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Weinert, Jonathan X.

Ogden, Joan M.

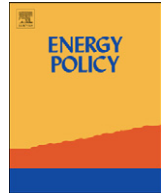
Sperling, Dan

et al.

Publication Date

2008-05-01

Peer reviewed



The future of electric two-wheelers and electric vehicles in China

Jonathan Weinert*, Joan Ogden, Dan Sperling, Andrew Burke

Institute of Transportation Studies, University of California, Davis, CA, USA

ARTICLE INFO

Article history:

Received 14 November 2007

Accepted 5 March 2008

Available online 5 May 2008

Keywords:

Electric two-wheeler

E-bike

Electric vehicle

ABSTRACT

The method of force field analysis is used to examine the future technological and market evolution of electric two-wheelers (E2W) in China. The authors identify key forces driving and resisting future E2W market growth, root causes behind these forces, and important insights about the likelihood of a wide shift to larger three- and four-wheel electric vehicles (EV). The authors conclude that the key forces driving E2W market growth are: improvements in E2W and battery technology due to product modularity and modular industry structure, strong local regulatory support in the form of gasoline-powered motorcycle bans and loose enforcement of E2W standards, and deteriorating bus public transit service. The largest forces resisting E2W market growth are strong demand for gasoline-powered motorcycles, bans on E2Ws due to safety concerns in urban areas, and growing support for public transit. The balance of these forces appears to favor E2W market growth. This growth will likely drive vehicle electrification through continued innovation in batteries and motors, the switch from lead-acid to Li-ion batteries in E2Ws, and the development of larger E2Ws and EVs. There are however strong forces resisting vehicle electrification, including battery cost, charging infrastructure, and inherent complications with large battery systems.

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1. Introduction

Electric two-wheelers (E2Ws) are gaining widespread acceptance in China; it is arguably the most successful electric-drive market in the world. If E2W success continues, it may accelerate the development of batteries and larger electric vehicles (EV). Their rapid adoption was a response to the timely convergence of some key trends that started in the late 1990s. Incomes were rising, allowing consumers to move from regular bicycles and public transport to E2Ws. Gasoline-powered motorcycles (including scooters) were banned in several cities due to worsening air pollution. Battery and motor technologies improved dramatically, allowing better E2Ws (Jamerson and Benjamin, 2005). Urban trip distances rose due to rapidly expanding cities, encouraging faster, longer-range bicycles.

Fig. 1 shows the growth in motorized vehicle sales over the past decade (CNBS, 2006; Honda, 2006; Jamerson and Benjamin, 2007; Ohara, 2006). By 2006, annual sales of E2Ws equaled those of gasoline two-wheelers (G2W). It is likely that E2Ws will continue to substitute for bicycles and public transit as incomes rise in China. Depending on policy initiatives, they may also continue to replace motorcycles, and may lead to wider electrification of China's transport sector.

1.1. Motivation

One billion cars—this is the projected size of the world's vehicle fleet in just 20 years, and a significant increase from the 700 million light-duty vehicles on the world's roads today (ExxonMobil, 2006). The majority of this vehicle growth over the next two decades will occur in non-OECD countries, with the largest growth expected in China and India. The fuel of these future cars is important to the health of the hundreds of millions who dwell in the densely packed cities of these countries due to the lower local emissions of EVs compared with gasoline vehicles.

The effect of vehicle electrification on carbon emissions is more dubious. China's grid is currently more carbon intensive than the US (1 kg CO₂/kWh_{China} vs. 0.58 g/kWh_{US}) due to high coal use (IEA, 2007), making the carbon benefits of EV over gasoline vehicles questionable (Hirota, 2008).¹ As China's grid decarbonizes from increasing generation from renewables and nuclear power, EV provide a pathway toward future low-carbon personal transportation.

This study attempts to understand the future role of E2Ws in China. This includes both their role in today's two-wheeler dominated market, and also the spillover effects they may have

¹ A study by Nissan in 2007 estimated the CO₂ emissions from a plug-in hybrid vehicle (PHEV) in China has roughly equivalent emissions as a regular gasoline hybrid electric vehicle (HEV), while the same PHEV in the US would have 70% the emissions of an HEV.

* Corresponding author.

E-mail address: jxweinert@ucdavis.edu (J. Weinert).

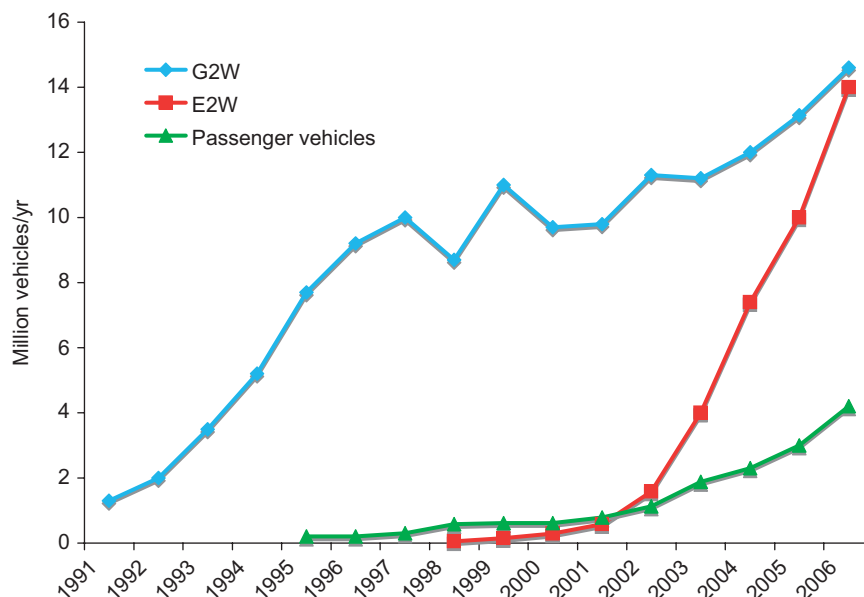


Fig. 1. Motorized vehicle sales in China.

on the growing automotive market by facilitating better batteries for hybrid, plug-in hybrid, and full battery EV.

1.2. Methodology

In this study, we use force field analysis (FFA) to understand the complex set of forces influencing future E2W growth in China and the relationships between these forces. FFA is useful tool for creating a descriptive model of a complex system that intersects many disciplines (technical, social, political, etc.).

1.2.1. FFA introduction

FFA is a tool for analyzing the forces pushing a system toward change and the forces resisting it. FFA, created by Kurt Lewin (1952), was originally used to study organizational behavior and group dynamics. Since then, it has been used to analyze the factors affecting complex systems, the interactions between these factors, and understanding how the system might respond. The philosophy behind this approach is that “a wider and wider realm of determinants must be treated as part of a single interdependent field and that phenomena traditionally parceled out to separate “disciplines” must be treated in a single coherent system of constructs” (Lewin, 1952). FFA has been used in a wide variety of disciplines from studying the technological innovation process within organizations (Levi and Lawn, 1993), to analyzing conservation efforts to improve biodiversity (Watts and Selman, 2004). It is also useful for corporations who are considering strategic or technological changes (Alexander, 1988, from (Levi and Lawn, 1993; Thomas, 1985), implementing cost reduction strategies (Ajmal, 1985), and as a decision management tool (Ajmal, 1985; Johnston, 2006).

