ELECTRIC BIKES in the People's Republic of China

Impact on the Environment and Prospects for Growth

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ISBN 978-971-561-793-2
Publication Stock No. RPT090040

Cataloging-In-Publication Data

Asian Development Bank.
Electric bikes in the People's Republic of China: impact on the environment and prospects for growth.
Mandaluyong City, Philippines: Asian Development Bank, 2009.

1. Transport. 2. Electric bikes. 3. Environmental effects. 4. People's Republic of China.
I. Asian Development Bank.

This report was prepared by consultants based on results of the Technical Assistance on Rolling Out Air Quality Management in Asia, funded by the Swedish International Development Cooperation Agency and the Asian Development Bank (ADB).

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Abbreviations

ADB	–	Asian Development Bank
AGM	–	absorptive glass mat
BAU	–	business as usual
BRT	–	bus rapid transit
BSEB	–	bicycle-style electric bike
CNY	–	yuan (People's Republic of China)
CO	–	carbon monoxide
CO_2	–	carbon dioxide
E2W	–	electric two-wheeler
e-bike	–	electric bike
FFA	–	force field analysis
FLA	–	flooded lead acid
G2W	–	gasoline two-wheeler
Li-ion	–	lithium-ion
NiMH	–	nickel-metal hydride
PM	–	particulate matter
SLI	–	starting, lighting, ignition
SCE	–	standard coal equivalent
SO_2	–	sulfur dioxide
SSEB	–	scooter-style electric bike
VRLA	–	valve-regulated lead acid

Weights and Measures

Ah	–	amp-hour
cc	–	cubic centimeter engine displacement
GJ	–	gigajoules
g/km	–	gram per kilometer
g/kWh	–	gram per kilowatt-hour
g/yr	–	gram per year
km/hr	–	kilometer per hour
mg/km	–	milligram per kilometer
MJ	–	megajoules
mtoe	–	million tons oil equivalent
pax-km	–	passenger-kilometer
ppm	–	parts per million
PSI	–	pound per square inch
V	–	volt
Wh	–	watt-hour

In this publication $ refers to US dollars.

Acknowledgments

This report is part of Sustainable Urban Mobility in Asia, a program supported by the Asian Development Bank through a grant from the Swedish International Development Cooperation Agency. It was prepared by Christopher Cherry of the University of Tennessee–Knoxville; Jonathan Weinert, independent consultant; Yang Xinmiao of Tsinghua University; and Eric Van Gelder of the Institute of Transportation Studies, University of California, Davis.

The authors would like to express their gratitude to Masami Tsuji, James Leather, and Yan Zong of the Asian Development Bank; and Sophie Punte, Herbert Fabian, and Sudhir Gota of the Clean Air Initiative for Asian Cities Center (CAI–Asia Center) for providing valuable comments and guidance in the preparation of this report.

Executive Summary

Electric bikes (e-bikes) provide cheap, convenient, and relatively energy-efficient transportation to an estimated 40 million to 50 million people in the People's Republic of China (PRC) as of 2007. They are quickly becoming one of the dominant travel modes in the PRC. As e-bike use grows, however, concerns are rising about lead pollution from their batteries and emissions from their use of grid electricity, primarily generated by coal power plants. This report examines the environmental performance of e-bikes relative to other competing modes, their market potential, and the viability of alternative battery technologies. The analysis is divided into five sections. Section 1 describes the environmental impact of e-bikes in the PRC. Section 2 analyzes the environmental impact of alternative modes and compares e-bike emissions with those of alternative modes. Section 3 discusses market potential and identifies factors that influence e-bike adoption. Section 4 presents prospects for battery technology improvements in the near and long term. Finally, section 5 frames the role of e-bikes in the PRC's transportation system and recommends policies for the central government and the cities of the PRC. A brief summary of each section follows.

Section 1: Energy Use and Emissions of Electric Bike Life Cycle

E-bikes generate environmental impacts through several processes. Although they do not emit any local "tailpipe" emissions, they do require traditional grid electricity sources to recharge their batteries. This electricity, generated mostly from coal power plants, emits traditional pollutants that are commonly associated with gasoline vehicles. They also emit disproportionately high levels of sulfur dioxide (SO_2) because of the high sulfur levels in coal burned to generate electricity. Power generation emission factors in grams per kilowatt-hour (g/kWh) are estimated and then extrapolated to e-bike emission rates during the use phase. A more detailed analysis shows that in some provinces, electricity generation has significantly lower emissions because of more reliance on hydropower (primarily in the south) than provinces where electricity generation is more reliant on coal (primarily in the north). Notably, medium-sized e-bike use-phase emissions are in the range of 15.8–27.3 grams (g) of carbon dioxide (CO_2) per kilometer (km), 4.2–39.7 g SO_2/100 km, 0.3–1.9 g particulate matter $(PM)_{2.5}$/100 km, 0.6–3.1 g PM_{10}/100 km, and 2.5–9.4 g nitrogen oxides (NO_X)/100 km, depending on region.

When considering the life-cycle environmental impacts of e-bikes, lead pollution from industrial processes stands out as a clear challenge to the environmental sustainability of this mode, even with nearly 100% recycling rates. Because the large batteries are replaced every 1–2 years, a medium-sized e-bike introduces 420 milligrams (mg)/km of lead into the environment through mining, smelting, and recycling. This pollution is emitted in various forms of solid, liquid, and airborne waste. Many of these emissions are the result of small-scale, informal lead-producing operations, which are difficult to regulate or monitor. Section 4 discusses alternative battery technologies that could resolve some of these problems.

Section 2: Environmental Impacts of Alternative Modes

The environmental performance of e-bikes relative to other competing modes in the PRC is an important comparison. E-bikes are more environmentally friendly on almost all metrics than cars or taxis. However, based on user surveys, most e-bike users would otherwise use other low-cost modes, such as bus or bicycle. In these cases, e-bikes have comparable or worse environmental performance on some metrics and better performance on others. E-bike environmental performance relative to bicycle, motorcycle, bus, and car is analyzed using reports and industrial statistics. The environmental impacts in this analysis include energy use and emissions of CO_2, SO_2, PM, hydrocarbons, carbon monoxide (CO), and lead over the production and use phases of the life cycle. This analysis shows that e-bike emissions, including material production and vehicle use phases, perform comparably to buses and significantly better than motorcycles and cars on most environmental metrics.

Compared with a loaded bus with 50 passengers, an average medium-sized e-bike emits about 15% less CO_2 per passenger-kilometer (pax-km). E-bikes also emit fewer hydrocarbons and CO and use less energy per pax-km than buses. Compared with buses, e-bikes emit higher levels of SO_2 and PM over their life cycle and two orders of magnitude higher lead emissions per pax-km.

Compared with a motorcycle, e-bikes perform very well on almost all metrics. All estimated motorcycle emissions are several times higher than those of an e-bike, with the exception of SO_2 and lead. This research shows that e-bikes and scooters can provide a more environmentally friendly alternative to motorcycles in cities where motorcycles are widely adopted. They can also fill a niche that is commonly filled by motorcycles in cities where motorcycles are restricted. Moreover, they can provide cost-effective and environmentally efficient transportation services where bus service is difficult to supply.

Section 3: Influence of Electric Bikes on Motorization Trends

This section examines the impact e-bikes may have on motorization by forecasting e-bike market growth and motorcycle market growth up to 2050 and identifying the most important factors driving and resisting future e-bike growth. Based on projections from literature, the motorcycle market is set to expand over the next 20 years and then decline around 2030 as per capita income begins to exceed CNY30,000 ($4,325), causing a shift toward automobiles. Because there are no long-term projections of e-bike growth in the literature, we create three future e-bike and motorcycle scenarios: "business as usual", "e-bike thrive", and "e-bike stagnate", using assumptions from literature and our own sources.

Results of this modeling and scenario analysis show three key points. First, in all scenarios, e-bike and motorcycle numbers grow rapidly over the next several years. Second, both motorcycle and e-bike numbers decline around 2030 as rising incomes drive a shift toward automobiles (although the rate of each depends on the spread of motorcycle bans throughout the PRC). Third, in the "e-bikes thrive" scenario, e-bike populations actually overtake motorcycle populations by 2040.

The method of force-field analysis is used to examine the future technological and market evolution of electric two-wheelers (E2W) in the PRC. 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. The key forces driving growth are improvements in E2W and battery technology because of 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 transportation service because of congestion and oversubscription. The largest forces resisting growth are strong demand for gasoline-powered motorcycles, bans on E2Ws because of safety concerns in urban areas, and growing support for public transport. The balance of these forces appears to favor E2W market growth.

This section also examines the e-bike market outside the PRC and finds that the market for e-bikes in Southeast Asian countries is small to nonexistent, although some project optimistic growth for India. Factors influencing e-bike growth in Southeast Asia are identified based on the force field analysis (FFA) of the future e-bike market in the PRC.

Section 4: Electric Two-Wheeler Battery Technology Status

Rapid growth of the e-bike market has been in part due to improvements in rechargeable valve-regulated lead acid (VRLA) battery technology in the PRC. Further growth in the market and a transition from VRLA to lithium-ion (Li-ion) batteries may in turn lead to greater improvements in performance and cost.

VRLA and Li-ion battery technology for e-bikes has been assessed in this section. For VRLA, a specific energy of 34 Wh/kg and a cost of $130/kWh were determined from a number of international brands. Li-ion batteries in the PRC on average have specific energy of 110 watt-hours (Wh)/kg and cost $560/kWh. In the case of nickel-metal hydride (NiMH), one manufacturer quoted a cost of $300/kWh for a NiMH battery pack. Although Li-ion batteries have significantly higher initial cost, they also have a longer lifetime. Considering the life-cycle user cost, Li-ion is 60% more expensive than VRLA. A widespread shift from VRLA to Li-ion batteries seems improbable for the mass market in the near term given the cost premium relative to the performance advantages of Li-ion batteries.[1] However, as Li-ion battery technology gains more real-world use in e-bikes and other applications, it may become more competitive. Unpredictable fluctuations in lead and lithium price may also alter economic competitiveness. Cell variability is a key problematic area to be addressed with VRLA technology. For Li-ion technology, safety and cost are the key problem areas, which are already being addressed through the use of new materials such as lithium iron phosphate ($LiFePO_4$). For NiMH, the key issues are material cost (nickel) and temperature effects in hot weather.

Results from e-bike testing show that the total "plug-to-wheel" energy use of three different e-bike configurations under a generic urban driving cycle is between 1.5 and 1.8 kWh/100 km. The energy use characteristics for the e-bikes tested in this report are consistent with expectations that an increase in weight and motor power would increase the energy use and that the Li-ion battery would improve efficiency. A 13% increase in vehicle weight including the rider and a 27% increase in the peak motor power for the medium e-bike lead to a 13% increase in energy use for stop-and-go city driving but only a 2% increase in energy use at top speed on the highway. Switching to Li-ion batteries improves energy use by 6% in the city and 7% on the highway. Li-ion batteries are more efficient than lead acid because they have less internal resistance. They are also lighter. Both of these factors lead to improved performance.

Conclusions and Policy Recommendations

Currently, e-bikes compete directly with buses and bicycles in most cities. Compared with a bus, they showed high levels of mobility with comparable emission rates. This report does not suggest that e-bikes are better than buses on all metrics, however. There are many important areas not examined in this report—such as safety, road capacity and utilization, congestion, and mobility—where the e-bikes perform relatively better or worse than buses. All of these factors should be considered when developing policy on the role of e-bikes in the transport system. Rather than compete with buses, they could complement bus service by providing high-quality, low-emission personal transport for short trips and public transport feeder service. These types of trips are difficult to serve with traditional fixed-route bus service. Longer-distance travel can still be served by high-capacity public transport services if adequate infrastructure is supplied to safely access the transit station and securely park a bicycle or e-bike. The biggest environmental problem is lead pollution from batteries. To mitigate this problem, there must be more advanced lead mining, battery production, and recycling practices adopted on a large scale. This includes increasing the recycling rate and, most importantly, assuring that batteries are recovered and recycled in formal, well-monitored, large-scale recycling facilities

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[1] The longer lifetime of Li-ion batteries relative to VRLA would justify the extra cost to a rational consumer. However, there are many many practical reasons why consumers are reluctant to pay a high up-front battery cost: unknown quality since they are relatively new, distrust in battery quality based on VRLA experience, and high rate of e-bike and battery theft in some areas. These are the author's speculations based on knowledge of the market and conversations with e-bike owners; they have not been verified with empirical data.

with advanced pollution-control technology. Another avenue is the adoption of advanced battery technologies, such as Li-ion or NiMH. Currently, price is the largest hurdle to adopting advanced battery technology. If policy makers could develop incentives or regulations to close this price gap, then e-bikes would be among the most environmentally sustainable motorized mode in the PRC. Given restrictions on motorcycle use in cities and supportive e-bike policy, e-bikes could thrive and the market could continue to grow. More research is needed to address the other important issues that inform the policy decision, including the safe integration of e-bikes into mixed traffic streams, managing speed, impacts on congestion, and mobility. Ultimately, there are trade-offs, but based on environmental performance and market potential, policy makers should encourage e-bikes to the extent that their lead pollution effects can be mitigated and they can be safely integrated into the transportation system utilizing existing bicycle lane capacity, which is often underused.

Introduction

Electric bikes (e-bikes) have developed faster than any other mode in the People's Republic of China (PRC). After a modest beginning in the mid-1990s, 16 million to 19 million were produced in 2006 and over 21 million in 2007. E-bikes have been criticized on a number of grounds, including environmental performance, contribution to congestion, and safety (Fairley 2005; Ribet 2005). This report focuses on environmental performance. The environmental impacts of e-bikes are unclear. It is clear that they emit zero tailpipe emissions at their point of use and that their overall energy efficiency is higher and emissions per kilometer are lower than that of gasoline scooters and cars, but, at least in the PRC, most e-bike users might not otherwise use cars or gasoline scooters. The environmental costs of this mode are largely related to the alternative mode, should the e-bike be prohibited or restricted. Taipei,China promoted and subsidized e-bikes in the 1990s (Chiu and Tzeng 1999) to induce a shift away from dirtier gasoline scooters. This report presents an analysis of the environmental costs of e-bikes and alternative modes in the PRC and can help inform policy that will affect millions of users. It investigates emissions during an e-bike's life cycle. This report also investigates e-bike market potential and potential technology improvements that could mitigate pollution from batteries. This report does not investigate the influence of e-bikes on safety, congestion, noise, or mobility and access. Interested readers can refer to dissertations written by the authors (Cherry 2007; Weinert 2007).

