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Market prospects, design features, and performance of a fuel cell-powered scooter

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Abstract

This study investigates the market opportunities, the design features, and the technical performance of a scooter powered by Polymer Electrolyte Membrane (PEM) fuel cells. Market research was conducted in Bangkok, Thailand. A low-power scooter was designed and tested for the analysis. It is based on more extensive research at the Department of Mechanical and Aerospace Engineering, Princeton University [W. Colella, Fuel Cell Powered Scooters, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, 1997]. © 2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

The market opportunities, the design features, and the technical performance of a low-power PEM scooter are described in the three sections that follow (Sections 2–4). Section 2 focuses on the emerging zero-emission scooter market in Asian countries. Motor scooters, which include motorcycles, mopeds, autorickshaws, and power-assist bicycles, are the fastest growing vehicle market in Asia. In most Asian countries, scooters comprise over half the vehicle fleet. To combat the conventional scooter's pollution, several governments have mandated the adoption of low or zero-emission scooters. This section discusses the present motor scooter market, the resulting pollution, and current legislation creating the demand for zero-emission scooters. It also discusses several advantages that PEM scooters may have, as compared with PEM cars, in the commercialising process.

Section 3 discusses practical design issues of a fuel cell scooter. It outlines the driving requirements for a low-power scooter in an Asian city. Research was conducted in Bangkok, Thailand to gather accurate information on consumer behavior. Based on these specifications, the paper analyses various drive cycles. From these, it derives the vehicle's power and fuel needs.

Section 4 compares the actual performance of a low-power fuel cell scooter with a popular battery-powered scooter. The scooters were tested against various road terrain and wind conditions. Tests revealed that the battery system had an extremely low overall efficiency, compared with both its theoretical capability and that of conventional gasoline scooters. Tests also revealed that the fuel cell system was sometimes difficult to operate due to a loss of humidity in the membranes.

2. Zero-emission scooter market in Asia

The first generation of mass-produced zero-emission vehicles may not be cars, but motor scooters. Motor scooters, which include motorcycles, mopeds, and autorickshaws, represent over 50% of the vehicle fleet in many Asian countries (Fig. 1). Compared with other vehicles, they are growing at a much faster rate. Asia's 40 million scooters are growing at 18% per year [1]. China's scooter population is growing even faster at 30% [2].

In Asia, motor scooters are more popular than cars for several reasons. Firstly, in an area of the world where the average GDP per person in most countries is a fraction, 10% or less, of that of European countries, scooters are more attractive than cars because they are more affordable,

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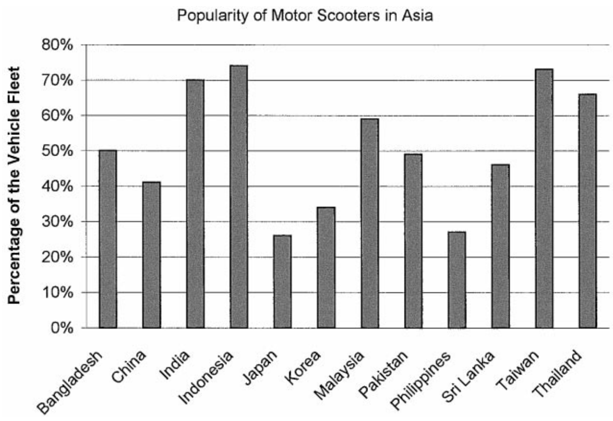

Fig. 1. Popularity of motor scooters in Asia.

at one-tenth the cost [3]. Secondly, scooters are popular because urban population densities are too high and the number of roads too few to support large numbers of cars. Because urban population densities are, on the average, three to five times higher than that of European cities, the typical city layout does not support an extensive car infrastructure [4]. Not only are roads too few, so are parking spaces. Thirdly, since traffic is a perennial problem in several cities, such as Bangkok, Shanghai, and Taipei, scooters are popular because they can more easily manoeuvre around the traffic.