1.2.2. FFA steps

This analysis has five steps:

1. Identify the system of focus and boundaries (Section 2);
2. Generate list of driving and restraining factors (Sections 3 and 4);
3. Determine the inter-relatedness of these factors (Section 5);
4. Quantify the forces (Section 6); and
5. Chart the force field diagram (Section 6).

The data used for this analysis draw upon previous work by Weinert et al. (2007a–c), which includes interviews with E2W manufacturers and users of E2Ws and bicycles, on-road observations of E2W traffic, visits to dealerships in 10 cities throughout China, and site visits to both battery and E2W factories. The remaining data have been gathered through the available literature, including company websites.

1.3. Background

The two-wheeler types most commonly used in China include bicycles, gasoline-powered motorcycles, and E2Ws. These types are classified in Table 1 according to key attributes.

1.3.1. Electric two-wheelers

E2Ws are a category of vehicles in China that includes two-wheel bikes propelled by human pedaling supplemented by electrical power from a storage battery (bicycle-style), and low-speed scooters propelled almost solely by electricity (scooter-style). There is a spectrum of styles between these two types that almost all E2Ws styles fall into. In most cities, E2Ws are allowed to operate in the bicycle lane and are considered a bicycle from a regulatory perspective (i.e. helmets and drivers licenses are not required).






1.3.2. Gasoline-powered motorcycles

Gasoline-powered motorcycles (henceforth referred to as “motorcycles”) in China include both scooters (or, mopeds) and traditional motorcycles. The main differences between these two types are scooters usually have “step-through” design with foot platform as opposed to the “cub” style, and do not have manual transmission (Meszler, 2007). LPG scooters are excluded from the analysis since they are found only in Shanghai.

1.3.3. Comparison of E2Ws and motorcycles

The following section compares E2Ws and motorcycles on the basis of cost, well-to-wheel energy use, mobility, and environmental impact (air and solid emissions). Using 2007USD, life-cycle E2W cost is ~\$4/100 km (\$9 using the PPP-adjusted exchange

Table 1
Classification of Chinese two-wheelers

Classification	Types	Power (engine size)	Top speed (km/hr)	Fuel consumption (/ 100 km)	Range (km)	Picture
Bicycle			10–15	n/a	n/a	
Electric two-wheeler (E2W)	Electric bicycle	0.25–0.35 kW	20–30	1.2–1.5 kWh	30–40	
	Electric scooter	0.3–0.5 kW	30–40	1.5 kWh	30–40	
Motorcycle	Gasoline moped/Scooter	3–5 kW (50–125 cc)	50–80	2–3 L (Feng et al., 2007)	120–200	
	Gasoline motorcycle	4–6 kW (100–125 cc)	60–80	2–3 L	120–200	

rate² (World Bank, 2008)) compared with bicycles at less than \$1 (\$2 PPP-adjusted) not including cost of food energy required, and \$7/100 km (\$15 PPP-adjusted) for motorcycles (Weinert et al., 2007a). In terms of well-to-wheels energy use, a motorcycle uses four to five times as much energy (10.3 MJ/km) as a similarly powered E2Ws (2–3 MJ/km).³ The main difference in energy use is at the tank-to-wheels stage, where motorcycles use 75% of their total upstream energy (Meszler, 2007). The E2W in contrast spends most of its energy in the production of electricity (Cherry, 2007; Wang, 2002). In terms of speed, E2Ws are generally faster than bicycles and slower than motorcycles (Ma, 2007). While CO₂, CO, VOC, PM, and NO_x emissions are lower for E2Ws, SO₂ and solid waste from E2W operation is significantly higher than motorcycles, based on a life-cycle analysis, with 2.7 g/km of solid waste (63% from coal combustion and 14% from the battery waste) compared with 1 g/km for the motor-bike (Cherry, 2007; Zhang et al., 2001). Lead emissions from E2Ws are estimated as high as 5–10 g/100 km due to inefficiencies in the dispersed, small-scale lead production and recycling process (Cherry, 2007).

1.3.4. The motorized two-wheeler market in China: past, present and future

E2Ws emerged from virtual non-existence in the 1990s to achieve annual domestic sales of 13.1 million and sales revenue (includes exports) of \$4.6 billion in 2006 (ZJBW, 2007). E2W

ownership is estimated between 33 and 45 million (Feng et al., 2007).⁴ In comparison, the domestic motorcycle market reached annual sales of 14.6 million units and its sales revenues (includes exports) are estimated at \$19.2 (CEIN, 2007) billion. According to official statistics, motorcycle ownership in China reached ~80 million by 2005 (CNBS, 2006).⁵ For comparison, there are ~460 million bicycles and 13 million cars.

Vehicle ownership statistics may underestimate the degree of E2W use in China's cities. Based on limited surveying by the author in 10 cities (small, medium and large), E2Ws make up 28% of total two-wheeler traffic on average, compared with 57% bicycles and 15% G2Ws.⁶ The majority of these users (70–90%) are shifting from bicycle and public transit, according to survey results from Shijiazhuang, Kunming, and Shanghai (Weinert et al., 2007a).⁷

Total M2W ownership is projected to grow until 2025, at which point private cars ownership begins to overtake them (ADB, 2006). Growth forecasts for the E2W industry are optimistic, with projected sales of 18.1, 22.7, and 30.1 million units in 2007, 2008, and 2010, respectively (Woolf, 2007).

⁴ Thirty-three million is based on the author's calculation of population from annual domestic sales data and an average vehicle lifetime of 5 years.

⁵ The Asia Development Bank estimates the 2005 motorcycle population lower at 55 million (ADB, 2006).

⁶ Data were obtained by measuring vehicle flow at various intersections throughout each city. Total sample size: 8297 (Hangzhou—364, Chengdu—487, Nanjing—224, Jinan—356, Xian—193, Shanghai-city—3226, Shanghai-outer suburbs—1270, Tai An—219, Weifang—41, Tianjin—976, Shijiazhuang—600, Beijing—341). This average only represents 11 cities throughout China and thus should not be taken as a true national average.

⁷ Survey data may under-represent a shift from motorcycles because it only includes cities where motorcycles have been banned for years and does not include rural areas.

² The purchasing power parity (PPP) exchange rate accounts for the difference in living standards between China and the US. The PPP exchange rate is 1 USD = 3.4 Chinese yuan, compared with 7.5 real exchange rate in 2007.

³ This assumes the fuel efficiency of a low-power gasoline-pedal bike (30 cc) is 31 km/l and an E2W (350W) consumes 1.5 kWh/100 km.

2. Driving forces: shift to E2Ws

The key forces supporting the growth of the E2W market are:

- Cost and performance improvements
- Motorcycle bans
- Local policy support for E2Ws
- Poor bus public transit service

2.1. Force 1: technology improvements

Improvements in E2W and battery technology are driving E2W market growth. This section provides evidence of past improvements in these technologies, examines their causes, and discusses why they are likely to continue. This force has three components: technology development, industry structure, and product structure. Innovations in both product and process have led to these improvements.