Energy Use and Emissions of Electric Bike Life Cycle

Most of the environmental impacts of electric bikes (e-bikes) can be divided into two categories: those that occur while they are being produced, and those that occur when they are being used. There are also some significant emissions when they are disposed of, although these are difficult to quantify given the infancy of this mode and little information on disposal practices. One notable disposal emission is that of lead from batteries.

Production Processes

There are hundreds of e-bike manufacturing companies in the People's Republic of China (PRC), including large factories producing components such as motors, controllers, and frames, as well as small and large plants where the bikes are assembled. To understand the production processes, five e-bike factories in Shanghai and in the provinces of Jiangsu and Zhejiang were visited. Their annual output ranged from 12,000 e-bikes to over 150,000 e-bikes in 2005. Assembly of an e-bike typically requires one main assembly line where the frame is passed through various stages. Generally, e-bike assembly lines have the capacity to produce one e-bike every 5 minutes. Individual components and processes of the e-bike—such as assembling wiring systems, brake systems, and painting—are produced and performed off-line.

Interviews with factory owners and publicly reported statistics on energy use and emissions from the manufacture of raw materials were used to estimate the environmental implications of the production process of e-bikes. Other estimates of energy use and emissions were made using the weight of raw materials required to produce an e-bike and the energy and pollution intensities of producing those materials in the PRC. In some cases, data were not available or were not collected because those factors were estimated to have a relatively small impact.

One of the larger e-bike manufacturers in the PRC reported that in 2005,[2] it produced 180,000 e-bikes and used 1,278,545 kilowatt-hours (kWh) of electricity, or 7.1 kWh per bike. The processes included in this calculation were frame welding and bending, painting, assembly, assembly of controllers, vehicle inspection and testing, packaging, and general electricity use of the factory.

Another energy-intensive process is the manufacture of lead acid batteries. A large

[2] Interview with e-bike factory owner on 3 April 2006.

scale e-bike battery manufacturer reported that total energy consumption per 12-volt (V) e-bike battery was approximately 2 kWh. A 36 V battery would require 6 kWh, and a 48 V battery would require 8 kWh.[3]

The energy required by the assembly process is very small compared with the energy requirements of the raw material manufacturing, such as steel, lead, plastic, and rubber. Moreover, different styles of e-bikes are composed of different materials. E-bikes are generally classified into two styles: bicycle-style (BSEB), and scooter-style (SSEB). The former look and operate much like bicycles, with functioning pedals. The scooter types in many cases have footboards, turn signals, headlights, brake lights, and mirrors. Table 1.1 is an inventory of e-bike components, the material they are composed of, their weight, and the energy required to produce them, calculated from national statistics and literature on the PRC's steel and lead industries (Price, Phylipsen, et al. 2001; National Bureau of Statistics 2003; Lawrence Berkeley National Laboratory 2004; National Bureau of Statistics 2004; National Bureau of Statistics 2005; China Data Online 2006; Mao, Lu, et al. 2006).

Several assumptions and omissions were made to develop Table 1.1. This table includes energy and environmental impacts due to the mining and production of ferrous and nonferrous metals, and the production of plastic and rubber. It does not include the impacts of battery electrolyte production or fillers in rubber production (particularly carbon black). It also does not include transport logistics impacts. The values presented in Table 1.1 should be considered lower bounds. The values also include the manufacture of replacement parts, specifically five sets of batteries, three sets of tires, and two motors over the life span of the e-bike.[4]

Table 1.1: Material Inventory, Emissions, and Energy Use of Electric Bike

Weight of Electric Bike Materials (kg/bike)		
	BSEB	**SSEB**
Total Steel	18.15	26.18
Total Plastic	5.67	15.22
Total Lead	10.28	14.70
Total Fluid	2.94	4.20
Total Copper	2.55	3.46
Total Rubber	1.14	1.22
Total Aluminum	0.52	0.58
Total Glass	0.00	0.16
Total Weight	**41.25**	**65.73**
Associated Energy and Emissions of Manufacturing Processes		
	BSEB	**SSEB**
Energy Use (ton SCE)	0.179	0.261
Energy Use (kWh)	1,456	2,127
Air Pollution (SO_2) (kg)	1.563	2.198
Air Pollution (PM) (kg)	5.824	8.173
Greenhouse Gas (ton CO_2 equivalent)	0.603	0.875
Wastewater (kg)	1,488	2,092
Solid Waste (kg)	4.463	7.139

BSEB = bicycle-style e-bike, CO_2 = carbon dioxide, kg = kilogram, kWh = kilowatt-hour, PM = particulate matter, SCE = standard coal equivalent, SO_2 = sulfur dioxide, SSEB = scooter-style e-bike.

Source: Authors, from representative electric two-wheeler manufacturers.

[3] Phone interview with e-bike battery factory manager on 3 April 2006.

[4] Personal communication with e-bike manufacturers and their estimation of component reliability.

End-of-Life

Because of the relatively recent appearance of e-bikes in the transportation system, little is known about the fate of e-bikes that have become obsolete or nonoperational. Many of the earliest e-bike models were simply modified bicycles, so if components failed the e-bike could still operate as a standard bicycle. More recent models would be inoperable if vital components failed. The most notable end-of-life pollution comes from lead, a toxic metal.

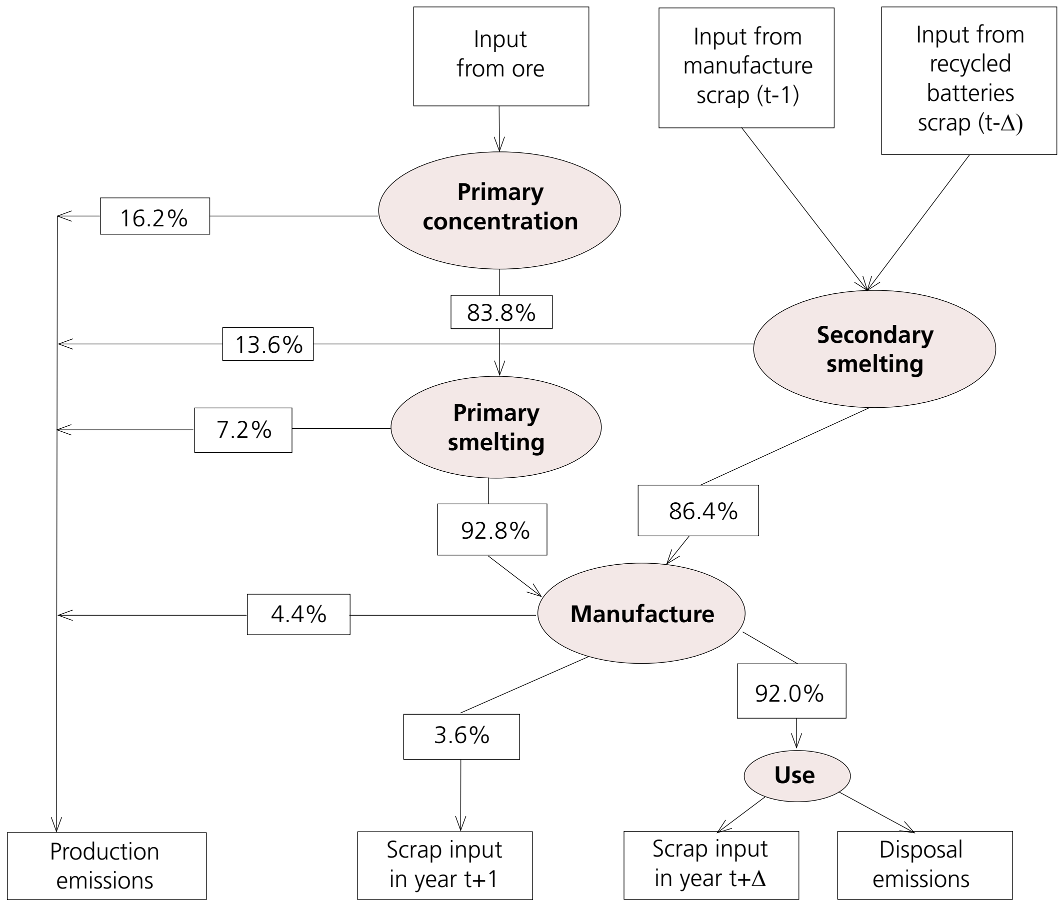
Lead Acid Batteries

Lead acid battery pollution is often cited as a reason to regulate e-bikes. Approximately 95% of e-bikes in the PRC are powered by lead acid batteries (Jamerson and Benjamin 2007), although this number is dropping because of more advanced battery technologies. Based on interviews with manufacturers and service facilities, the life span of an e-bike battery is considered to be 1–2 years or up to 10,000 kilometers (km). Bicycle-style e-bikes typically use 36 V battery systems, on average weighing 14 kilograms (kg). The scooter style typically uses 48 V battery systems weighing 18 kilograms. The lead content of electric batteries is 70% of the total weight, so BSEB batteries contain 10.3 kilograms of lead, compared with 14.7 kg for SSEB batteries.

This is perhaps the most problematic issue for e-bikes and is the same problem that influenced the demise of electric car development in the United States (US) in the early 1990s (Lave, Hendrickson, et al. 1995). Because of the relatively short life span of deep-discharge e-bike lead acid batteries, an e-bike could use five batteries in its life, emitting lead into the environment with every battery. Lead is emitted into the environment during four processes: mining and smelting of the lead ore, manufacturing of the battery, recycling of the used lead, and disposal of the nonrecycled lead into the waste stream. Loss rates can be expressed in terms of unit weight of lead lost per unit weight of battery produced for each process. Lave, Hendrickson, et al. (1995) cite that, in the US, 4% (0.04 tons lost per ton of battery produced) of the lead produced is lost in the virgin production processes, 1% is lost during the battery manufacturing, and 2% is lost in recycling. So, a battery composed of 100% recycled lead emits 3% of its lead mass into the environment. A battery composed of 100% virgin material emits 5% of its lead content into the environment. In most industrialized countries, lead recycling rates exceed 90%.

The PRC's lead acid battery system is very different from that of more industrialized countries (Roberts 2006). Mao, Lu, et al. (2006) investigated the PRC lead acid battery system. They found that 16.2% of the lead content of a battery is lost during mining and concentrating, 7.2% is lost during primary smelting, 13.6% is lost during secondary (scrap and recycled) smelting and recycling processes, and 4.4% is lost during the battery manufacturing process. These rates reflect loss in terms of final battery production (not initial lead input). For instance, 1 ton of final lead output represents 0.044 tons of lead lost during battery manufacturing. Figure 1.1 is derived from the analysis conducted by Mao, Lu, et al. (2006). These very high loss rates are mostly because of poor ore quality and a high proportion of lead refined at small-scale factories using outdated technology. The official recycling rate of lead in the PRC's lead acid battery industry is 31.2%. Mao, Lu, et al. (2006) estimate that the actual number is approximately double that

Figure 1.1: Lead Loss Flows from Lead Acid Battery Production



Source: Derived from Mao, Lu, et al. 2006.

because of unreported recovery by informal, small-scale recyclers. Because of the high value of lead, most analysts project the recycle rate is above 85%. More recently, the price of lead has tripled, suggesting that this value might push recycling rates near 100%. This lead recycling rate partially determines the proportion of recycled lead in each battery.

Mao et al. (2006) use data from 1999, before e-bike batteries were a significant share of the market. Several of the values (specifically recycling rate) are estimates and could have changed since e-bikes entered the market. As e-bikes surpass the total number of cars, e-bikes represent a large proportion of lead acid battery production. Because e-bikes use batteries quickly, some informal recycling and collection practices have developed. In most cases, an e-bike customer can exchange an exhausted battery for one-quarter of the price of a new battery, or around CNY100 ($14.30) in 2008, a significant amount of money in most PRC cities. The used batteries are then collected from service centers and sent to formal and informal lead recycling facilities. This practice could increase the average recycling rate of all lead acid batteries. Interviews with factory owners estimate that 85%–100% of e-bike batteries are

Table 1.2: Lead Losses to the Environment

BSEB with 10.3 kg lead content battery						
	Lead Acid Battery Recycle Rates					
Loss Components (kg)	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Mining and Concentration Loss (Primary)	1.7	1.5	1.4	1.3	1.2	1.1
Smelt Loss (Primary)	0.6	0.6	0.5	0.5	0.4	0.4
Smelt Loss (Secondary)	0.5	0.6	0.7	0.8	0.9	1.0
Manufacture Loss	0.5	0.5	0.5	0.5	0.5	0.5
Total Production Emissions	3.3	3.2	3.1	3.1	3.0	2.9
Solid Waste	5.2	4.1	3.1	2.1	1.0	0.0
SSEB with 14.7 kg lead content battery						
	Lead Acid Battery Recycle Rates					
Loss Components (kg)	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Mining and Concentration Loss (Primary)	2.4	2.2	2.0	1.8	1.7	1.5
Smelt Loss (Primary)	0.9	0.8	0.8	0.7	0.6	0.6
Smelt Loss (Secondary)	0.7	0.9	1.0	1.1	1.3	1.4
Manufacture Loss	0.7	0.7	0.7	0.7	0.7	0.7
Total Production Emissions	4.7	4.6	4.5	4.4	4.3	4.2
Solid Waste	7.4	5.9	4.4	2.9	1.5	0.0

BSEB = bicycle-style e-bike, kg = kilogram, SSEB = scooter-style e-bike.

Source: Authors, derived from Mao et al. 2006.

recycled.[5] Recycling practices and technology have also improved dramatically. The PRC has developed new technologies for smelting lead, which is more environmentally friendly than alternative technologies.

The values in Table 1.2 are generated using the loss rates presented above. The proportion of recycled material that contributes to the content of a battery is dependent on previous years' recycling rates and the growth rate of lead demand (15%–20%) (China Data Online 2006). It is assumed that all new demand is met by virgin lead production. Additionally, all lead that is lost to the environment in recycling is also met by virgin production. The maximum amount of recycled content in lead acid batteries, assuming 100% recycling rates, would be about 60% (considering previous loss rates and increased demand). The bottom two rows of each section show total production emissions (or the sum of all emissions from mining, smelting, and

[5] Interview with factory owners and managers on 15–18 May 2006.

manufacturing) and the solid-waste emissions (or lead lost due to battery disposal). It should be noted that losses during the primary production processes (mining, concentration, and smelting) all occur at localized mining facilities, and losses (solid and liquid) are often contained to some extent, reducing but not eliminating exposure to the emitted lead. Secondary smelting and manufacture losses are much more widely distributed and potentially less contained.