Despite their popularity, motor scooters have a debilitating effect on local air quality and human health. They produce a disproportionate amount of vehicle pollution for their size. The majority of scooters use two-stroke engines. Two-strokes pollute more than conventional engines because they expel significant levels of unburned hydrocarbons during the dual intake and exhaust stroke, and they tend to misfire under low load conditions. As a result, organic particulate emissions from the average two-stroke in Asia are about the same level as those from a diesel truck [5]. Hydrocarbon, carbon monoxide, and lead emissions are also disproportionately high for their power output. For example, in Bangkok, motor scooters are responsible for between 50% and 80% of total particulate emissions from vehicles, and 30% to 60% of carbon monoxide and hydrocarbon emissions, despite the fact that they form only 36% of the vehicle population [6]. Consequently, scooters can be blamed for a preponderance of vehicle emissions in Asian cities. The effects of these emissions have already taken a serious toll on human health. For example, benzene, a hydrocarbon commonly found in exhaust, has been strongly linked with a greater incidence of leukemia [7]. The effects of these emissions have led communities to demand zero-emission motor scooters.

Many Asian governments have passed legislation to either restrict or ban two-stroke motor scooters. Zero-emission scooter initiatives have begun in Taiwan, India, Indonesia, Bangladesh, and China. For example, Taiwan's government recently ruled that in the year 2000, 2% of scooters must emit no pollutants [8]. The government also recently banned the production of additional two-stroke scooters, despite the millions of dollars this industry contributes to the local economy. Other Asian countries are following suit. As these examples show, the market is growing for zero-emission alternatives, such as a scooters powered by Polymer Electrolyte Membrane (PEM) fuel cells.

The introduction of zero-emission PEM scooters could significantly reduce pollution in Asian cities. If PEM scooters replaced 20% of the two-stroke market, this substitution would reduce emissions of carbon monoxide, hydrocarbons, and particulate matter by 6%, 11%, and 12%, respectively. Their introduction could play an even more significant role in certain Asian cities that rely particularly on scooters for transport. For example, if PEM scooters replaced 25% of two-strokes in Bangkok, the total particulate emissions from vehicles would be reduced by 20% [9]. According to the World Bank, a 20% reduction in particulate matter levels would reduce excess deaths from respiratory causes by between 362 and 4446 cases per year, with a saving in health costs and loss of productivity of between US$100 and US$1500 million [10]. [1]

In addition to its clear environmental benefits, a PEM-powered scooter may be able to achieve commercialisation with relative ease, especially as compared with a PEM-powered car. The reasons are both technical and financial.

One important, yet informal, rule of engineering is to keep an engineering project simple, at least in the initial stages. The more straightforward a system is, the easier it is to build, operate, and repair. The classic example is Henry Ford's Model T version of the automobile. Like the Model T, the power system for a scooter is a much simpler version of the power system for a car. The scooter's simpler system thereby gains weight, volume, and cost reductions. A scooter's power system is 10 to 20 times smaller than a car's, and with that reduction in power comes a simpler heat management system and fewer parts to manufacture. A scooter's power system also avoids the complexity of an onboard reformer. Considering that most reformers are, as yet, in proof-of-concept stage, by avoiding their use, one eliminates the need to overcome an additional technical hurdle. Altogether, the simplicity of the scooter's power system gives it an initial advantage in development and commercialisation.

An additional advantage in commercialisation is the probable simplicity of the refueling infrastructure as compared with that for a car. A fleet of PEM scooters avoids the need for a new, capital-intensive fuel infrastructure. If fueled by hydrogen, these scooters could be refueled by replacing a small (2 to 4 l) tank on board with a new one.

[1] The wide range here is due to uncertainty in the dose–response curve.

These tanks could be exchanged for new ones at convenience stores or local shops. Alternatively, if fueled by metal hydrides, the metal hydride cartridge could be replaced in the same way. As compared with a car fleet, a scooter fleet configured in this way would avoid the need for a capital-intensive refueling network and also achieve fast refuelling times, about 5 min.