2.1.1. Technology development

Cost reduction and performance improvement of E2W and battery technology has been occurring at a steady rate since E2Ws were first commercialized in the mid 1990s. Since the late 1990s, there have been improvements in battery lifetime (160%), energy density (30%), and motor efficiency (60%) (Weinert et al., 2007a). By 2006, VRLA battery technology from three top E2W suppliers had reached cost and performance levels achieved by a leading Japanese supplier (Weinert et al., 2007c). Meanwhile, the price of E2Ws has steadily decreased due to a combination of both falling costs and shrinking profit margins. Between 1999 and 2005, average E2W price dropped nearly 30% from \$380 to \$240 (\$840 to \$529, PPP-adjusted) (CMIC, 2007).⁸

An indicator of E2W technology improvement is their increasing size, power, and speed. At the Zhejiang E2W Exhibition in October 2007, seven manufacturers displayed E2Ws with 500 W, 60 V battery systems and regenerative braking. Two companies displayed products with power as high as 1 and 1.5 kW, attaining speeds of 60–80 km/h. Manufacturers stated these products were for the domestic market and were sold mostly in suburban areas where commute distances are longer.

The emergence of large scooter-style E2W in suburbs and rural areas where incomes are low, travel distances far, and motorcycles are not banned is significant. It could indicate that they are becoming competitive with motorcycles, if not on a performance basis yet, at least on a cost-basis. E2Ws are even found in mountainous areas where topography demands higher power.⁹

Another sign of innovation is the growing proportion of advanced batteries used in E2Ws. The majority of the E2Ws in China use valve-regulated lead-acid (VRLA) batteries, though E2Ws using lithium-ion (Li-ion) and nickel-metal hydride (Ni-MH) are for sale at a limited amount of dealerships and retail outlets. Between 2005 and 2006, the share of advanced-battery E2Ws produced increased from 10% to 13% (1.1–2.1 million) (CMIC, 2007). Although the majority of advanced-battery E2Ws are likely destined for export markets based on observations of E2Ws in use around China, Chinese Li-ion battery manufacturers and the E2W companies they supply are reporting increasing domestic sales.¹⁰

There are at least four battery manufacturers in China producing Li-ion batteries for E2Ws and EVs.¹¹

2.1.2. Industry structure

Technology improvements of Force 1 described above can be partly attributed to the highly decentralized, “open-modular” E2W industry structure. This type of industry structure, coined by Ge and Fujimoto (2004), is also found in the modern computer industry and several other Chinese manufacturing industries (Steinfeld, 2002). It is worth examining because it has been shown to drive rapid product innovation and cost reduction via fierce price competition. It contrasts with the more traditional closed-integral structure characteristic of more mature manufacturing industries.

In an open-modular (O-M) industry, manufacturers act primarily as assemblers and source components (“modules”) produced by a large decentralized network of suppliers. This type of structure is typically found when a product exhibits high modularity, meaning it can be divided into several modules that are copied, mass-produced, standardized, and easily bought on the market. “Open” refers to the nature of the relationship between assemblers and suppliers, who are free to design and develop parts independently and thus able to work with multiple firms due to the high degree of product modularity (Baldwin and Clark, 1997). The O-M structure typically results in increased competition and lower costs (Fig. 2).

In a closed-integral (C-I) architecture, assemblers work together closely with a few key suppliers to develop a product in a top-down approach. The assemblers develop high technical capability and in turn nurture this capability in their few trusted suppliers. This industry structure was adopted by the Japanese motorcycle industry in the 1960s, and is characteristic of the automotive industry in general (Ohara, 2006). Fig. 3 adapted from (Ge and Fujimoto, 2004) contrasts the two structures.

The emergence of open-modular industries is a relatively recent phenomenon, and its effect on innovation has been the subject of much analysis (Steinfeld, 2002; Sturgeon, 2002; Tapscott and Williams, 2007; Yusuf and al., 2003). They conclude that this structure (along with other factors) leads to lower production costs compared with a closed-industry structure due to enhanced competition and cross-pollination of ideas. Evidence of this exists in the Chinese motorcycle industry and its ability to capture the lead market share position from the incumbent Japanese motorcycles industry (Ge and Fujimoto, 2004; Ohara, 2006; Sugiyama, 2003). The key drawback of this structure, however, is that assembler firms do not develop as much technological capability and thus risk the threat of “technology lock-in”. Table 2 compares the key differences of these two structures, summarizing the work of the researchers listed above.

Typically, industries are highly decentralized until a dominant design is settled on and considerable shake-out and industry rationalization occur (Utterback, 1994). Despite the emergence of a dominant E2W design, the E2W industry has thus far shown little evidence of concentration. Sales data from the top five manufacturers made up only 15.2% of national E2W sales in 2006; the top 10 manufacturers made up 27.2% (CMIC, 2007). There were 1300 E2W assemblers in 2005, resulting in a industry-average production volume of a merely 8000 units/company (CEBQMI, 2006a). Some manufacturers believe there are as many as 1000 more “unofficial” assemblers illegally producing E2Ws (Weinert, 2006). There are reportedly 100’s of VRLA, motor, and controller assemblers as well.

⁸ In a personal communication, one Taiwanese motorcycle manufacturer conceded that E2Ws are beating motorcycles in some markets on the basis of cost.

⁹ Based on visits to several homes in the countryside, where it was observed that many families own both motorcycles and E2Ws, and roadside observations.

¹⁰ Includes Zhejiang’s LBH and Tianjin’s Lantian.

¹¹ Includes Phylion (Suzhou), Wanxiang EV Company (Hangzhou), Lantian (Tianjin), and Qingyuan EV Company (Tianjin).

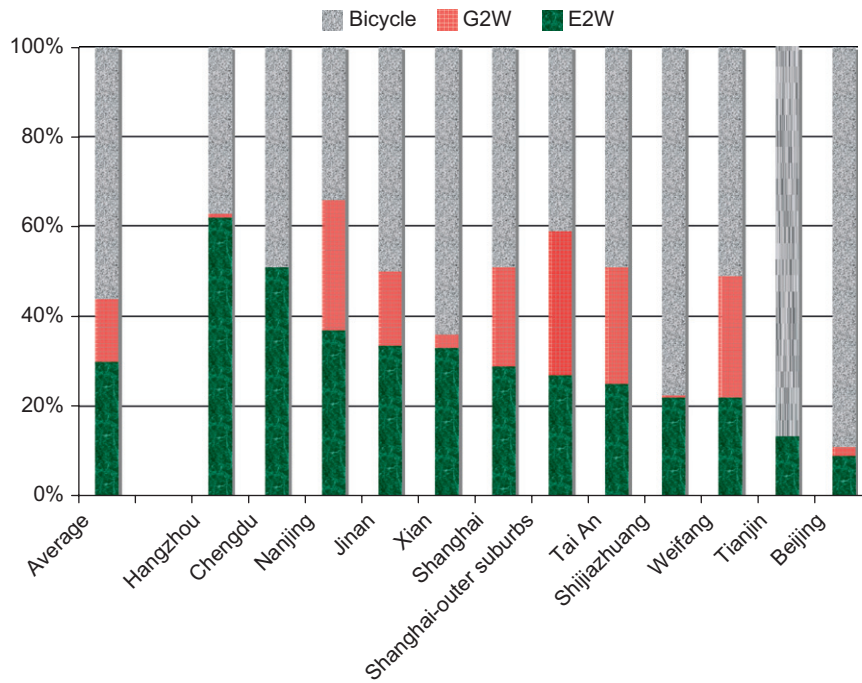


Fig. 2. Observed two-wheel vehicle proportions in Chinese cities, 2006–2007.