Unfortunately, improving the battery recycling rate does not do much to cut the release of lead into the environment during the production processes. The loss rates during the secondary smelting process are nearly as high as the loss rates during the primary concentration and smelting processes. Of course, the biggest gain in improving the recycling rate is in removing lead waste from the municipal solid-waste stream.

Common estimates of battery life are up to 300 cycles or 10,000 kilometers (km), although some evidence suggests that batteries have significantly lower usable lifetimes. If 80% of lead is recycled, this results in the emission of 520 milligrams (mg)/km of lead for BSEBs and 730 mg/km of lead for SSEBs. To put this into perspective, a car in the 1970s in the US running on leaded fuel with a 7.9-liter (L)/100 km (30 miles per gallon) fuel economy emitted 33 mg/km of lead into the environment (Lave, Hendrickson, et al. 1995). Even if 100% of the batteries were recycled, lead emissions would still be an order of magnitude higher than an automobile running on leaded fuel (cars also use lead batteries, but less frequently). It should be noted, however, that lead pollution from fuel is emitted into the air in urban areas, while lead pollution from battery production is emitted at mines and manufacturing facilities.

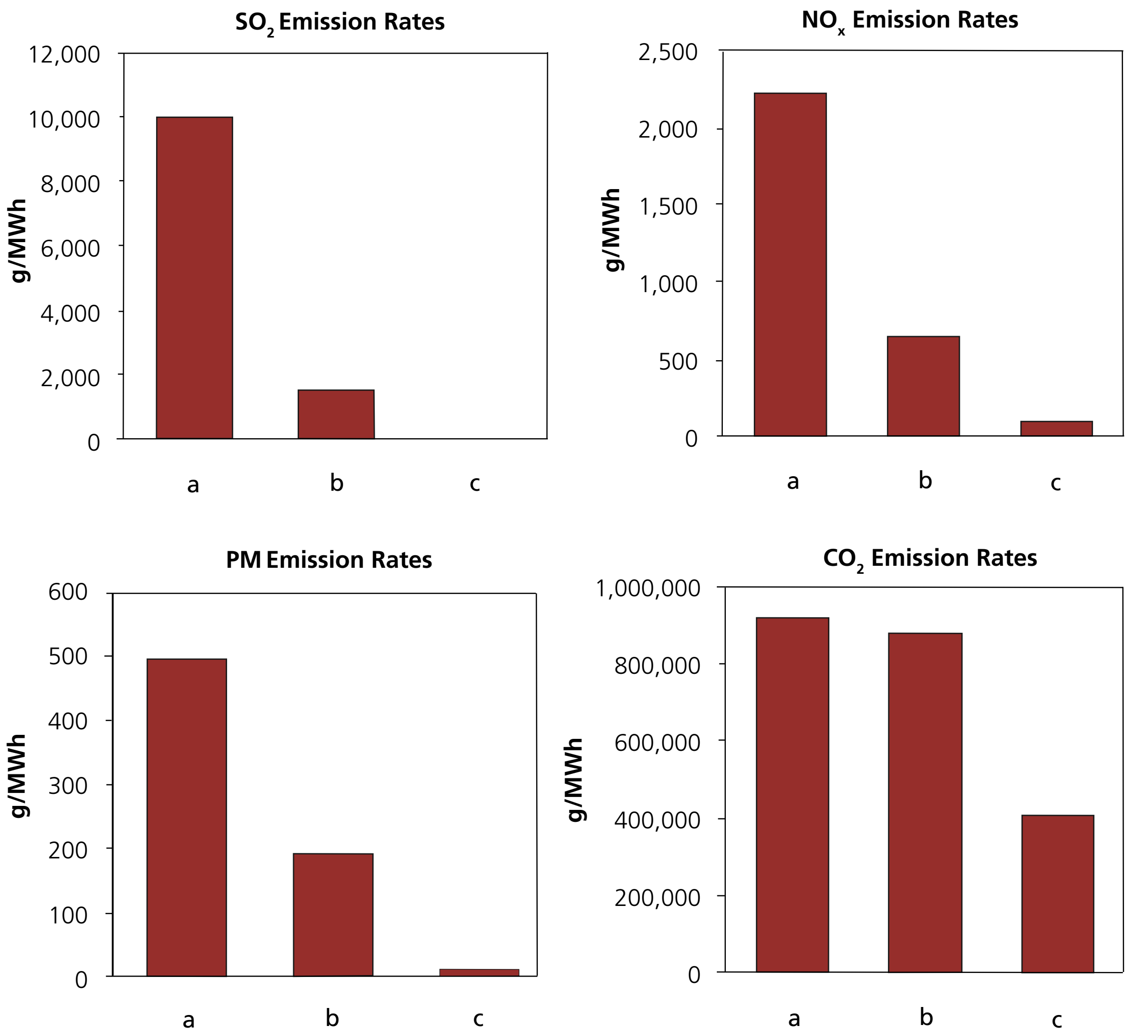
Use Phase

E-bikes are recharged by plugging into standard wall outlets. This is a great advantage because there is no need for dedicated refueling and/or recharging infrastructure. Most e-bikes have removable batteries and chargers so that these can be transported into an apartment or workplace and recharged during the day or night. With the increased popularity of e-bikes, many apartments or workplaces are retrofitting bicycle parking areas to accommodate e-bikes by providing electrical outlets.

Batteries take about 6–8 hours to charge. Moreover, charging e-bikes at night can increase the efficiency of the electric power generation network because excess electricity production capacity can be used to charge batteries that will be used during the day, when electricity demand is at its peak. This has the effect of smoothing the demand peak and could potentially require little or no electricity generation capacity improvements.

Although e-bikes have zero tailpipe emissions, they do use electricity, the generation of which emits high amounts of conventional pollutants and greenhouse gases. Most e-bikes have a range of about 40–50 km on a single charge. Considering an average SSEB with a 350-watt (W) motor and a 48 V, 14 amp-hour (Ah) battery, the electricity requirement is 1.5 kWh/100 km. Considering efficiency losses in the battery charger, it is estimated that an e-bike could require up to 1.8 kWh/100 km from the wall outlet. Moreover, there are transmission losses and in-plant use losses that are in the order of 12%–14% of the total energy produced (National Bureau of Statistics 2005). This results in an electricity generation requirement of about 2.1 kWh/100 km for a standard

Figure 1.2: Emission Rates from PRC Power Plants



Note: a = average PRC coal boiler, b = new coal boiler, c = gas combined-cycle turbine.

CO_2 = carbon dioxide, g/MWh = gram per megawatt-hour, NO_x = nitrogen oxides, PM = particulate matter, PRC = People's Republic of China, SO_2 = sulfur dioxide.

Source: Energy Foundation PRC. 2005.

e-bike. Some estimates indicate that the actual transmission loss rates might be double those officially reported (Lawrence Berkeley National Laboratory 2004). In the PRC, the energy mix is 75% coal, 15% hydro, 8% gas, and 2% nuclear (National Bureau of Statistics 2005). The emission factors of typical power plants are presented in Figure 1.2.

Most of the PRC's electricity is generated by coal power plants, but the actual energy mix of a city depends on its region. The PRC is divided into 15 power grids that have limited levels of connectivity (Zhu, Zheng, et al. 2005). Each of these grids has a different energy mix, and each city within a power grid receives most of its electricity from the grid in which it is located.

Table 1.3: Regional Emission Rates of Typical Scooter Style Electric Bikes
(units at g/100 km except CO_2)

Network Name	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC	CO_2 (g/km)
Hainan Grid	0.87	3.43	0.56	0.31	7.41	0.35	22.70
Guangdong Grid	0.70	2.53	0.72	0.43	4.25	0.28	18.90
Fujian Grid	1.14	3.83	1.25	0.75	5.15	0.46	19.10
Xinjiang Grid	1.34	6.21	1.32	0.76	7.32	0.53	27.30
Yunnan Grid	1.53	5.81	1.34	0.76	14.05	0.62	18.10
East Network	1.50	5.59	1.37	0.81	9.26	0.61	21.80
Guangxi Grid	0.86	3.53	1.37	0.85	12.38	0.35	19.70
Shandong Grid	1.64	6.42	1.46	0.87	16.75	0.66	25.60
Sichuan Grid	1.56	6.41	1.77	1.05	23.24	0.63	15.80
North Network	1.84	7.18	1.78	1.06	15.27	0.74	24.80
Chongqing Grid	1.54	6.41	1.82	1.08	20.36	0.62	26.70
Guizhou Grid	2.10	8.02	2.02	1.19	39.37	0.85	18.90
Central Network	2.18	8.55	2.20	1.32	17.13	0.88	18.30
Northwest Network	1.84	6.76	2.29	1.33	15.79	0.74	21.30
Northeast Network	2.28	9.35	3.07	1.86	10.23	0.92	23.00
Weighted Average	**1.65**	**6.38**	**1.72**	**1.02**	**13.03**	**0.67**	**21.50**

CO = carbon monoxide, CO_2 = carbon dioxide, g/km = gram per kilometer, NO_x = nitrogen oxides, PM = particulate matter measuring 10 microns or less, SO_2 = sulfur dioxide, VOC = volatile organic compounds.

Source: Authors.

To calculate the regional electricity generation emission factors, the emission inventory by sector across the PRC was extracted from the National Aeronautics and Space Administration's Intercontinental Chemical Transport Experiment (NASA INTEX) database (Argonne National Lab 2006). Given a regional distribution of emissions, one can add all emissions in a power grid and divide by the total electricity generation in that grid to calculate emission rates tons (T per gigawatt-hour [T/GWh]) of various pollutants. Table 1.3 shows the emission rates (g/100 km) of e-bikes operating in various power grid networks. The CO_2 emissions were extracted in a similar manner using data extracted from the Carbon Monitoring for Action (CARMA) online database (CARMA 2007).

It is worth noting that these emissions, like all emissions from e-bikes, are nonlocal. Power plants are distributed throughout the country and serve specific population centers. Exposure to most pollutants decreases significantly as population centers are located away from thermal power generating stations (Li and Hao 2003; Zhou, Levy, et al. 2003, 2006). This could have significant public health benefits compared with modes with same emission rates in urban areas.

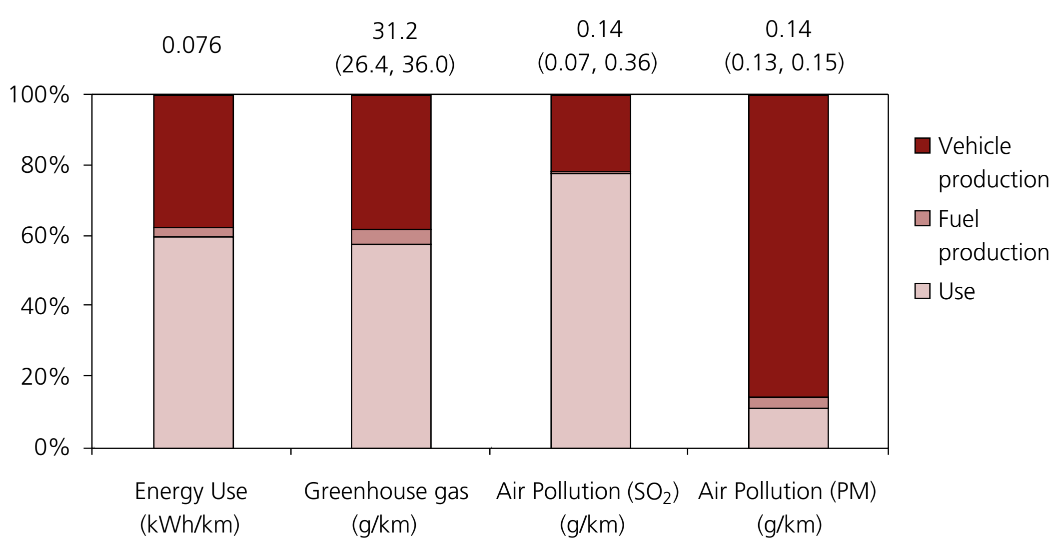
Total Environmental Impacts of Electric Bike Life Cycle

Data from previous research and interviews of members of the e-bike industry were used to make estimates of the energy used and the emissions released during the life cycle of an e-bike, from production through to end of use. These estimates should be considered a lower bound rather than a comprehensive total, but they do include the most energy-intensive processes.

The primary energy use of e-bikes is dependent upon the fuel used to generate electricity. If all electricity is generated from renewable resources, then the total in-use energy requirement is merely the electricity generated from such a source. If some portion of the electricity is generated from fossil fuel power plants, then the total energy use must include the primary energy embedded in the fuel. For instance, the energy density of coal is about 29 Gigajoules/ton and the energy density of natural gas is about 39 megajoules/cubic meter (m^3). The average efficiency of fossil fuel power generation is approximately 33.4% (Lawrence Berkeley National Laboratory 2004). For an average SSEB, the primary energy requirements could range from 2.1 kWh/100 km for electricity generated exclusively from renewable sources to 6.3 kWh/100 km for electricity generated exclusively from fossil fuel sources.

Since e-bikes efficiently convert energy (electricity) into movement, large portions of e-bike energy use and emissions occur during production,

Figure 1.3: Pollution of Bicycle Style e-bike Over Life Cycle



g = gram, km = kilometer, kWh = kilowatt-hour, PM = particulate matter, SO_2 = sulfur dioxide.