As compared with cars, scooters might be able to achieve commercialisation more easily for purely financial reasons as well. All other aspects of a proposed business venture being equal, a less capital-intensive project may be perceived to be less risky than a more capital-intensive one. Due to the positive correlation between risk and expected return, a project with a lower perceived risk may obtain financing at a lower rate [11]. Scooter production is less capital-intensive than car production due to both the lower cost and complexity of the vehicle and the lower cost of the surrounding fuel distribution network. Regarding the first point, a given level of investment produces 10 times as many zero-emission scooters as cars. Considering the second point, a refueling network for a scooter fleet is likely to be less expensive than for a car fleet. A scooter refueling network avoids the high initial fixed cost of constructing a hydrogen pipeline infrastructure and capitalizes upon economies of scale in the mass-production and distribution of interchangeable fuel tanks. As a result of a lower level of capital intensity, a scooter project may be perceived to have a lower level of risk, and may, therefore, obtain finance more easily.

3. Design of a fuel cell scooter

In this study, a low-power PEM scooter based on a reasonable envelope of performance has been designed and built. A low-power scooter was chosen over a high-power one because of the limitations of the technology at the time of construction (1997) and the limitations of the budget. Although higher power PEM plants (between 1 and 10 kW) seem more suitable for certain types of scooters, such as motorcycles and autorickshaws, plants of this size had not yet been demonstrated in a sufficiently compact form [12]. Thus, the type of scooter with the lowest power requirements, a power-assisted bicycle, has been chosen. It was necessary to fund-raise US$6000 to cover the project costs.

A power-assisted bicycle uses a low-power source to turn a small motor attached to the bicycle's wheel at the hub or at the tire. Usually, such bicycles are powered by either two-stroke engines or batteries. In most power-assisted bicycles, the rider can pedal in combination with the power source to magnify power to the wheel. While also used in North America for recreation purposes, such bicycles are more commonly used in Asia on a daily basis for commuting. The demand for motor-assisted bicycles is over several thousand annually and, in recent years, has grown steadily.

3.1. *Envelope of performance*

The scooter was designed to meet the needs of the average urban commuter in Asia. An envelope of performance was developed based on urban driving cycles for scooters in Beijing and Taipei. The fuel cell plant was required to meet power demands under various scenarios. These are illustrated in Fig. 2 and Table 1.

The maximum speed is based on the average peak-hour driving speed for vehicles in Beijing (16 km/h) and concurs with maximum speeds achieved by many commercially sold assisted-bicycles [13]. The level of acceleration was chosen based on a reasonable zero to full-speed performance in 15 s. Although many of the major Asian cities have very flat terrain, the bicycle was required to have the capability to accelerate up a 10% gradient under power. Although cities like Beijing exhibit low average annual wind velocities [14], the bicycle was still required to withstand a wind of 2 m/s under another scenario. The bicycle was modeled as a Roadster, an old British Policeman's bicycle, due to the added weight and bulkiness of the power system. The bicycle was assumed to have the Roadster's aerodynamic drag coefficient, frontal area, and coefficient of rolling friction [15]. The bicycle's rider was assumed to have the same weight as an average Asian male (68 kg) [16]. Based on this information, the total power is then the sum of the power needed to overcome aerodynamic drag, the power to accelerate, the power to overcome friction, and the power needed to overcome gravity when travelling uphill.

The analysis highlights a few key points. Firstly, the power of the fuel cell system does not need to be as large as that of a battery system. Battery bicycles are overpowered due to their need for more energy capacity. Batteries, unlike fuel cells, contain a fixed amount of energy per unit weight. To increase their range, one must increase their size and, as a side-effect, their power level as well. Thus, battery-powered scooters cannot be used as a complete benchmark for sizing fuel cell scooters. Secondly, the analysis illustrates that at high speeds, most power is needed for overcoming wind resistance. Therefore, in designing scooters, special attention must be paid

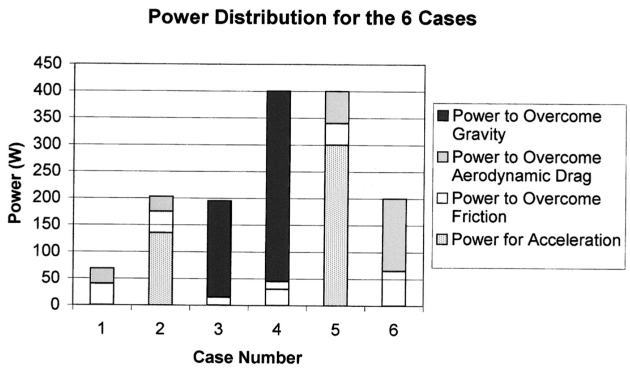

Fig. 2. Power distribution.