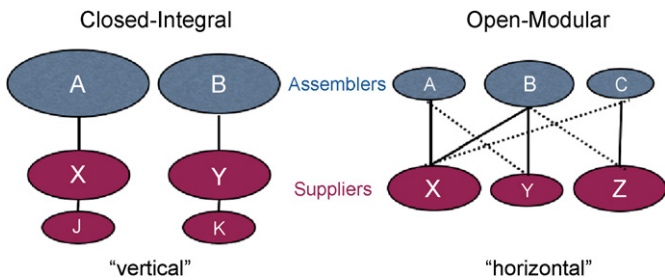


Fig. 3. Industry structure comparison, closed-integral vs. open-modular.

2.1.3. Product structure

The open-modular structure of the E2W industry and its rapid pace of innovation is due in part to the highly modular product architecture of E2Ws¹² (Ulrich, 1995). Product modularity reduces the cost of manufacturing through mass production of standardized components, allows for greater flexibility in design and manufacturing, and lowers barriers to entry for firms.

A product is considered *modular* if it can be segmented into parts that are functionally and structurally independent, do not require much information exchange, and whose interfaces are relatively simple. A computer is an often-cited example of a highly modular product. Modularity in manufacturing is not a new concept, but has gained more attention since the late 1990s due to globalization and increasing recognition of its importance for businesses managing global supply chains (Baldwin and Clark, 2004; Ge and Fujimoto, 2004; Ulrich, 1995; Utterback, 1994).

E2Ws meet the first criteria of modularity because most key functions of the vehicle are assigned to just one component (e.g. battery stores energy, motor delivers power). E2Ws also meet the second and third criteria of modularity: simple interfaces with minimal information exchange. For instance, the core modules of the drivetrain are connected through electrical wire interfaces. This both increases design flexibility and reduces assembly cost. Vehicle assembly in most plants is accomplished by unskilled manual labor using pneumatic tools.¹³ Machining is not required at the assembly plant because components are pre-fabricated, and interfaces exhibit greater tolerance to error. Designers also have more flexibility in positioning modules to enhance comfort, convenience, and styling, as seen in the various models shown in Fig. 4 (folding E2W, standard E2W, and e-scooter).

Interface flexibility and simple information exchange between the interfaces of E2W are one of reason for the wide variance in body style (e.g. E2W vs. e-scooter), module positioning, and

¹² Product architecture refers to the “arrangement of functional elements of a system” and “the specification of the interfaces between interacting components” (Ulrich, 1995).

¹³ Based on site visits by the author to six E2W plants.

Table 2 Comparison of open-modular vs. closed-integral industry structure

Industrial architecture	Open-modular (networked production)	Closed-integral
Driver of innovation	“Creative destruction”, simultaneous competition and cross-pollination (Schumpeter, [1911] 1968; Steinfeld, 2002)	Steady accumulation of tacit knowledge within long-lived corporation
Source of competitive advantage	Cost cutting	Large R&D budget
Product development	Bottom-up (supplier-driven)	Top-down (assembler-driven)
Process development	Mastering open, codified processes	Developing proprietary processed
Firm size	Small- and mid-size	Large
Supplier network	Large, isolated, open, horizontal	Small, integrated, closed, vertical
Firm relationship with suppliers	Arms length	Close
Component interface between different brands and models	Standardized	Limited to within company
R&D capability	Low	High
Higher profit margins	Supplier	Assembler
Unit of importance	Environment/clusters	Firms



Fig. 4. E2W design flexibility.

Table 3
E2W modules and standardized options

Component	Standardized features	Options
Battery	Type	VRLA, Li-ion, Ni-MH
	Voltage	36, 48, 60 V
Motor	Power	240, 350, 500 W
	Configuration	In hub (with or without rim), external to hub
	Type	Brush, brushless
Controller Charger	Control mode	Brush-type, brushless type
	Input/output voltage	One size fits all

module technology substitution (e.g. VRLA vs. Li-ion). In contrast, motorcycle design has inherent limitations in module positioning and fuel flexibility.¹⁴

The highly modular nature of E2Ws has led to standardized sizes, performance levels, and interfaces. Once standardized, components become easily interchangeable between models and manufacturers, giving assemblers and suppliers more freedom in their choices for partners and facilitating a more open industry structure. Because a supplier's product can potentially be sold to many different assemblers, it leads to increased production volume and lower cost.

Standardization also facilitates substitution of competing battery or motor technologies with little or no redesign required of the other modules. This allows for faster design changes and technology upgrading. It is driving innovation in the VRLA, Li-ion, and Ni-MH battery industries as each competes for a larger stake in the expanding E2W market, both domestically and internationally. Table 3 shows the standardized specifications of the key modules within an E2W.

Standardized technology with simple interfaces has lowered the barriers to entry into this industry, another reason for the large number of firms in the industry. Manufacturers of bicycles, appliances, toys, and motorcycle have all been successful entering the E2W business.¹⁵

2.2. Force 2: local motorcycle bans

The power of policy in China has given E2Ws a strong advantage via the banning of gasoline-powered motorcycles in many large- and medium-sized cities throughout China. This policy, driven by air quality concerns, has spread from 30 cities in 1998 to 148 by 2006 and effectively diminished motorcycle demand (Sinocars.com, 2006; Sugiyama, 2003). Fig. 2 illustrate

the large difference in motorcycle share between cities that allows motorcycles (Shanghai, 32%, only LPG type), and cities where they are strictly banned (Chengdu, 0%).

2.3. Force 3: local policy support for E2Ws

Besides banning motorcycles, cities have adopted other approaches to encouraging the use of E2Ws and the growth of the E2W industry. These local regulatory approaches, including policies aimed at traffic congestion relief, loose enforcement of national E2W and battery standards, and loose enforcement of intellectual property rights, are also driving a shift to E2Ws.

Traffic congestion in urban areas drives regulatory support of E2Ws. While E2Ws are less efficient users of road space than buses (per passenger), they are more efficient than automobiles (Cherry, 2007). In 2006, Beijing reversed their intended ban against E2Ws, in part due to the worsening traffic congestion in the city. A testimony from one E2W user in Beijing illustrates the advantage of E2Ws in congested traffic: "I want to buy an electric bicycle to deliver and pick up my son from school. It's less of a headache and quicker," says the 34-year-old mother. "It takes only 10 min by electric bicycle, but a half-hour drive in the Beijing traffic" (Mo and Chihua, 2007).

National E2W standards are seldom enforced at a local level, allowing manufacturers to produce and consumers to buy larger E2Ws with higher speed and power. These standards set strict limits to performance criteria and require a minimum level of quality, though few manufacturers adhere to them. The strong market demand for faster, higher power models creates an incentive to produce models that violate the standard. This problem is not unique to the E2W industry, and is thought to be due to the way power at a state level is distributed amongst local governments. Though supporting evidence on why this occurs is insufficient, some speculate it is because local governments who control quality inspections like to support local manufacturers to boost tax revenue (Steinfeld, 2004). This support sometimes comes in the form of exemptions or minor fines for violating the standard (Weinert et al., 2007a).