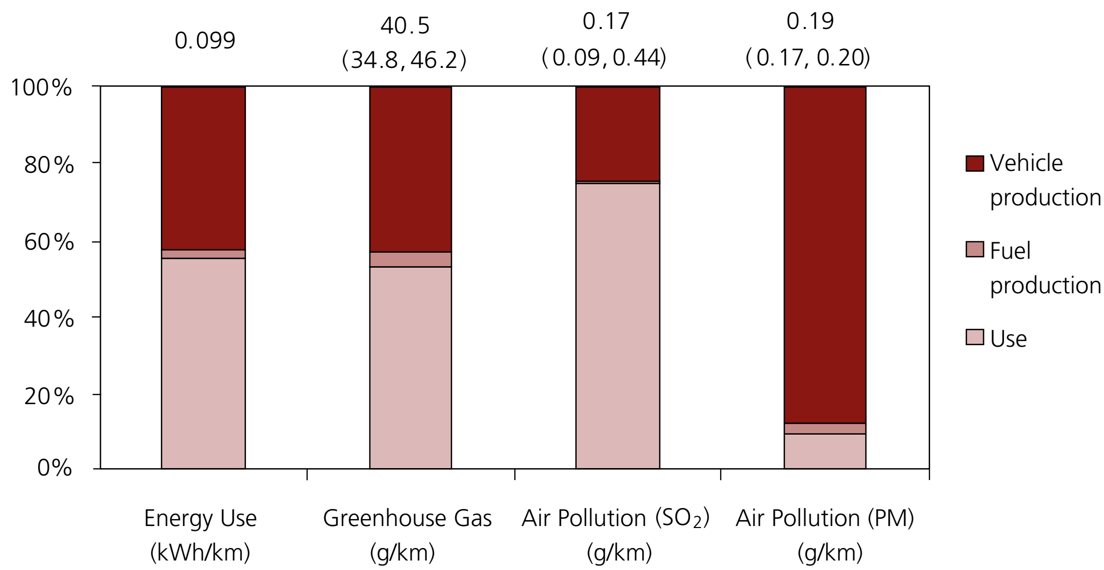
Note: Assumes a life span of 50,000 km.

Source: Authors.

particularly in energy-intensive processes such as producing steel and lead, the two materials that the e-bike uses the most. By contrast, life-cycle inventories of internal combustion engine personal cars or buses have shown 80%–90% of their environmental impacts occur during the use phase (Sullivan, Williams, et al. 1998; Danielsson and Gunnarsson 2001). The use phase of the e-bike's life cycle emits high amounts of SO_2 as a result of e-bikes' reliance on high-emitting coal power plants.

Figures 1.3 and 1.4 illustrate the proportion of energy use and emissions from each process of a typical BSEB and SSEB, averaged over all of the PRC and assuming a life span of 50,000 km. Average emission rates are provided as well as minimums and maximums, given varying regional emission rates. An e-bike operating in a cleaner power sector has a lower overall life-cycle emission rate than an e-bike operating in a dirtier power sector.

Figure 1.4: Pollution of Scooter Style e-bike Over Life Cycle



g = gram, km = kilometer, kWh = kilowatt-hour, PM = particulate matter, SO_2 = sulfur dioxide.

Note: Assumes a life span of 50,000 km.

Source: Authors.

Environmental Impacts of Alternative Modes

When identifying the environmental impacts of any policy decision, energy use and environmental comparisons must be made between the competing alternatives. Since electric bikes (e-bikes) provide a transport service, the assumption is that the users would make the trip by another mode if the e-bike were not available. User surveys show that the predominant alternative modes of e-bike users are public buses and bicycles, and that very few e-bike users would cancel a trip if e-bikes were banned (Cherry and Cervero 2007; Weinert, Ma, et al. 2007). To identify the net environmental impact of e-bikes, comparisons should be made that show the difference between the same trip made by the competing modes of transport.

Energy Use and Emissions of a Bicycle

Production Phase

The vast majority of bicycle impacts come from the production phase. Most bicycles used in the People's Republic of China (PRC) for commuting are constructed primarily of steel, plastic, rubber, and aluminum. Unlike e-bikes, there are no electronic components, batteries, or body components, so the overall weight of a bicycle is significantly lower than a bicycle-style e-bike (BSEB), and most of the weight difference is due to the absence of a battery. Table 2.1 shows the material inventory, emissions, and energy use of an average city bicycle in the PRC.[6]

Table 2.1: Material Inventory, Emissions, and Energy Use of Bicycle

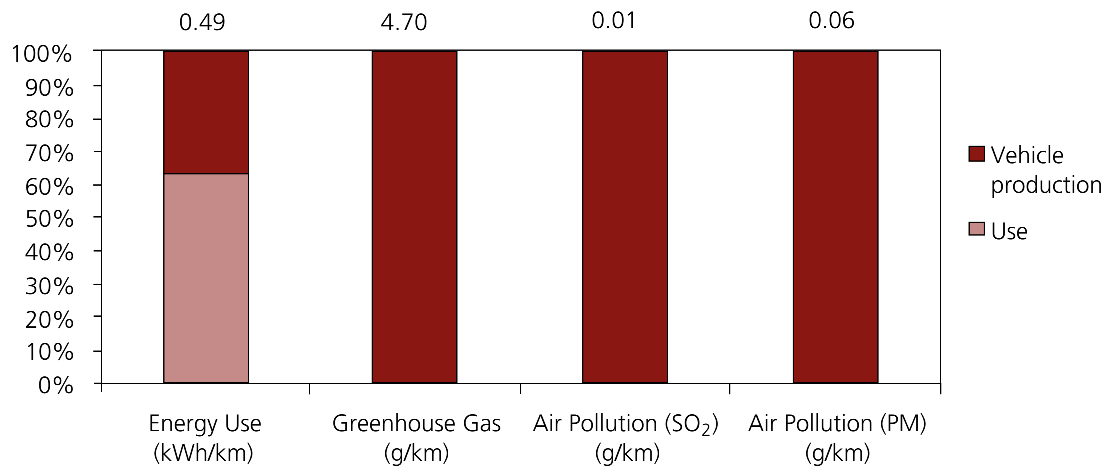
Weight of Materials (kg/bike)	
Total Plastic	2
Total Rubber	2
Total Steel	13
Total Aluminum	1
Total Weight	18
Associated Energy and Emissions of Manufacturing Processes	
Energy Use (ton SCE)	0.045
Energy Use (kWh)	363
Air Pollution (SO_2) (kg)	0.275
Air Pollution (PM) (kg)	1.176
Greenhouse Gas (ton of CO_2-equivalent)	0.097
Wastewater (kg)	393
Solid Waste (kg)	0.641

CO_2 = carbon dioxide, kg = kilogram, kWh = kilowatt-hour, PM = particulate matter, SCE = standard coal equivalent. SO_2 = sulfur dioxide.

Source: Authors, representatives of bicycle manufacturers.

[6] These values are based on interviews and product websites of large bicycle manufacturers in the PRC.

Figure 2.1: Pollution of Traditional Bicycle Over Life Cycle



g = gram, km = kilometer, kWh = kilowatt-hour, PM = particulate matter, SO_2 = sulfur dioxide.
Note: Assumes life span of 20,000 km.
Source: Authors.

Use Phase

There is debate as to how the energy used during the use phase of a bicycle should be calculated, since bikes use human power. Estimated energy use of moderate bicycle riding (12–14 kilometers per hour [km/hr]) ranges from 15 to 35 calories per kilometer (reduced by a factor that accounts for calories used while resting). Assuming a 10-year life span for the bicycle and 2,000 km per year (Cherry and Cervero 2007; Weinert, Ma, et al. 2007), this is approximately 600 kilowatt-hours (kWh) of energy use over its lifetime. This energy use is generated from food, and it is debatable whether the net increase in energy requirements is equal to the food intake. An obesity study in the PRC shows that people who shift from bicycle to motorized modes gain weight as a result of that shift (Bell, Ge, et al. 2002), implying that cyclists do not consume calories equal to the energy needs of bike riding; they just weigh less than people who do not cycle. If they do require more food, there could be considerable environmental impacts of producing that food as well as several other secondary effects (Ulrich 2006). Figure 2.1 shows the relative amounts of energy used and emissions produced in the production and use of bicycles.

As expected, most of the environmental impacts occur during the production phase, primarily through the steel production processes.

Energy Use and Emissions of Motorcycles and Scooters

E-bikes are becoming more powerful, and some models are more similar to scooters and motorcycles than to bicycles in terms of performance. Identifying motorcycle emissions can provide a frame of reference for evaluating the relative environmental impacts of e-bikes.

Motorcycles in the PRC come in three main styles: scooter style, underbone style, and traditional motorcycle (or horseback) style; there are very few mopeds. The following classification from Wikipedia (2007) is helpful in characterizing the wide range in motorcycle types:

> *Mopeds* are small, light, inexpensive, efficient rides for getting around town. Usually started by pedaling (motorcycle + pedals = moped). *Scooters* are motorcycles with a step-through frame and generally smaller wheels than those of a traditional motorcycle. Can be ridden without straddling any part of the bike.
>
> *Underbones* are small motorcycles which are a crossover between a scooter and a true motorcycle with step-through frame, popular in Southeast Asia. *Standard motorcycles* (Horseback-type) are characterized by tear-shaped fuel tanks located at the top and just behind the instrument panel, whereas the fuel tank for an underbone motorcycle is located under the seat.

Liquefied petroleum gas scooters are popular in Shanghai because they are exempt from the city-side motorcycle ban. They are excluded from the analysis, however, since they are exclusive to Shanghai.

Motorcycle engine type and style have changed since the early 1990s, as documented in Ohara (2006). During the first half of 1990s, the most prevalent motorcycles were two-stroke, 110-cubic centimeter engine displacement (cc) or below, and horseback type. In the second half of the 1990s, the market share of four-stroke scooters with 125 cc or greater engine size increased sharply. From 2000 onwards, underbone frame types have gained increasing popularity and are the most common in Southeast Asia (especially ones based on the Honda C100). By 2002, there were only a few models of two-stroke motorcycles available because of the tightening of environmental regulations. In the PRC in 2002, market share by displacement was 45% for 125 cc, 28% for 50–110 cc, and less than 8% for up to 50 cc. Market share by type was 37% for four-stroke standard motorcycle type,

Table 2.2: Material Inventory, Emissions, and Energy Use of Gasoline Motorcycle and Scooter

Weight of Motorcycle and Scooter Materials (kg/bike)		
	125 cc Motorcycle	**100 cc Scooter**
Total Steel	88.3	76.4
Total Plastic	9.4	9.1
Total Lead	2.1	1.7
Total Nickel	0.3	0.3
Total Copper	1.0	1.0
Total Rubber	4.1	3.2
Total Aluminum	20.0	1.5
Total Zinc	0.8	0.8
Total Weight	126.0	94.0
Associated Energy and Emissions of Manufacturing Processes		
	125 cc Motorcycle	**100 cc Scooter**
Energy Use (ton SCE)	0.431	0.188
Energy Use (kWh)	3,510	1,534
Air Pollution (SO_2) (kg)	3	1
Air Pollution (PM) (kg)	13	4
Greenhouse Gas (ton CO_2-equivalent)	0.825	0.284
Wastewater (kg)	3,552	1,397
Solid Waste (kg)	10	3

cc = cubic centimeter, engine displacement, CO_2 = carbon dioxide, kg = kilogram, kWh = kilowatt-hour, PM = particulate matter, SCE = standard coal equivalent, SO_2 = sulfur dioxide.

Source: Authors, representatives of motorcycle and scooter manufacturers.

30% for four-stroke scooter type, 18% for underbone, and 11% for two-stroke motorcycle or scooter style.

Production Phase

Material inventories for a scooter and a motorcycle were obtained from a large-scale motorcycle producer and were used to estimate emissions and energy use. Table 2.2 shows the significantly different environmental impacts of a standard 125 cc motorcycle and a 100 cc scooter, primarily because of the large differences in aluminum content—a very energy-intensive material.

Lead Pollution from Motorcycle Batteries

Following the same methodology as previous sections, lead pollution is calculated for gasoline motorcycles and scooters. Gasoline motorcycles and scooters require small starting, lighting, and ignition (SLI) batteries that are expected to last 3 years. This is significantly longer than e-bike batteries because motorcycles do not require deep discharge cycles the way electric vehicles do and therefore have longer battery life. Table 2.3 shows the lead loss of each battery under various recycling scenarios.

Table 2.3: Lead Losses to the Environment

Gasoline motorcycle with 2.1 kg lead content battery						
	Lead Acid Battery Recycle Rates					
Loss Components (kg)	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Mining and Concentration Loss (Primary)	0.34	0.31	0.29	0.26	0.24	0.21
Smelt Loss (Primary)	0.13	0.12	0.11	0.10	0.09	0.08
Smelt Loss (Secondary)	0.10	0.12	0.14	0.16	0.18	0.20
Manufacture Loss	0.10	0.10	0.10	0.10	0.10	0.10
Total Production Emissions	0.67	0.65	0.64	0.62	0.61	0.59
Solid Waste	1.05	0.84	0.63	0.42	0.21	0.00
Gasoline scooter with 1.7 kg lead content battery						
	Lead Acid Battery Recycle Rates					
Loss Components (kg)	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Mining and Concentration Loss (Primary)	0.27	0.25	0.23	0.21	0.19	0.17
Smelt Loss (Primary)	0.10	0.09	0.09	0.08	0.07	0.06
Smelt Loss (Secondary)	0.08	0.10	0.11	0.13	0.14	0.16
Manufacture Loss	0.08	0.08	0.08	0.08	0.08	0.08
Total Production Emissions	0.54	0.53	0.52	0.50	0.49	0.48
Solid Waste	0.85	0.68	0.51	0.34	0.17	0.00

kg = kilogram.

Source: Authors, derived from Mao et al. 2006.

Since motorcycle batteries are small and have relatively low lead content and users are highly dispersed, the economic incentive to recycle a motorcycle battery could be significantly lower than for a heavier battery, potentially leading to lower recycling rates.

Use Phase

There are few empirical measurements of motorcycle emission rates in the developing world. A recent report outlines the current state of worldwide motorcycle emission rates (Meszler 2007). Table 2.4 shows estimated motorcycle emission rates, coupled with the PRC's motorcycle emission standards, which are far below the actual estimated emission rates. This could be because motorcycles in the PRC have much smaller engines and thus lower emission rates. The PRC's two-stroke motorcycle stock has been declining over the past decade to less than 15% of the motorcycle fleet (Wang 2001). Because of this, this report focuses on four-stroke emissions.

Based on field observations and literature, the assumed fuel efficiency of motorcycles and scooters is 3 liters (L)/100 km. Using emission estimates by Meszler (2007), Figure 2.2 illustrates the energy use and emissions of motorcycles and scooters, based on a life span of 60,000 km.