Table 1
Envelope of performance

Case	Road conditions	Speed (km/h)	Acceleration (m/s^2)	Power output by power system (W)	Power output by rider (W)
1	No wind, no hills	16	0	68	0
2	No wind, no hills		0 to 16 km/h in 15 s	205	0
3	No wind, 10% grade	6.5	0	200	0
4	No wind, 10% grade	12.6	0	200	200
5	Wind at 2 m/s, no hills	16	0.64	200	200
6	No wind, no hills	26.3	0	200	0

to the coefficient of drag and the frontal area to reduce drag force. Thirdly, to meet the envelope of performance requirements, the power plant onboard needs only to provide 200 W of power to the wheels. This conclusion assumes that a healthy rider can pedal fast enough to produce 200 W of power during peak demand times of 400 W, such as in scenarios 4 and 5 in Fig. 2. This is a reasonable assumption. Therefore, the power plant can be quite small (250 to 300 W to cover drive train and parasitic losses) while producing useful work.

A few additional calculations reveal that the fuel tank can also be quite small (2.4 l — the size of a soft drink bottle), while also providing a useful range for an Asian urban commuter. In Taipei, 70% of the daily driving time is for less than 1.5 h, and the average length of trips in many cities is less than 12 km [17]. Therefore, it is reasonable to design a scooter with endurance for a range of 3 h in between refills. Based on this range, it is appropriate to use a small cylindrical tank of hydrogen at 200 bar with a radius of 0.06 m and a length of 0.21 m for an urban commuter.

4. Testing and performance of PEM fuel cell and battery scooters

The PEM scooter specified above was tested against a battery electric scooter. One of the purposes of the analysis was to determine the present-day performance of each to illustrate where technological advancements still need to be made. Another was to provide a performance benchmark. Table 2 summarizes pertinent technical information about the two systems tested. The common feature of both technologies is their weight of about 5.4 kg.

The fuel cell system precisely matches the requirements specified above in terms of desired power output and range. The lead–acid battery system was chosen to match the weight of the fuel cell system and was provided by the electric bicycle company, ZAP Power Systems. As a result of the weight constraint, the maximum power outputs and volumes of the two technologies differed.

The two bicycles were tested against each other using a computer program and a dynamometer that together simulate changes in wind resistance and hill grade on the bicycle. The simulation program allowed both bicycles to be tested under various urban driving cycles in a consistent manner. Both systems relied on the same drive train and external control systems. The motor operated via friction drive on the back wheel.

The following discussion highlights only a few of the main conclusions from testing and analysis. More detailed discussions can be found in the associated thesis [18]. Tests revealed a direct trade-off between simplifying the design of the stack and reducing its performance.

4.1. Global efficiency

As shown in Table 3, while both the battery and the fuel cell performed below their theoretical global efficiencies, the battery performed comparatively much worse than its optimum point. Global efficiency is defined here as the overall efficiency from primary fuel production to the mechanical energy used to turn the bicycle's wheels. This was calculated on the basis that electricity and hydrogen were produced from coal [19]. In the case of the battery, a lower efficiency primarily resulted from a very low charging and discharging efficiency, peculiar to this battery system. Over half of the energy reaching the charger was dissipated as heat. Although this low charging efficiency was peculiar to this system, it is important to note that this system has been sold to thousands of customers, including 5000 units to China. Thus, systems in widespread use may deviate significantly from their optimal performance level.