Loose IP protection in the E2W industry has lowered barriers to entry for E2W and battery firms, resulting in a more open-modular industry and lower costs. Several of the managers surveyed by the author from large E2W companies complain that IPR is not well protected in the industry (Weinert, 2006). The thousands of models of E2Ws show very little variation in performance and only moderate variation in design. Many manufacturers model their E2W designs and even their logo to an almost perfect duplication of a more famous company.

2.4. Force 4: deteriorating bus public transit service

The quality and service level of bus public transit is worsening in cities, causing greater demand for cheap motorized private

¹⁴ Shanghai is the only successful market in China of alternative fuel motorcycle use, where they use liquefied petroleum gas.

¹⁵ One surveyed E2W manufacturer used to make only motorcycles but started producing E2Ws when the market took off stating, "it was easy for us to make the shift to producing E2Ws because the technology is much simpler."

transportation. For most low and middle-income users, bus public transit's largest user base, E2Ws are their next best alternative. A survey in Shijiazhuang found the majority of E2W users shifted from bus public transit because it was too slow and over-crowded (Weinert et al., 2007b). Another study comparing bus and E2W speeds in Kunming and Shanghai traffic reveals that for travel distances under 18 km, it is faster to take an E2W than bus due to the slow travel speeds of buses on congested corridors (Cherry, 2007). Note, however, that substitution from bus to E2W does not imply that traffic conditions overall will improve.¹⁶

There are several reasons why urban bus transit is losing its competitiveness; the root causes can be traced to urbanization and rising income. Transit systems have difficulty adding capacity fast enough to serve its rapidly growing low-income user base, mainly people from rural areas. Rising income is driving motorization in cities (Schipper and Ng, 2006), resulting in more private vehicles (two-wheelers and automobiles) on the road, increasing traffic congestion, and making buses slower.¹⁷ As buses become slower, it has the cyclic effect of shifting even more people to private transport. Thirdly, cities expand and decentralize due to the increase in urban population and growing use of private vehicles (both motorized two-wheelers and automobiles) (Zegras and Gakenheimer, 2006). Decentralization increases the set of trip origins and destinations, an inherent challenge for public transit systems that are most profitable when serving high-corridor routes. The trends of urbanization and rising income are expected to continue. Between 2006 and 2030, 40 million people are forecasted to move from the countryside to the city, equivalent to roughly two more Shanghais (Schipper and Ng, 2007).¹⁸

2.5. Other forces

E2Ws have been encouraged by the Development Research Center of the National Development and Reform Commission to support national energy efficiency goals stated in the 11th Five-year plan. While road-based passenger transportation makes up 70 million tons of oil equivalent (mtoe) in China in 2006, it is expected to increase to 165 mtoe by 2020 (Menon, 2006). E2Ws energy use per km is ~20–25% that of motorcycles on a well-to-wheels basis. They have been recommended by the state as a means of saving energy and improving the environment (Wang, 2006).

The existing legacy of bicycle infrastructure pervasive throughout China's cities is another factor driving E2Ws growth. Users rely on the non-motorized vehicle lane and parking infrastructure to improve travel speed, safety, and convenience. This extensive infrastructure, a legacy from 1949 policy decisions, may explain E2W's current success in China versus other Asian countries with high two-wheeler use. Shanghai is restructuring its middle-ring road to create a dedicated lane for bicycle and E2W traffic. It marks the cities first extensive restructuring for cyclists since they first banned cycling in certain parts of downtown during the past decade (Zhang, 2007).¹⁹

¹⁶ In fact, the contrary may occur due to erratic driving of E2Ws in traffic, which is a reason Guangzhou has banned motorized two-wheelers in favor of public transit.

¹⁷ Motorization increases with rising income, a pattern followed by every developed country, due to demand for greater accessibility and safe, comfortable travel.

¹⁸ Based on urban population of 560 million in 2006 and a projected population of 600 million by 2030 (Schipper and Ng, 2007)

¹⁹ In Shanghai, LPG scooters are allowed so this policy will also likely benefit them as well.

3. Resisting forces: shift to E2Ws

The forces resisting a shift towards E2Ws include:

- Strong demand for motorcycles;
- E2W bans; and
- Increasing support for public transit.

3.1. Force 1: strong demand for motorcycles

In most of Asia, motorcycles using the internal combustion engine and gasoline (and sometimes LPG) have become the dominant choice for personal mobility because of their high power and speed, low cost, ease of refueling, reliability, and long life. In response to air quality concerns and rising fuel price, motorcycle fuel economy and emissions control technology continues to improve through innovation on engine design and emission control technology (Meszler, 2007).

For the higher-income market segment, E2Ws using VRLA battery technology have difficulty competing with motorcycles due to inherent limitations in terms of power, speed, refueling, and lifetime (Weinert et al., 2007c). In addition, their performance (range and lifetime) degrades quickly in areas where temperatures are very high throughout the year, or very low (Ohmae et al., 2006). This partially explains why they have failed to catch on in SE Asia and India where bicycles and motorcycles dominate the roads (Jamerson and Benjamin, 2007). For the domestic Chinese E2W market, the benefit to cost ratio of Li-ion batteries is not yet compelling enough to create a noticeable shift away from Pb-acid batteries, as indicated by the state of the domestic E2W market.

3.2. Force 2: E2W bans

Seven cities throughout China have banned or restricted E2Ws in recent years, in addition to banning motorcycles. Some officially cited reasons for the bans include improving traffic flow, increasing road accidents, and reducing environmental pollution from worn-out batteries (ShanghaiDaily, 2005). As automobile ownership grows, it is reasonable to assume pressure to improve traffic flow and allow automobiles to move at a faster speed by removing two-wheelers from roads, will also grow. Two-wheelers (electric or gasoline powered) create several disadvantages to automobiles because of their slower speeds and erratic driving behavior, which disrupt traffic flow and pose safety risks. They also "occupy more road space (compared with buses), and dilute the market for public transport" (Zegras and Gakenheimer, 2006).

Pressure for E2W bans may also increase due to the abundance of low-quality and unsafe products on the market, which can be traced back to loose enforcement of E2W standards. Many users complain that E2W brakes are insufficient for the weight and speed of the vehicle. Low-quality VRLA batteries have poor lifetime and thus lead to greater lead waste. A sample of E2W products from 40 manufacturers in 2006 revealed only 74% of them passed the quality standards (CEBQMI, 2006a). A sample of E2W VRLA batteries from 35 manufacturers revealed only 77% of the batteries passed the quality standards (CEBQMI, 2006b). Thus loose enforcement of standards is a double-edged sword for E2Ws (see Driving Force 3). It allows manufacturers to sell products that violate the standard though are highly desirable by customers, however, it also leads to more low-quality products on the market.

Lead pollution from VRLA battery production and recycling use could lead to greater environmental backlash against their use.

The lead mining, smelting, and recycling industries in China are highly dispersed and many are small scale, resulting in high loss rates due to poor management, weak regulation, and the use of out-dated inefficient technologies (Cherry, 2007; Roberts, 2006). It is estimated that 44–70% of the lead from lead-acid batteries in China is released into the environment as waste (Cherry, 2007). Ground water and crop contamination from hazardous chemical and metals has already caused some local health problems throughout the country (Zamiska and Spencer, 2007).