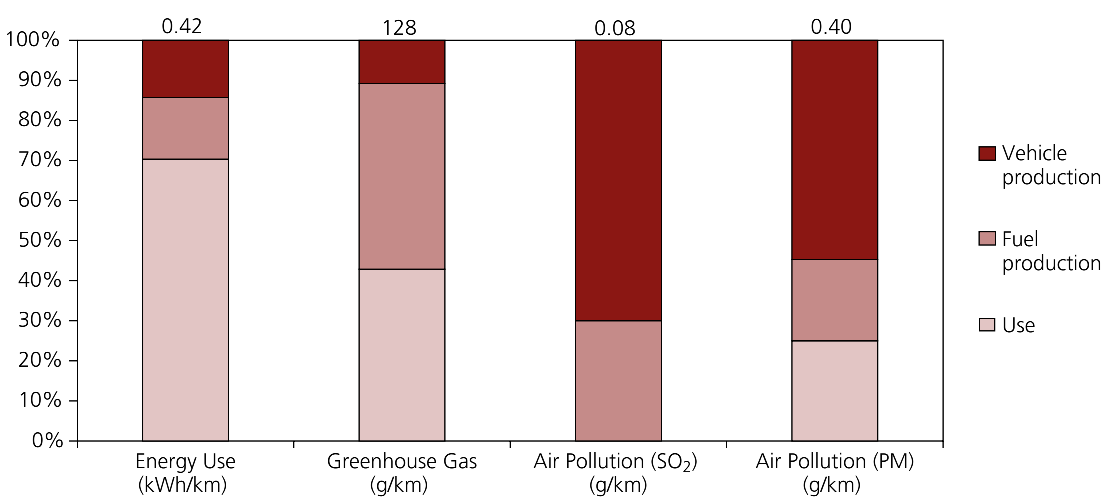
Table 2.4: Motorcycle Emission Rates (g/km)

Engine Type	CO	CO_2	VOC (HC) (Exhaust and Evaporative)	NO_x	SO_2	PM
2-stroke	18.0	40	16.75	0.05	0	0.5
4-stroke	12.5	55	2.25	0.15	0	0.1

CO = carbon monoxide, CO_2 = carbon dioxide, g/km = gram per kilometer, HC = hydrocarbon, NO_x = nitrogen oxides, PM = particulate matter, SO_2 = sulfur dioxide, VOC = volatile organic compounds.
Note: SO_2 emissions reported as zero, but there are likely trace amounts from sulfur content in fuel.

Source: Meszler 2007.

Figure 2.2: Pollution of Gasoline Motorcycle and Scooter Over Life Cycle



g = gram, km = kilometer, kWh = kilowatt-hour, PM = particulate matter, SO_2 = sulfur dioxide.

Source: Authors.

Energy Use and Bus Emissions

The environmental impacts of bus transport are significantly different from those of bicycles and e-bikes. Most of the environmental impacts are from the use phase of the life cycle because of diesel fuel use and processing. Buses are not single-occupant vehicles, so emission rates are expressed in terms of passenger kilometers and are generally a function of load factors and operating mode. Since they are multiple-occupant vehicles, the impacts can be reduced by the load factors to estimate per-capita energy use and emissions.

Production Phase

Bus material inventories were acquired from the Volvo Bus Company, which manufactures Sunwin buses in the PRC (Volvo 2006). This is the second-largest bus company in the PRC and could represent an average city bus.

The values presented in Table 2.5 include the environmental impacts of the production of all materials listed with the exception of wood and "other" materials, for which there were no reliable emission data available. The average energy and emission intensities (impact/kilogram [kg]) of all materials were calculated and multiplied by the weight of the unknown materials (704 kg) to adjust the total impacts by an appropriate factor. The energy use and emissions of the assembly processes were not considered in this analysis because of difficulty obtaining those data and the assumption that the assembly process does not constitute a high proportion of manufacturing impacts.

Table 2.5: Material Inventory, Emissions, and Energy Use of Bus

Weight of Bus Materials (kg/bus)	
Total Plastic	553
Total Rubber	405
Total Wrought Iron	502
Total Cast Iron	1,029
Total Rod Steel	2,408
Total Hot Rolled Steel	1,590
Total Colled Rolled Steel	586
Total Stainless Steel	690
Total Aluminum	1,666
Total Copper	109
Total Glass	490
Total Lead	90
Total Oil	78
Total Wood	396
Total Other	308
Total Weight	**10,900**
Associated Energy and Emissions of Manufacturing Processes	
Energy Use (ton SCE)	34,345
Energy Use (kWh)	279,605
Air Pollution (SO_2) (kg)	274
Air Pollution (PM) (kg)	1,064
Greenhouse Gas (ton CO_2-equivalent)	70,601
Wastewater (kg)	291,182
Solid Waste (kg)	756

CO_2 = carbon dioxide, kg = kilogram, kWh = kilowatt-hour, PM = particulate matter, SCE = standard coal equivalent, SO_2 = sulfur dioxide.

Source: Volvo 2006.

Lead Pollution from Bus Batteries

The same approach was taken as the e-bike battery analysis regarding the emissions of lead from bus batteries. Even under the best scenarios, e-bikes emit an enormous amount of lead into the environment through the mining, production, recycling, and disposal processes. Buses use very large lead acid batteries also and thus emit lead into the environment. These batteries are much heavier than e-bike batteries but need to be replaced less often—about every

Table 2.6: Lead Losses to the Environment

Bus with 90 kg lead content battery						
	Lead Acid Battery Recycle Rates					
Loss Components (kg)	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Mining and Concentration Loss (Primary)	14.5	13.4	12.4	11.3	10.2	9.2
Smelt Loss (Primary)	5.4	5.0	4.6	4.2	3.8	3.4
Smelt Loss (Secondary)	4.4	5.2	6.0	6.9	7.7	8.5
Manufacture Loss	4.3	4.3	4.3	4.3	4.3	4.3
Total Production Emissions	28.7	28.0	27.4	26.7	26.1	25.4
Solid Waste	45.0	36.0	27.0	18.0	9.0	0.0

kg = kilogram.

Source: Authors, derived from Mao et al. 2006.

three years or 250,000 km. Table 2.6 identifies the lead lost to the environment through the various production processes.

It is highly unlikely that bus batteries are not recycled since the systems are centralized and the battery itself has a high value of lead. Under the 90% recycling scenario, a battery with 90 kg of lead would represent 35.1 kg of lead lost. This seems high, but considering that each battery lasts 250,000 km and a reasonable load factor for buses is 50 passengers, the emission rate drops to 3.6 milligrams (mg)/passenger-kilometer (pax-km), two orders of magnitude lower than e-bikes.

Use Phase

The energy use and emissions from the use phase of a bus constitute a majority of the environmental impacts of the life cycle. This is because the vast majority of buses in the PRC use diesel internal combustion engines. Local emissions, greenhouse gas emissions, and energy use are highly related to fuel efficiency, vehicle power, vehicle loading, operating modes, and fuel quality. The diesel-powered buses examined here use about 45 L of diesel fuel per 100 km. The tailpipe emissions are highly related to the sulfur content of the fuel. Likewise, carbon monoxide emission rates increase with increased sulfur content. Conversely, increased sulfur content reduces nitrogen oxide and hydrocarbon emission rates. All of the PRC's diesel fuel is limited to a maximum sulfur concentration of 2,000 parts per million (ppm). Major cities such as Shanghai and Guangzhou have adopted more stringent 500 ppm standards, and Beijing has adopted 350 ppm standards. In 2002, the PRC officially adopted Euro II heavy-duty diesel exhaust standards, and these are thought to be an optimistic estimate of current bus emission rates. Shanghai and Beijing have more recently adopted Euro III heavy-duty diesel exhaust standards. Although the authors found no empirical studies of emission rates of buses operated in the PRC, several studies report bus emission rates for Euro II–III emission technology ranges with different fuel qualities (Air Resource Board 2001; Air Resource Board 2002; Nylund and Erkkilä 2005; Embarq 2006). These rates are reported in Table 2.7.

Table 2.7: Emission Factors of Urban Buses (g/km)

	Euro II[a]	Volvo-Sunwin[b]	MEX[c]	ARB[d]	VTT[e]	Average Value	Per-Cap Emissions[f] (g/pax-km)
CO	6.66	1.91	19.3	4.43	1.5	7.97	0.159
CO_2		1,175	1,299		1,350	1,275	25.49
HC	1.832	0.314	0.156	0.213	0.2	0.728	0.015
NO_X	11.66	11.12	12.27	9.96	14	13.51	0.27
SO_2		0.073				0.073	0.0015
PM	0.416	0.257	1.57	0.888	0.2	0.769	0.015

CO = carbon monoxide, CO_2 = carbon dioxide, g = gram, HC = hydrocarbon, kWh = kilowatt-hour, L = liter, NO_x = nitrogen oxides, pax-km = passenger-kilometer, PM = particulate matter, ppm = parts per million, SO_2 = sulfur dioxide.

Notes:

[a] Euro II emission standards converted from g/kWh to g/km by using conversion factor that is the product of the engine efficiency (%), fuel energy density (kWh/L), and fuel economy of vehicle (L/km). For the Volvo–Sunwin city bus, this is a factor of 1.67. Others report a factor of 1.8 (Nylund and Erkkilä 2005).

[b] Values adjusted from source document to reflect lower fuel economy than reported and multiplied emissions by ratio of Euro II standards to Euro III standards to reflect lower fuel quality and emission technology (Volvo 2006).

[c] Used values presented for 12-meter Volvo city bus using diesel fuel with a sulfur content of 350 ppm.

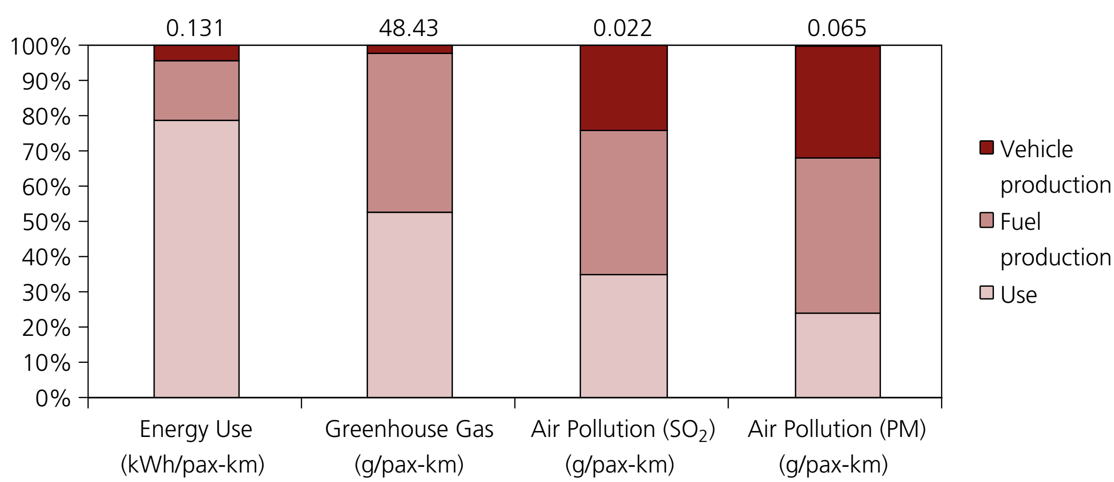
[d] Used average values for mid-1990s bus fleet in the EMFAC2000 and speed-adjusted EMFAC2001 models (Air Resource Board 2001, 2002).

[e] Euro II technology operating on diesel fuel with 50 ppm sulfur content. Because of this, CO and PM rates are likely to be lower than those for buses in the People's Republic of China, and NO_x and hydrocarbon rates are likely to be higher (Nylund and Erkkilä 2005).

[f] Assumes an average load factor of 50 passengers.

Sources: Air Resource Board 2001, 2002; Nylund and Erkkilä 2005; Volvo 2006.

Figure 2.3: Pollution of Bus over Life Cycle



g = gram, kWh = kilowatt-hour, pax-km = passenger-kilometer, PM = particulate matter, SO_2 = sulfur dioxide.

Source: Authors.

Emissions from refineries also contribute greatly to energy use and emissions, especially sulfur dioxide (SO_2) and particulate matter (PM). Figure 2.3 shows the estimated total life-cycle energy use and emissions of a bus manufactured and used in the PRC. This figure assumes a life span of 1 million km and a load factor of 50 passengers. The refining and burning of fossil fuels constitute over 90% of the energy use and greenhouse gas emissions. These processes also contribute to over 60% of the SO_2 and PM emissions. This is consistent with other studies of internal combustion engine vehicles (Sullivan, Williams, et al. 1998; Delucchi 2003; Volvo 2006).

Modal Comparison of Environmental Impacts

The life-cycle emissions of a bus, motorcycle, bicycle, and e-bike differ greatly as a result of their different material inventories, fuels, and usable life span. Buses use more energy and emit more air pollution—several orders of magnitude higher than bicycles or e-bikes—but they also carry more passengers and travel more kilometers. Buses are also the most efficient users of road space, and well-managed bus transport reduces congestion, thereby creating secondary emissions reductions from all modes.

Table 2.8 compares the life-cycle emissions and energy use per passenger-kilometers of the different modes. This table includes the average emission factors of all PRC power plants in the calculation of e-bike emissions.

Another important note is that the bus emissions consider the operation emission along a bus route, which is often longer than a more direct path taken by personal modes of transportation. Personal modes will perform relatively better than the table implies because they make the most efficient route choice. Routing analysis done for Kunming and Shanghai indicate that buses take a route that is 10% longer than the shortest path, resulting in 10% more emissions than those reported in Table 2.8. The table also shows ranges of emission rates that reflect different passenger-loading assumptions.

E-bikes outperform most modes on almost all environmental emissions. E-bikes do have higher emission rates of SO_2 than all motorized modes (with the exception of the car) because e-bikes derive their power predominantly from coal. Compared with a bus, e-bikes still have lower average energy use and comparable greenhouse gas and nitrogen oxide (NO_X) emissions. Compared with a motorcycle, e-bikes are much more energy efficient and have orders of magnitude fewer emissions of most pollutants. Bicycles, on the other hand, outperform all modes in terms of environmental impacts and energy efficiency.

