrastructure, etc.] to be gradually put in place; sales to increase
2002	150,000	50% of two-stroke motorcycle sales anticipated to be replaced by electric motorcycle sales; four-stroke motorcycles will absorb the other half.
2003	200,000	Electric motorcycle technology to become mature; production of nickel [metal] hydrogen batteries to begin Introduction of fourth stage emissions standards; improvements in battery-powered scooter technology to reduce price below that of (not necessarily equivalent) four-stroke motorcycles.
2006	400,000	Continued growth of electric motorcycle sales; annual sales of electric motorcycles to reach 40% of *total* motorcycle sales.

The description of this plan is paraphrased from an Engine, Fuel, and Emissions Engineering, Inc. study and the March 1998 issue of the Taiwan EPA's *Environmental Policy Monthly*.[74,75] The latter source writes that

> Current trends indicate that by 2010 annual sales of motorcycles will reach 9 million units. It is estimated that electric motorcycles will make up one-third of this total, or three million units sold. If this sales rate is achieved, the EPA has calculated that carbon monoxide (CO) emissions can be reduced by 42,000 metric tons annually . . . Hydrocarbon and nitrogen oxide (NOX) emissions can be reduced by 23,400 tons, and carbon dioxide (CO2) can be reduced by 62,800 tons annually. As for energy savings, each year 2.2 million megawatt hours can be saved and off-peak electricity use rates can be raised.[76]

The “three million electric scooters” target seems extremely high, consider that only 400,000 are expected to be sold by 2006. A TTVMA (Taiwan Transportation Vehicle Manufacturers’ Association) study was also not as optimistic, estimating that by 2010 only 150,000 electric motorcycles will be produced, for an average unit price of $909 and a sales value of $136 million.[77]

For comparison, current electric scooters like the SWAP (Shang Wei Air Preserver) cost approximately $2,000[78], while ordinary two-stroke scooters cost on the order of $1,000.[79] Scooters currently have very low range and recharging is inconvenient due to the times involved and the fact that not all scooter owners have access to an electric outlet (for example, they may not have enclosed garages or parking off the street).

1.2.7.4 Research interest in fuel cell scooters

As of July 1999, several Taiwanese scooter manufacturers have explored the possibility of fuel cell scooters with North American research groups, hydride supplies, and fuel cell companies. Projects begun in the past two years include the following:

- A Department of Energy - funded contract awarded in 1998 to Energy Conversion Devices, a Michigan metal hydride manufacturer, to study hydrogen fuel for transportation (especially scooters) in developing countries.[80]

- A 1998 feasibility study of fuel-cell powered scooters performed by Sanyang Industry Company, the Taiwan Institute of Economic Research, the Desert Research Institute, and Texas A&M's Engineering Experiment Station. Partial funding supplied by the W. Alton

Jones foundation; one of the projects was to build a prototype scooter.[81] Please see Appendix G for more information on this prototype scooter.

- A collaborative fuel cell scooter development project spearheaded by the Taiwan Institute for Economic Research and including other Taiwan scooter concerns, announced in July 1999, and growing out of the previous study. The power system is to be based on a 3 kW fuel cell stack developed by fuel cell scientist John Appleby of Texas A&M, and hydrogen is expected to be produced by the China Petroleum Corporation, the Taiwan government's gasoline monopoly.[82]

Interest in fuel cell scooters has been growing rapidly in 1998 and 1999. The first step in understanding the technological issues, then, is the next chapter which describes electric scooters, and how they can be powered by either batteries or fuel cells.

1.2.8 Conclusion

Historically, two-stroke engines have been used for their high power density and low cost. Two stroke scooters have become a major cause of concern in many Asian countries due primarily to hydrocarbons short-circuiting through the chamber and escaping, unburned, in the exhaust.

Tightening government air pollution standards are squeezing out two-stroke engines in the policy leader, Taiwan. Four-stroke engines are a cheap and effective replacement. However, an additional benefit of several hundred, or even a thousand dollars could be realized by switching to electric scooters with their zero tailpipe emissions.

The target vehicle in this study is thus an electric replacement for the small 5 kW two-stroke scooter. A detailed comparison will be made between fuel cell scooters and battery-powered scooters using both conventional and advanced technologies

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2. Although relatively little work has been done, the interest is there from several parties as of September 1999. Vehicle manufacturers from Taiwan, which has more scooters than any other country in the world, have explored the possibility of fuel cell scooters with several North American fuel cell companies. The Desert Research Institute in Nevada had run a program to produce a prototype fuel cell scooter, while Energy Conversion Devices, a Michigan metal hydride and battery manufacturer, has analyzed the market possibilities for both combustion and fuel cell scooters run on hydrogen. Yamaha of Japan has studied the prospects for fuel cell motorcycles. So far, no results have yet been published aside from this work.

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