Cities banning E2Ws as of 2007 include Guangzhou, Dongguan, Haikou, and Changzhou (no longer licensing E2Ws, preparing to issue a ban). E2Ws are partially banned in Zhuhai, Shenzhen, and Xiamen. Guangzhou, one of China’s largest and most motorized cities, banned motorized two-wheelers to improve traffic safety and traffic flow.

3.3. Force 3: increased support for public transit

Increasing financial and political support for public transit, especially bus rapid transit, could reduce the shift from bus to E2W discussed in Section 2.4. Bus rapid transit (BRT) has been gaining support in China as a means to improve transit performance by converting or constructing bus-only lanes, building stations, and leveraging information technology (Chang, 2005; Darido, 2006). BRT can be a lower cost alternative to light or heavy rail, which only China’s large wealthy cities have built (e.g. Shanghai, Beijing, Shenzhen, Guangzhou, Hong Kong, Nanjing, and Tianjin). The first cities to demonstrate BRT systems were Beijing (21 km), Hangzhou (28 km), and Kunming (32 km). In recent years, cities like Dalian (14 km), Jinan (135 km planned), Shijiazhuang, Chengdu, Changzhou, and Shanghai have constructed or have plans for building a BRT network. Successful demonstrations in these cities may lead to even greater support and more demonstrations throughout China. Guangzhou and Shanghai have announced in their Five-year plans their intention to strongly enhance public transit service, both rail and bus transit.

4. Inter-relatedness of forces

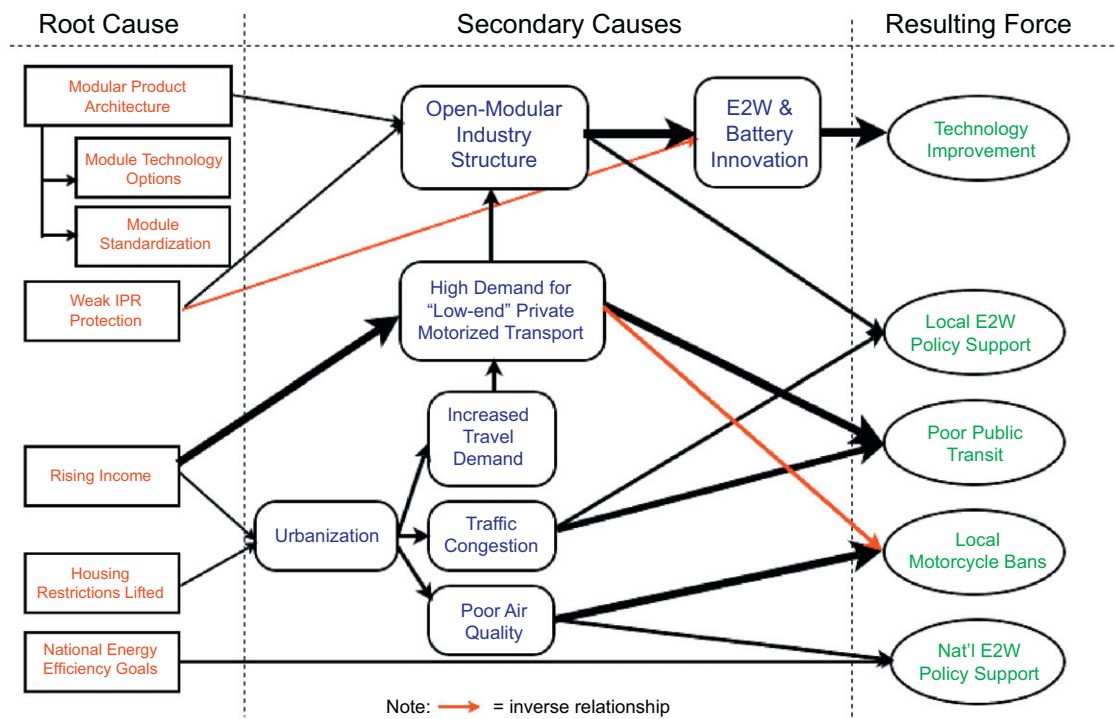
The forces and their root causes listed in Section 3 are inter-related in complex ways. To add clarity to the complexity of these relationships, they are mapped into visual diagrams (Figs. 5 and 6). Direct relationships (*increasing X increases Y*) are joined with black lines; inverse relationships (*increasing X decreases Y*) are joined with red lines. Thick arrows indicate major force while thin arrows indicate minor, though these rankings are to some degree subjective. The diagrams for driving forces and resisting forces inter-relatedness are separated for clarity, though there are some inter-relationships between the two. While we have attempted to include the most important root causes for these forces, this diagram is necessarily incomplete due to the limited scope of the paper.

5. Quantifying the forces

The driving and resisting forces described in the above sections are “quantified” by relative ranking. It is challenging and perhaps impossible to assign a measurable quantity to forces involving a market of hundreds of millions of people, several large industrial sectors, and complex regulatory dynamics. Quantification is thus simplified by ranking the effects of each force in terms of magnitude of impact and probability of occurring using a rating of low (L), medium (M), and high (H) (Table 4). The ratings are based on an understanding of the root causes for each force described in the previous sections though they are of course largely subjective. An improvement to this method would be to ask people within the E2W industry or government officials to rank each factor and compile the results.

The rankings above indicate driving forces (via their key effects) outweigh the resisting forces pushing a shift to E2W are charted in Fig. 7.

Through this qualitative and semi-quantitative analysis of the key factors driving and resisting growth of the E2W market, driving forces appear to outweigh resisting forces 19 to 12.



Note: → = inverse relationship

Fig. 5. Forces driving E2W market growth.

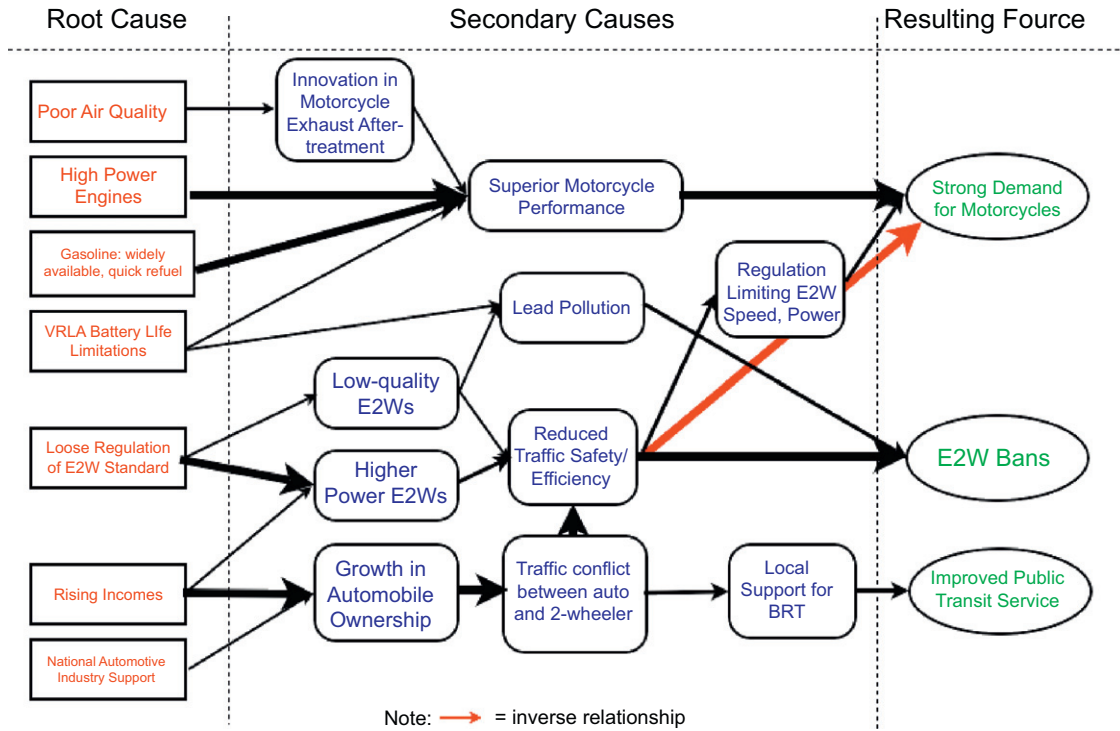


Fig. 6. Forces resisting E2W market growth.