As discussed earlier, lead pollution of e-bike battery production and disposal processes are two orders of magnitude higher than buses, on a per passenger-kilometer basis. While e-bikes have higher emission rates for some pollutants, they perform well against the two most efficient and sustainable modes we know of—bus and bicycle. Compared with other motorized modes that e-bikes could potentially displace (motorcycles and cars), e-bikes perform very well.

Table 2.8: Life-Cycle Environmental Impact Per Passenger-Kilometer Traveled[a,b]

	Energy Use (kWh/100 pax-km)	CO_2 (g/pax-km)	SO_2 (g/pax-km)	PM (g/pax-km)	CO (g/pax-km)	HC (g/pax-km)	NO_x (g/pax-km)	Pb[c] (mg/pax-km)
Car[d]	47–140	102–306	0.23–0.69	0.09–0.28	3.4–10.1	0.57–1.67	0.44–1.32	18–53
Bus	8.7–26.2	24.2–96.8	0.01–0.04	0.04–0.14	0.08–0.32[e]	0.008–0.030[e]	0.14–0.54[e]	1–4
Motorcycle	21–42	64–128	0.04–0.08	0.20–0.40	6.3–12.5[e]	1.13–2.25[e]	0.08–0.15[e]	16–32
Bicycle	4.88	4.70	0.01	0.06	Unknown	Unknown	Unknown	0
BSEB	3.8–7.6	15.6–31.2	0.07–0.14	0.07–0.14	0.007–0.014[e]	0.027–0.053[e]	0.010–0.020[e]	145–290
SSEB	4.9–9.9	20.2–40.5	0.09–0.17	0.10–0.19	0.009–0.017[e]	0.032–0.064[e]	0.014–0.027[e]	210–420

BSEB = bicycle-style electric bike (e-bike), CO = carbon monoxide, CO_2 = carbon dioxide, g = gram, HC = hydrocarbon, kWh = kilowatt-hour, mg = milligram, NO_x = nitrogen oxides, pax-km = passenger-kilometer, Pb = lead, PM = particulate matter.

Notes:

[a] Assuming life span of 197,000 km for car; 1,000,000 km for bus; 20,000 km for bicycle; 60,000 for motorcycle; and 50,000 km for e-bike.

[b] Ranges indicate assumed average load factors of 1–3 pax for car, 25–75 pax for bus, 1 pax for bicycle, 1–2 pax for motorcycle, and 1–2 pax for e-bike (although multiple passengers on e-bikes are illegal in many cities).

[c] Assuming 100% recycle rate and one battery every 10,000 km for e-bikes and one battery every 3 years or 250,000 km for buses, one battery every 3 years or 75,000 km for car, one battery every 3 years or 18,000 km for motorcycle (Wang, Huo, et al. 2006).

[d] Sullivan et al. 1998. Life-cycle inventory of generic United States car (cautiously compare because of different methodology).

[e] Only use phase emission rate, no production processes included.

General Note: Different vehicles have different impacts on congestion, with cars being the least efficient and buses being the most space efficient forms of mobility. Increasing congestion will yield higher emissions per km. The above emission factors assume generally uncongested city driving cycles.

Source: Sullivan et al. 1998; Wang, Huo, et al. 2006.

Distribution of Environmental Impacts

Internal combustion engine vehicles (buses and cars) consume most of their energy and emit most of their pollutants during the use phase, so most of their impacts are local. E-bikes are efficient energy users with zero tailpipe emissions, so their impacts are regional and national pollution from the power plants they use for electricity. (These power plant emissions can have even international effects, particularly in the case of small particles, which travel long distances.) A larger portion of e-bike life-cycle impacts are imposed on non-local communities, where production processes occur. Bicycles impose almost all of their life-cycle impacts non-locally for the same reason. All modes emit greenhouse gases (with global consequences) during various stages of their life cycle, but e-bikes perform well compared with most alternatives.

Direction of Public Health Impacts

Public Health Impacts of Air Pollution

E-bikes have higher emission rates over the life cycle of some pollutants (SO_2 and PM) and lower rates of others (NO_X) compared with motorized alternative modes such as buses and cars. From PRC literature, the mortality rates for increased NO_X and SO_2 concentrations are similar to each other but four to six times higher than mortality from PM (Health Effects Institute 2004). Thus, one can calculate net changes in mortality from a change in the mode of transportation. For example, each e-bike on the road in Shanghai might result in net increases of 152 grams per year (g/yr) of PM and 137 g/yr of SO_2, and a net decrease of 773 g/yr of NO_X. The mortality weighted sum of these emissions is negative (152 / 4 + 137 - 773 = –598), indicating that the decreased mortality from reduced NO_X emissions is greater than the increased mortality from increased PM and SO_2 emissions. Or to put it another way, shifting e-bike users to other motorized transport to reduce SO_2 and PM impacts would probably cause more severe public health impacts from NO_X.

Public Health Impacts of Lead Pollution

People are exposed to lead from a number of sources, including air, contact with solid waste, and water. Lead is a neurotoxin, and children are the most adversely affected by lead poisoning, causing a high incidence of developmental disorders, low IQ, and even premature mortality (US EPA 2006). Unfortunately, it is difficult to estimate exposure to lead pollution in the same way as air pollution. Because exposure pathways vary depending on the source of pollution, most lead exposure tests are done based on blood lead tests. High levels of exposure can be estimated if blood levels are above certain thresholds. There have been few lead exposure and public health impact studies in the PRC related to battery production (Shen, Wu, and Yan 2001; Wang and Zhang 2006), and it is difficult to quantify the public health impacts of such large releases into the environment as shown in Table 1.2. Some studies in other Southeast Asian countries suggest that lead levels in neighborhoods surrounding lead recycling plants suffer from significantly higher lead exposure (Yeh, Chiou, et al. 1996; Suplido and Ong 2000; Cortes-Maramba, Panganiban, et al. 2003). Anecdotally, there was a recent uprising of local residents that caught international attention at the factory of one of the largest e-bike battery producers (about 25% of the market[7]) following the hospitalization of hundreds of children because of lead poisoning from the factory (Zhang and Shao 2005). Short of doing a public health study of blood lead levels in communities neighboring lead mines, smelters, battery producers, and recyclers, it is difficult to quantify public health impacts of lead acid battery use in the PRC. But based on the high life-cycle emission rates (10–20 times as high as tailpipe emissions from leaded fuel), the public health impacts are probably significant and should be remediated.

Lead pollution is an inherent problem with electric vehicles. As long as they use lead acid batteries, they will always have pollution rates several times as high as their gasoline counterparts. This is because of heavier batteries used more frequently. A recent global analysis of lead emissions showed that even the most efficient regions still have 4%–6% emission rates during the production and manufacturing processes (Mao, Dong, et al. 2008). This is significantly lower than the PRC's lead emission rates. Over half of emissions during these processes are in the form of tailings during the mining process. If tailings are properly disposed of, the public health impacts of lead loss in the tailings are likely to be small. If tailings are allowed to infiltrate the ecosystem, these emissions could lead to significant

7 Based on an interview with a company manager on 16 April 2006 at the Shanghai Bike Expo.

environmental impacts. The phase that often has the highest environmental consequences is smelting of primary and secondary lead, which is often performed in the informal sector.

Programs to encourage improvements in the manufacturing of lead batteries can be adopted by businesses and government. Preferred purchasing programs can provide incentives to companies that reduce environmental lead emissions and take back used batteries for environmentally sound recycling. Independent third-party certification has been introduced to reward battery manufacturers that meet minimum emission standards and used battery recovery. The Better Environmental Sustainability Targets certification allows companies that demonstrate compliance with specific performance measures in an annual audit to place an eco-label on lead batteries.

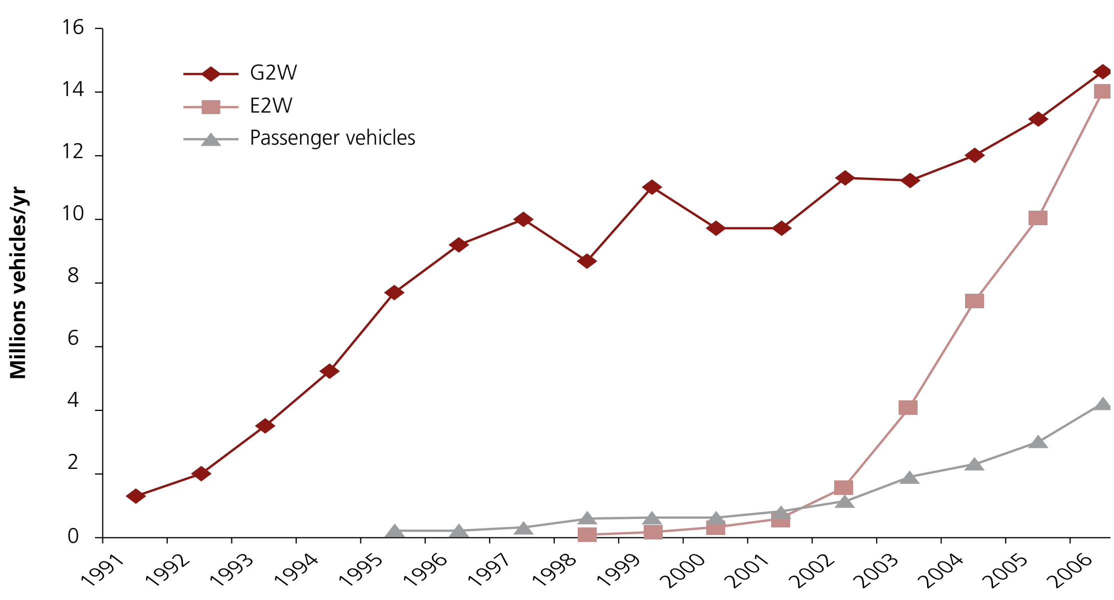
Influence of Electric Bikes on Motorization Trends

Introduction to Motorized Two-Wheeler Market: Past and Present

Strong economic development in the People's Republic of China (PRC) over the past 20 years has brought about rapid growth in motorized vehicle sales, which began to take off in the early 1990s, as shown in Figure 3.1.

Electric bikes (e-bikes) emerged from virtual nonexistence in the 1990s to achieve annual domestic sales of 13.1 million and sales revenue (including exports) of $4.6 billion in 2006 (National Bureau of Statistics 2007). By 2006, annual sales of electric two-wheelers (E2W) equaled those of gasoline two-wheelers (G2W). It is likely that E2Ws will continue to substitute for bicycles and public transport as incomes rise in the PRC. Depending on policy initiatives, they may also continue to replace G2Ws and may lead to wider electrification of the PRC's transport sector.

Figure 3.1: Motorized Vehicle Sales in the People's Republic of China



E2W = electric two-wheelers, G2W = gasoline two-wheelers, yr = year.

Sources: Honda 2006; Ohara 2006; Jamerson and Benjamin 2007; National Bureau of Statistics 2007.

E-bike ownership is estimated to be between 33 million and 45 million (Feng, Jiang, et al. 2007; Zhejiang Bike Web 2007).[8] Motorcycle ownership in the PRC reached 80 million by 2005 (National Bureau of Statistics 2007).[9] For comparison, there are 460 million bicycles and 13 million cars. The figures for two-wheel vehicle ownership by region in 2005 are presented in Figure 3.2.

There is no category for e-bikes in the National Statistics Bureau data set. Therefore, it is difficult to determine whether e-bikes are counted as bicycles or small utilitarian motorcycles (which could include mopeds), or not counted at all since registration requirements differ from city to city. Vehicle ownership statistics may underestimate the degree of e-bike use in the cities. Based on limited surveying by the author in 11 cities (small, medium, and large), e-bikes make up 28% of total two-wheeler traffic on average, compared with 57% for bicycles and 15% for G2Ws.[10] The majority of these users (70%–90%) are shifting from bicycle and public transport, according to survey results from Shijiazhuang, Kunming, and Shanghai (Weinert, Ma, et al. 2007).[11]

Projections for Motorized Two-Wheeler Market Growth from Literature

Two studies have examined future long-term growth in motorcycle ownership in the PRC (ADB 2006; Wang, Huo, et al. 2006). These studies project ownership to continue growing during roughly 2025–2030 and then declining as incomes rise to levels high enough to enable greater automobile ownership. (ADB projects a much larger growth in the medium term—close to 200 million motorcycles in 2025 compared with almost 100 million reported in 2005 Wang et al.). According to Wang, et al., motorcycles are a "transitional" transportation mode. Motorcycle ownership grows rapidly when per capita annual income is under CNY20,000 ($2,700). Between CNY20,000 and CNY30,000 per year ($4,000), ownership rates slow and reach saturation. At CNY30,000 ($4,325), car ownership starts to rise as motorcycle ownership begins to decline. As of 2005, per capita income in the PRC was CNY10,500 ($1,400). Average per capita income in rural areas is only CNY3,300 (National Bureau of Statistics 2007).

Wang, et al. point out that motorcycle growth is difficult to predict and depends on economics, geography, policy, climate, and topography as well as income. Motorcycle ownership is higher in the warmer southern regions, for example. Within the PRC, there are also irregular patterns of motorcycle use. For example, many cities ban G2Ws, which creates a skewed ratio of ownership between rural and urban areas—as high as 10:1.

Because of the relatively recent rise in e-bike ownership, there is limited literature on growth projections. One near-term forecast projects annual sales of 18.1 million, 22.7 million, and 30.1 million units in 2007, 2008, and 2010 (Woolf 2007).