Table 2
Comparison of fuel cell and battery systems

	Battery	Fuel cell
Total cost (US$)	95	6000
Total weight (kg)	5.4	5.4 (fuel cell), 1.8 (tank), 0.9 (valves)
Total volume (cm^3)	2304	14,009
Maximum power (W)	800	300
Energy storage (kJ)	700	5360
Range (h)	0.25 to 1.25 depending on load	4 at full power
Refueling time (min)	5 to switch to a new battery	5

Table 3
Battery scooter

	Power plant conversion of coal to electricity	Charging and discharging	Motor and drive system	Global efficiency	
Estimated efficiency	35%	80%	90%	25%	
Measured efficiency	35%	30%	50%	5%	
Fuel cell scooter					
	Gasification of coal to hydrogen and compression	Compression at refill station	Fuel conversion	Motor and drive system	Global efficiency
Estimated efficiency	64%	86%	50%	90%	25%
Measured efficiency	64%	86%	46%	50%	13%

The battery bicycle's global efficiency of 5% is so low as to engender genuine concern as to whether an environmental improvement is being made with the substitution of two-stroke scooters for battery-powered ones.

By contrast, the fuel cell system demonstrated a high fuel conversion efficiency, relative to its stated efficiency, 46% vs. 50%. Most of the drop in global efficiency results from the poor efficiency of the drive train, 50% vs. 90%. Yet, poor motor performance can be easily remedied by substituting a hub mounted motor for the friction drive one. Hub motors for bicycles have been produced by at least one Japanese company and have achieved a 95% efficiency [20]. Therefore, in the comparison between these two systems, the fuel cell achieved a global efficiency closer to its theoretical maximum. The poor results for the battery are peculiar to this particular battery, but are still significant because this is the type of battery system that is being mass-produced.

4.2. Humidity imbalance with simple stacks

The correct balance of moisture proved to be an operational problem for the membrane-electrode assembly. The membrane may dry out or flood. In the case of a dried out membrane, a hole may form. The stack dried out while sitting in a heated room and three holes formed in the membranes. Holes allow the direct combination of hydrogen and oxygen. This is perhaps the greatest danger for the PEM fuel cell [21]. On the other hand, if a membrane becomes overly moist, the reactant ports may flood, which greatly inhibits the delivery of reactants to the cell. After a system has been left to sit for days, the relative moisture in each cell will vary greatly. The correct balance of moisture is a particular problem with simple systems because, to simplify the system and reduce its volume, the inlet gases are not humidified. The humidity of the inlet stream then depends much more heavily on ambient conditions. This dependence on outside humidity has implications for design considerations; the stack must be designed to withstand humidity changes that result from changes in climatic region, changes in the seasons, and daily variations. Despite the problems encountered here, humidity imbalance may be overcome with better engineering design, more precise control systems, and proper care of the stack.

4.3. Response

As expected, the battery system responded instantaneously to changes in demand, although the quality of its power degraded with time. The same maximum power could not be achieved in the fifth minute as in the first minute. As a result, electric vehicle engineers must design around this problem, for example, by projecting the maximum speed level that the battery system will produce over time as the battery discharges, and then, limiting the power drawn by the motor to within the battery's power plateau.

The fuel cell system also achieved instantaneous response. However, it did encounter some problems in doing so. Rapid acceleration caused flooding of the stack and decreased instantaneous efficiency in the absence of purging. With respect to response at start-up, after the stack had remained dormant for a period, it performed below its average for the first few minutes of operation as humidity levels stabilized.

4.4. Separation of cooling and oxidant streams

One of the fuel cell stack's drawbacks is the tendency of its membranes to dry out. Drying may result from flushing water out of the cells with too large a stream of air. In this particular system, the air flow may have been too high because the cooling and oxidant streams were combined into one. For this size of stack, the oxidant stream need move at only one-third the pace of the cooling stream to deliver adequate quantities of air. Although combining the two streams simplifies the stack's construction, it also exacerbates the tendency of the membrane to dry out.

5. Conclusion

Although they must overcome many technical obstacles, PEM scooters show great promise as a product for the long-term future. Progress is continually being made towards their development. For example, this research was later continued at Princeton; a paper study of PEM power systems for large scooters has now been published as part of a Masters dissertation [22]. Also, a year after the completion of this research, H-Power of Belleville, NJ, built its own, more sophisticated PEM-powered scooter. Finally, in the summer of 1999, Ballard Power Systems announced a US$250,000 contract to supply fuel cells to Yamaha Motor of Japan, one of the largest motorcycle manufacturers in the world. For PEM-powered scooters, the future looks increasingly promising.

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