Table 4
Rankings of driving and resisting forces

Force	Magnitude of impact	Likelihood	Ranking (L = 1, M = 2, H = 3)
<i>Driving</i>			
Technology improvement	M	M	4
Motorcycle bans	H	H	6
Local E2W policy support	H	M	5
Strained public transit	M	M	4
<i>Resisting</i>			
Strong motorcycle demand	H	M	5
Spread of E2W bans to more cities	H	L	4
Enhanced support for public transit	M	M	4

6. Implications on vehicle electrification

The previous sections show that future E2W market growth is likely to continue. This section examines the impact this growth may have on adoption of EV (sub-compact and 3-wheel type). Using a simplified FFA, we examine the driving and resisting forces to this adoption and their causes.

6.1. Driving forces

6.1.1. Battery improvements

Based on the pace of innovation in E2W and batteries over the past decade and its root causes (see Fig. 5), improvements are expected to continue. In 2007, several new products aimed at increasing VRLA battery lifetime and E2Ws with Li-ion batteries were displayed at the 2007 Shanghai Bicycle and E2W Exhibition, and several of the larger manufacturers sell E2Ws with regenerative braking systems.

System: Chinese 2-Wheeler Market

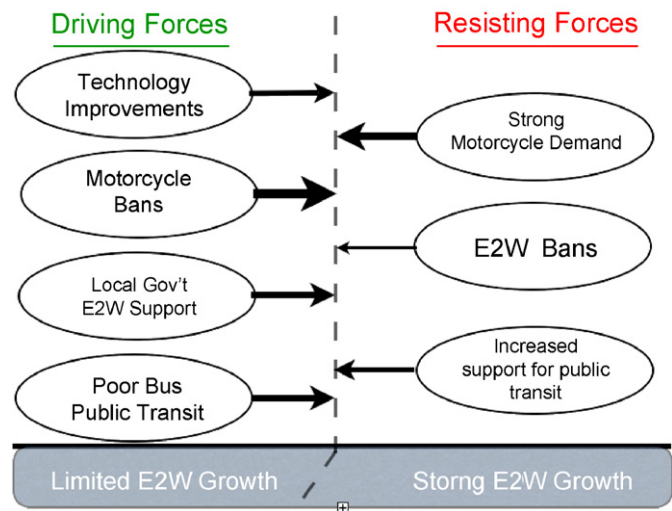


Fig. 7. Force field analysis of driving and resisting forces to E2W growth.

Innovation in Li-ion battery technology for EVs could be accelerated by the shift to VRLA to Li-ion in the E2W market. Because of similarities between E2W and EV batteries, experience gained in R&D, manufacturing, and operation in the E2W battery market will transfer to EVs. At least three Li-ion battery companies are making batteries for E2Ws with the strategy to build up production volumes with the E2W market and eventually shift to producing batteries for EVs.²⁰ Currently, the domestic market for Li-ion battery EVs is small due to high battery cost, though the market is growing (Weinert et al., 2007c). The rapid rise in lead price since late 2006 may further hasten the shift to

²⁰ Personal communication with one Li-ion battery manufacturer, April 2007.



Fig. 8. Electric vehicles offered by E2W firms.

Table 5

Specifications of electric vehicle made by E2W makers

	Company		
	Yadea 3-wheel EV	Incalcu EV	Shiwei EV
Cost (\$USD)	2600–7900	2600–5300	3800
Range (km)	80–120	100–150	100–150
Speed (km/h)	45 ± 10%	45	45–60
Power (kW)		3	3
Dimensions (l,w,h) (m)	2.9 × 1.3 × 1.7	3.1 × 1.6 × 1.5	
Weight (kg)	400	650	750
Battery	VRLA	VRLA, 48 V, 9 kWh	VRLA, 48 V (120Ah, 12 V modules)

advanced batteries for E2Ws in the domestic Chinese market.²¹ (Walls, 2007) VRLA battery price (75% lead by weight) has increased by 50% since that time.

6.1.2. Expansion into new product lines

E2W and battery manufacturers are already expanding into producing higher-margin product lines due to the competitive nature of an open-modular industry structure. Companies typically expand into higher-margin product lines to escape fierce cost competition in the existing low-margin product line. Historical evidence of this trend exists in the E2W evolution from bicycle-style to scooter-style to motorcycle-style, and in other open-modular industries in China (Steinfeld, 2004). According to one E2W manufacturer, profit margin for luxury E2Ws is 8% vs. 5% for standard bicycle-style E2Ws (Weinert, 2006).

Producing automobiles clearly requires much greater technological capability and resources than producing two-wheelers, depending on the size and type of vehicle. However, the challenges are not insurmountable, as proven by at least one motorcycle manufacturer. Chongqing Lifan, one of China's largest motorcycle manufacturers, has successfully begun producing and selling automobiles in 2007 after 3 years of preparing its technological capability and receiving authorization from central government (Li, 2006). Four of the top 10 E2W firms have crossed the chasm from two to four wheels by selling electric three- and four-wheel fully enclosed EV, each using the same VRLA battery technology from E2Ws (sample models shown in Fig. 8).²² Their specifications are listed in Table 5.

²¹ The price spike has reportedly been caused by both the rapid rise in demand in China, combined with a supply constraint due to a mine problem in Australia are the main reasons for this price increase (Walls, 2007).

²² From manufacturer websites: <http://www.yadea.com.cn/tezhong.htm>, <http://www.incalcu-ev.com/product/view.asp?id=1533>, http://www.shiweichina.com/product_info.asp?id=7579.

6.2. Resisting forces to vehicle electrification

Future vehicle electrification is impeded by high battery cost, lack of recharging infrastructure, constraints on electricity supply, and inherent technical challenges of large battery systems. The current high cost of batteries relative to transmission/engine drivelines is the major barrier to EV commercialization. Table 6 shows the large cost difference between E2W and EV battery system. Future battery cost is difficult to predict and is a function of cumulative production volume, design, material composition, and raw material price. The recent growth in market share of advanced-battery E2Ws discussed in Section 2.1 reflects the current market trend. In the global hybrid electric vehicle market, no automakers have yet sold vehicles using Li-ion battery technology though Toyota and GM plan to switch to Li-ion on some of their models in 2009.