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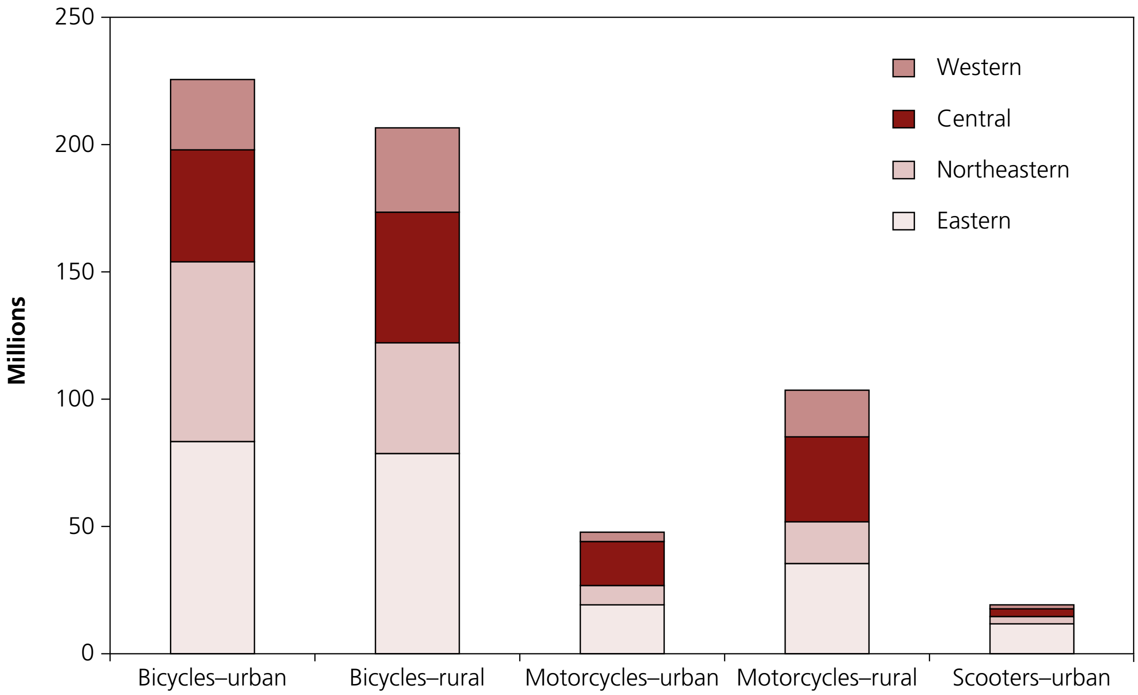
8 The figure of 33 million is based on the author's calculation of population from annual domestic sales data and an average vehicle lifetime of 5 years.

9 The Asian Development Bank estimates the number in 2005 lower at 55 million (ADB 2006).

10 Data were obtained by measuring vehicle flow at various intersections throughout each city. Total sample size: 8,297 (Beijing–341; Chengdu–487; Hangzhou–364; Jinan–356; Nanjing–224; Shanghai city–3,226; Shanghai outer suburbs–1,270; Tai An–219; Tianjin–976; Weifang 41; Shijiazhuang–600; Xi'an–193).

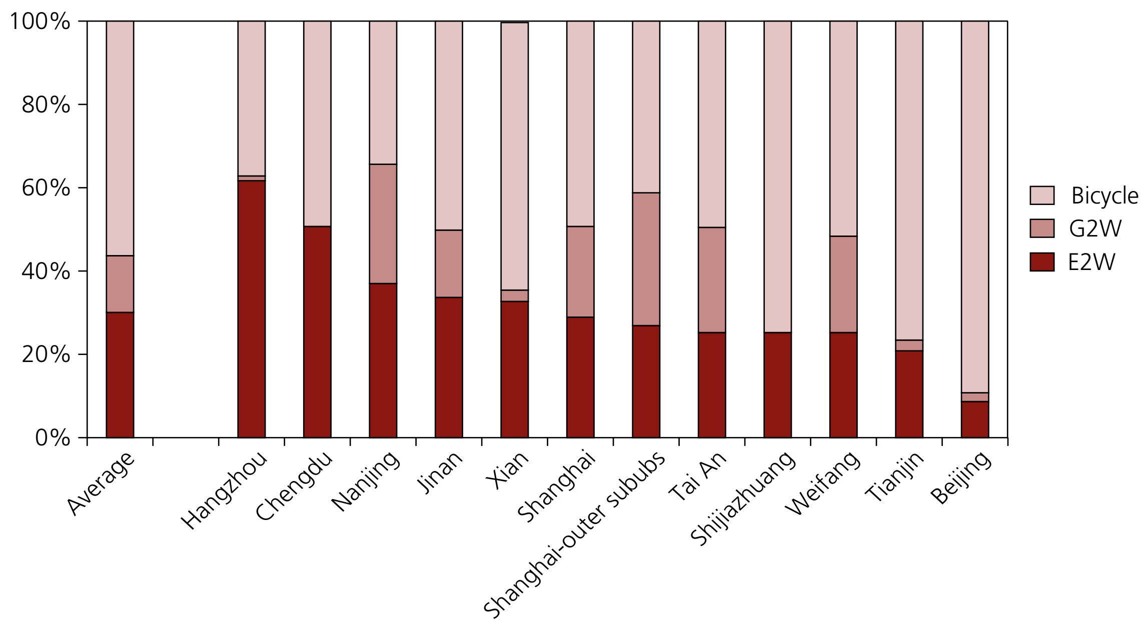
11 Survey data may underrepresent a shift from motorcycles because it includes only cities where motorcycles have been banned for years and does not include rural areas.

Figure 3.2: Vehicle Population by Region and Type



Source: National Bureau of Statistics 2007.

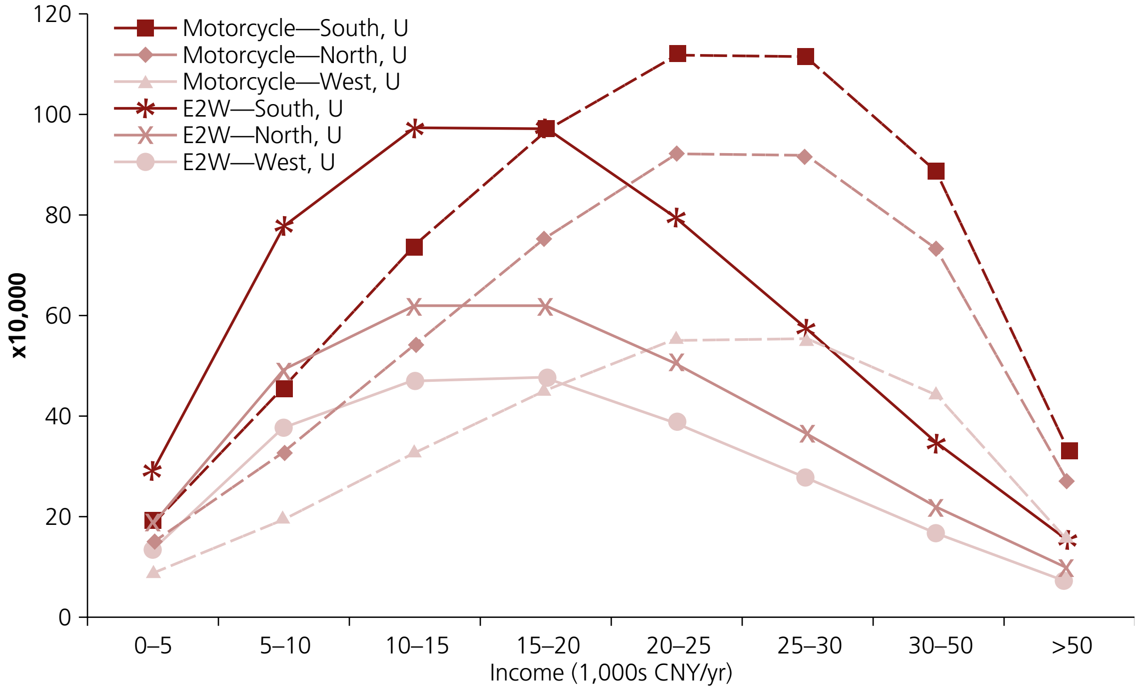
Figure 3.3: Observed Two-Wheel Vehicle Proportions in the PRC Cities, 2006–2007



E2W = electric two-wheelers, G2W = gasoline two-wheelers, PRC = People's Republic of China.

Source: Authors.

Figure 3.4: Regional Urban Motorcycle and Electric Bike Ownership versus Income, 2005



CNY = yuan, E2W = electric two-wheeler, U = urban, yr = year.

Source: Authors.

Motorcycle and Electric Bike Ownership Growth Scenarios through to 2025

Motorcycle and e-bike long-term forecasts are presented for three alternative scenarios.

Methodology

To estimate the future growth of e-bikes and motorcycles, a vehicle growth model was created using a similar approach to, and some of the same data as, Wang, Huo, et al. (2006). This approach integrates three sets of data:

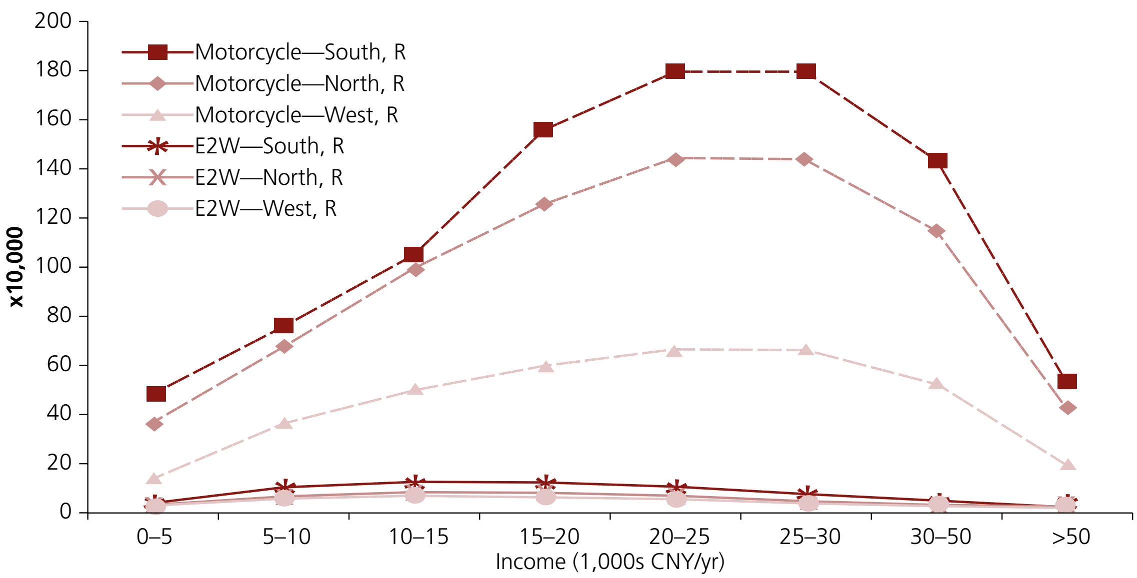
1. Current two-wheeler ownership (per 1,000 people) versus income level.
2. Current and future share of population (%) within each income level.
3. Current and future urban/rural population share and future growth in urban share.

E-bike ownership is estimated at 21 million in 2005.[12] Ownership share is assumed to be 80% urban versus 20% rural, and the regional distribution is 50% southern, 35% northern, and 15% western.

Figures 3.4 and 3.5 show e-bike ownership by income group and region for urban and rural areas. They are based on the assumption that e-bike ownership peaks at a lower-income level since e-bikes are less expensive and are a lower-value product than motorcycles (slower and less power).

[12] The figure 21 million is based on annual estimated E2W sales data between 1999 and 2005. Sales in 2006 were 13.1 million.

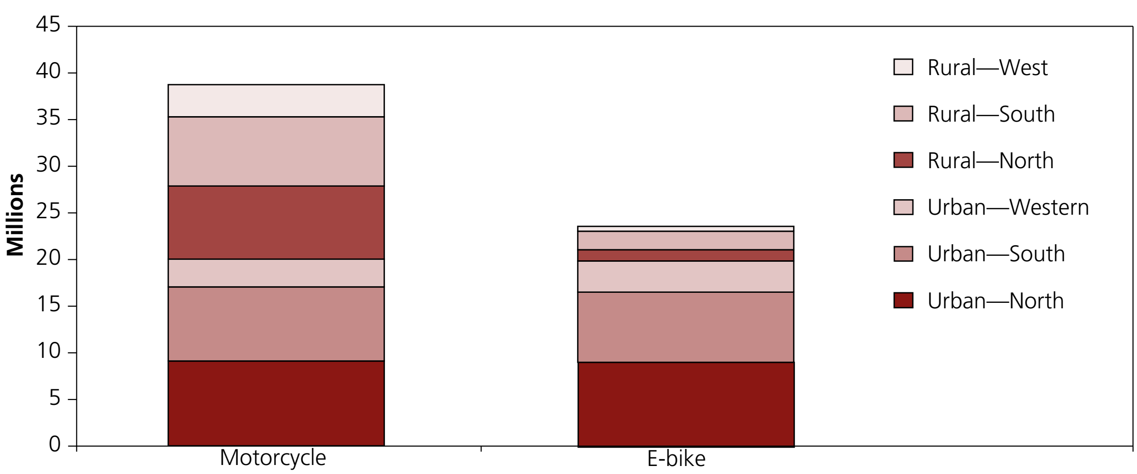
Figure 3.5: Regional Rural Motorcycle and Electric Bike Ownership versus Income, 2005



CNY = yuan, E2W = electric two-wheelers, R = rural, yr = year.

Source: Authors.

Figure 3.6: 2005 Motorcycle and Electric Two-Wheelers by Region

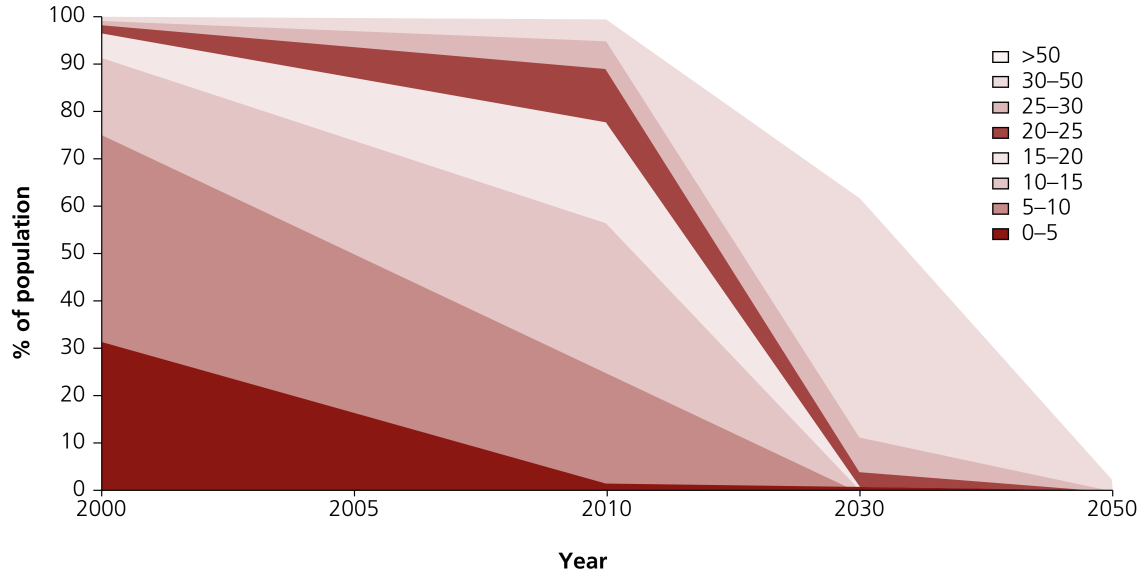


Source: Authors.