The lack of recharging infrastructure is another obstacle. High-voltage recharging stations would be required for EVs, unlike E2Ws whose batteries are removable and can be charged from the ubiquitous 120V AC outlet. To recharge an EV requires the user to have daily access to a high-voltage charging station. In a country where the urban majority live in multi-level residences, it is extremely challenging to provide universal access to recharging facilities.

Electricity-generating capacity is another potential constraint to EV growth. Rolling brownouts were common throughout China in 2004 due to demand for electricity out-stripping peak production. In 2007, manufacturers in Guangdong Province experienced several brownout alerts due to tight electricity supply (Greising, 2007). Increasing EV use would increase peak electricity demand if users charge during the day. A fleet of one million EVs would require roughly 10 TWh of additional power generation capacity, equivalent to a fleet of 50 million E2Ws.²³ This is less than 0.5% of China's projected electricity demand in 2020, which is estimated between 2200 and 5800 TWh (Kahrl and Roland-Holst, 2006). It is possible that many EV users would recharge at night using off-peak electricity. A survey of E2W users reveals that the majority recharge at night due to long recharge time and to take advantage of off-peak pricing, however, it is common to see E2Ws being charged during daytime at work locations.²⁴

Managing battery safety and lifetime is one of the key differences between E2W and EV battery systems. Due to the large number of cells in an EV battery pack, it requires careful heat management, cell state-of-charge monitoring, and current leakage detection to ensure safe charging/discharging and minimum cell

²³ Assumes vehicle efficiency of 0.40 kWh/km, annual driving distance of 14,000 km/yr/vehicle, combined electricity transmission and charging efficiency of 60%. E2Ws are assumed to consume 0.015 kWh/km and travel 8000 km/yr.

²⁴ 20 E2W users were surveyed. Some who stated they charge at home said they sometimes charge at work to take advantage of "free" electricity.

Table 6
Cost comparison of battery systems for E2W and EVs

	E2W battery system		EV battery system		Gasoline engine (20 kW)
	VRLA	Li-ion	VRLA ^a	Li-ion	
Cost (\$)	100	420	800	4850	1000
Mass (kg)	20	8	270	90	60
Lifetime (yr)	3	9	2	6	12
Volume (L)	10	5	110	60	6
Max continuous power (kW)	2.4	3.8	27	44	20
Assumptions	VRLA	Li-ion	Gasoline engine		
Specific energy (kWh/kg)	0.035	0.11	n/a		
Energy density (kWh/L)	0.086	0.17	n/a		
Max continuous specific power (kW/kg)	0.1	0.5	0.33 (Heywood, 1988)		
Power density (kW/L)	0.67 ^b	0.74 ^b	3.5 (Heywood, 1988)		
Cost (\$/kWh)	130	500	50 (\$/kW)		
Cycle life	300	800	n/a		
Battery energy required	E2W = 0.84 kWh, EV = 9.6 kWh				

^a The EV in this table is based of the Reva two-door Classe model. Gasoline engine characteristics for a similar sized car (20 kW) are provided for comparative purposes.

^b Based on specific power and densities of 2.8 and 2.1 kg/L for VRLA and Li-ion batteries, respectively.

variability in order to maximize battery life (Rossinot et al., 2003).²⁵ This is especially true for Li-ion battery systems, whose safety risks include battery overheating, combustion, and explosive disassembly. These risks increase with the amount of energy contained within the battery pack.²⁶ To reduce the risk of safety problems with Li-ion batteries, China's *Center for Electric Bicycle Products Quality Monitoring & Inspection* should adopt rigorous standards and testing procedures to prevent low-quality products entering the market (CEBPQMI, 2006).

7. Conclusions

This analysis examines the key forces driving and resisting strong market growth of E2W, what is causing these forces, and how these forces are inter-related using FFA methodology. Through this analysis, we conclude improvement in E2Ws and battery technology is a driving force that can be partially attributed to the open-modular industry structure of suppliers and assemblers. This type of structure was made possible by the highly modular product architecture of E2Ws, which resulted in product standardization and enhanced competition amongst battery technologies. Growing air quality and traffic problems in cities in part due to rapid urbanization has led to strong political support for E2Ws at the local level in the form of motorcycle bans, and loose enforcement of E2W standards. There are softer signs of national support for this mode in part due to national energy efficiency goals. Public transit systems in cities have become strained from the effects of urbanization and motorization, which has stimulated greater demand for “low-end” private transport.

There are also formidable forces resisting E2W market growth. The superior performance of motorcycles is a powerful limiting factor, especially in areas where motorcycles are not banned and incomes are high. Bans on E2Ws could also limit their growth if it continues to spread to more cities. Two factors influencing this spread are automobile use and loose enforcement of E2W

standards that allow low-quality E2Ws to be sold. Some large cities around China are also trying to promote public transit in order to reduce automobile congestion. Added investment in transit infrastructure such as BRT may improve performance to compete better with E2Ws and other forms of private transit.

Based on results of the FFA, we conclude that driving forces appear to outweigh the resisting forces for E2Ws. This may lead to accelerated adoption of EV. Growth in the EV market is dependent on continued improvement in battery cost and performance and the development of larger E2Ws vehicles. Two trends in the E2W industry may facilitate this development, namely its open-modular industry structure and modular product design.

However, there are some major obstacles facing EVs that will not be easy to overcome in China. The largest is the issue of recharging infrastructure, which will need to be built since EV batteries are not portable like E2W batteries. Even with advancements in Li-ion specific energy, battery packs will be too heavy to remove from the vehicle to a charging station in or near the residence of the EV owner. Cell variability, safety issues related to high-voltage and unstable battery chemistry in Li-ion are other obstacles.

A shift from gasoline-powered vehicles to EVs in Chinese cities, like the shift from G2Ws to E2Ws in recent years, would have several concrete benefits including local air quality improvement and reduced dependence on imported petroleum. However, because of the high carbon intensity of grid electricity caused by heavy reliance on coal power, a shift to EVs could result in a net increase in CO₂ emissions. Furthermore, if future EVs use lead batteries, lead contamination of soil and water could be exacerbated.

To capitalize on the full benefits of electric-drive transport, policy makers in China should consider measures to lower the carbon intensity of the grid. The recently passed Renewable Portfolio Standard and increasing crackdown on small inefficient coal power plants are examples of policies that will help achieve that goal. Encouraging a transition to advanced batteries (e.g. Li-ion, Ni-MH) for EVs would also reduce environmental waste problems from lead batteries.

From a local perspective, E2Ws can be an energy efficiency, low-emission form of private transport in small and medium size cities where public transit service is limited or the city is geographically disperse. On the other hand, larger cities with

²⁵ When connecting several cell modules in series, any variance in cell voltage between modules causes accelerated aging because the “weakest” module of the pack ages most rapidly (Rossinot et al., 2003).

²⁶ The high voltage of EVs (300 V vs. 36–48 V for E2Ws) creates another safety concern during vehicle repair or emergency response.

the resources to construct efficient public transit systems may benefit from reducing motorized two-wheeler use on roads with high motorized vehicle use.

Acknowledgments

The authors would like to acknowledge the China Center for Energy and Transportation at the Institute of Transportation Studies—UC Davis for financial support to conduct this research. We would also like to acknowledge the contributions of Jack Johnston, Xinmiao Yang, Chaktan Ma, Chris Cherry, Wei Xuezheng, Lee Schipper, and Haixi Ni for their helpful guidance and research assistance.

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