Baseline two-wheeler vehicle stock is presented in Figure 3.7. Motorcycle data are from Wang et al. (2006), and e-bike data are based on sales from the past 9 years. This figure shows that motorcycle and e-bike numbers in urban areas are roughly equal at 20 million.

The human population data for the model are used for studying income distribution. Figure 3.7 shows this data set for the urban north of the PRC. The general trend is a rapid increase in the percentage of population with incomes of CNY30,000 ($4,325) or more between 2010

Figure 3.7: Projections of Population Share in Different Income Brackets versus Time



Note: Urban areas in the north.

Source: Authors.

and 2030, which will have a significant impact on two-wheeler sales.

The vehicle growth model uses an adjustment (labeled "Policy Factor") to account for the gasoline motorcycle ban that has been enacted in over 160 cities throughout the PRC and for rising gasoline prices. It assumes that these two factors together cause a certain percentage of motorcycle users to switch from motorcycle to e-bike. Since the actual value of this factor is difficult to quantify and is subject to unpredictable policy and price trends, three different scenarios are examined using high and low ranges (Table 3.2). Wang, et al. assume regulations reduce motorcycle ownership by 20% by 2020, an additional 5% after 2030, and another 5% in 2040. The assumptions made in this study are shown in the table. In this table, the percentages correspond to the policy factor model inputs in the market estimation model on the next page. The higher the percentage (policy factor), the more motorcycles will be displaced by e-bikes.

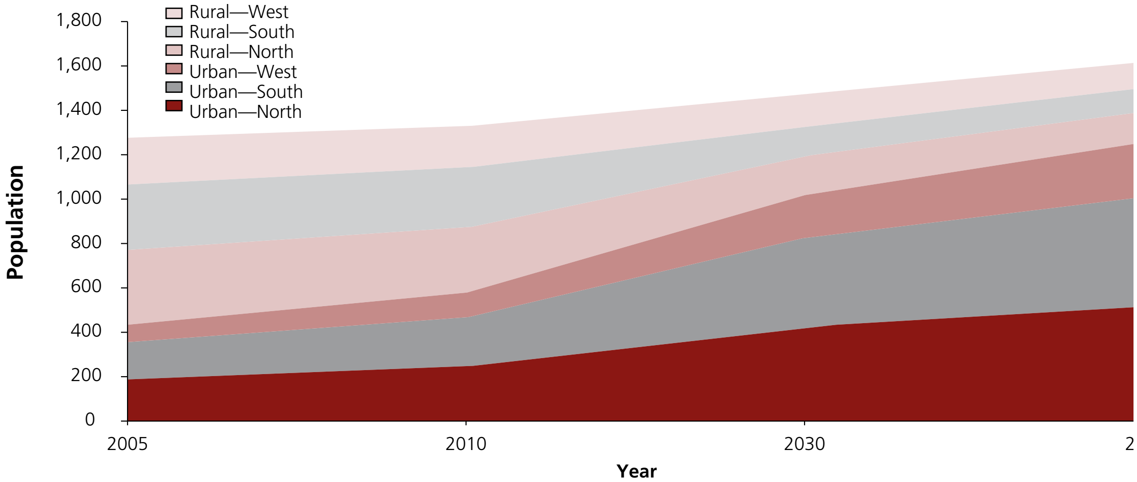
Table 3.2: Policy Factors Over Time in Three Scenarios

Year	Business as Usual (%)	E-Bike Thrive (%)	E-Bike Stagnate (%)
2010	10	15	8
2030	20	30	10
2050	30	50	15

Source: Authors.

The first scenario, Business as Usual, uses policy adjustment factors that correspond to the observed rapid growth in e-bike sales from 2005 to 2007 and near-term sales projections. The second scenario, E-bikes Thrive, accounts for a future where the e-bike market develops even more rapidly. Factors influencing rapid growth might include increased policy pressure on gasoline-powered motorcycles due to air quality and fossil fuel dependence, rising gasoline prices, and rapid advances in battery technology for e-bikes. The third scenario, E-bikes Stagnate, is a future where the e-bike market experiences

Figure 3.8: Projected Population Growth by Region for Urban and Rural People's Republic of China



Source: Authors.

several setbacks. Setbacks might include improvements in the emissions and performance of gasoline-powered motorcycles (and thus lower incentive to ban in cities), a significant drop in gasoline prices, limited battery technology advancement, or a backlash against e-bikes due to lead acid battery pollution, congestion, and safety concerns.

The input data for the model are integrated using the following equations:

$$MC_i = (1 - PF) \times \sum_j [\mathrm{Inc\_Dis}_j \times MC^*_j]$$

$$MC\_Disp_i = MC_i \times PF$$

$$E2W_i = \sum_j [Inc\_Dis_j \times \mathrm{E2W}^*_j] + MC\_Disp$$

Where:
MC_i = Motorcycle ownership (per 1,000 people) in year i
PF = Policy factor outlined in Table 3.2
e-bike_i = e-bike ownership (per 1,000 people)
Inc_Dis_j = % of population in income bracket j for year i
MC^*_j = Motorcycle ownership level (per 1,000 people) of people in income bracket j
e-bike^*_j = e-bike ownership level (per 1,000 people) in income bracket j
MC_Disp_i = Motorcycles displaced by e-bikes

To convert from ownership per 1,000 people to actual vehicle population, 2005 population statistics was used (National Bureau of Statistics 2007), a forecasted population growth rate of 0.5% per year,[13] and a forecasted shift from rural to urban from Wang, et al. (2006). The urban and rural population growth in each region is presented in Figure 3.8.

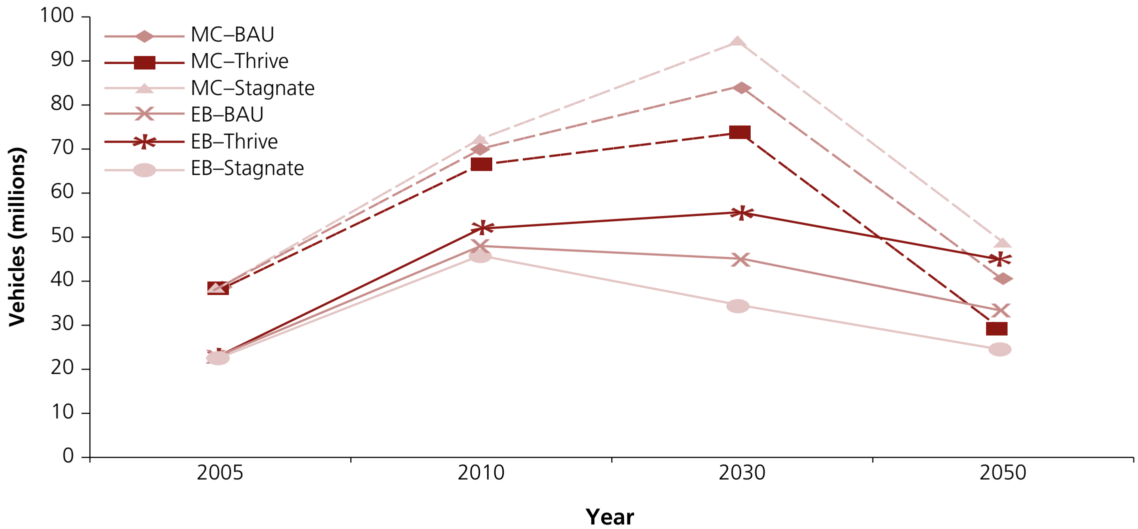
Nearly 60% of the PRC's population will reside in urban areas in the south and north by 2050.

Results

Combining all the data, projected motorcycle and e-bike numbers from 2005 to 2050 are presented in Figure 3.9. Dashed lines represent motorcycles, solid lines represent e-bikes, and colors represent different scenarios.

[13] Population in the PRC grew 1% annually between 1990 and 2000 although the annual growth rate has been declining each year since. In 2003, it was 0.6%. Available: www.unescap.org/STAT/data/statind/pdf/t2_dec04.pdf

Figure 3.9: Electric Two-Wheeler and Motorcycle Stock Over Time in Three Scenarios



BAU = business as usual, EB = electric bike, MC = motorcycle.

Source: Authors.

In all scenarios, e-bike and motorcycle numbers grow rapidly over the next several years. Then, both motorcycles and e-bike numbers decline around 2030 because of rising income levels driving a shift toward automobiles. In the E-bikes Thrive scenario, e-bike numbers actually overtake motorcycle numbers by 2040.

Figure 3.10 gives a breakdown between urban and rural vehicle numbers.

Factors Influencing Future Growth in Electric Two-Wheeler Market

The scenarios presented in the previous section reflect potential two-wheeler growth based mainly on economic growth, population growth and migration, and policy changes. However, many other factors may influence the growth of the e-bike and motorcycle markets. This section creates a framework for identifying and evaluating these forces.

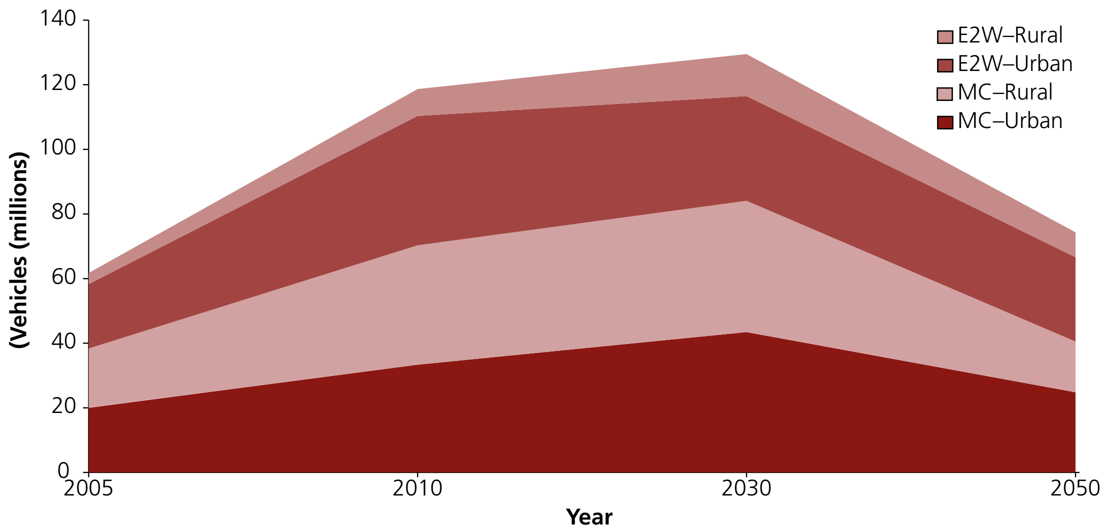
Methodology

In this section, force-field analysis (FFA) is used to understand the complex set of forces influencing future e-bike growth in the PRC. FFA, created by Kurt Lewin (Lewin 1952), was originally used to study organizational behavior and group dynamics. Since then it has been used to analyze the factors affecting a complex system, the interactions between these factors, and how the system might respond. FFA examines the forces pushing a system toward change and the forces resisting it. It is a particularly useful tool for describing the PRC's e-bike market, since it is a system affected by many different and interrelated factors (technical, social, political, etc.).

Force-field analysis typically has five steps:

1. Identify the system of focus and boundaries.
2. Generate a list of driving and restraining factors.
3. Determine the interrelatedness of these factors.
4. Quantify the forces.
5. Chart the force-field diagram.

Figure 3.10: Electric Two-Wheeler and Motorcycle Growth in "Business as Usual"



E2W = electric two-wheeler, MC = motorcycle.

Source: Authors.

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

Driving Forces

The key forces supporting the growth of the e-bike market are

- technology improvements,
- motorcycle bans,
- local policy support for e-bikes, and
- poor public bus service.

Force 1: Technology Improvements

Improvements in e-bike and battery technology are driving e-bike market growth. This section examines past improvements in these technologies and discusses why improvement is likely to continue.

Cost reduction and performance improvement of e-bike 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, Ma, et al. 2007). By 2006, valve-regulated lead acid (VRLA) battery technology from three top E2W suppliers had reached cost and performance levels achieved by a leading Japanese supplier (Weinert, Burke, et al. 2007). Meanwhile, the price of E2Ws has steadily decreased because of falling costs and shrinking profit margins. Between 1999 and 2005, the average E2W price dropped nearly 30% from $380 to $240 ($840 to $529, inflation-adjusted) (China Market Intelligence Center 2007).

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-watt (W), 60-volt (V) battery systems and regenerative braking. Two companies displayed products with power as high as 1.5 kilowatts (kW), attaining speeds of 60–80 kilometers per hour (km/hr). 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 E2Ws in suburbs and rural areas where incomes are low, travel distances great, 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 greater power.

Another sign of innovation is the growing proportion of advanced batteries used in E2Ws. The majority of the e-bikes in the PRC use VRLA batteries, although E2Ws using lithium-ion (Li-ion) and nickel-metal hydride (NiMH) are for sale at a limited number of dealerships and retail outlets. Between 2005 and 2006, the share of advanced-battery E2Ws produced increased from 10% to 13% (1.1 million to 2.1 million) (China Market Intelligence Center 2007). Although the majority of advanced-battery E2Ws are probably destined for export markets (based on observations of E2Ws in use in the PRC), Li-ion battery manufacturers in the PRC and the E2W companies they supply are reporting increasing domestic sales.[14] There are at least four battery manufacturers in the country producing Li-ion batteries for E2Ws and larger electric vehicles.[15]

The force of technology improvements described above can be partly attributed to the highly decentralized, "open-modular" e-bike industry structure. This type of industry structure, coined by Ge and Fujimoto (2004) and Steinfeld (2002), is also found in the modern computer industry and several other manufacturing industries in the PRC (Baldwin and Clark 1997). 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.

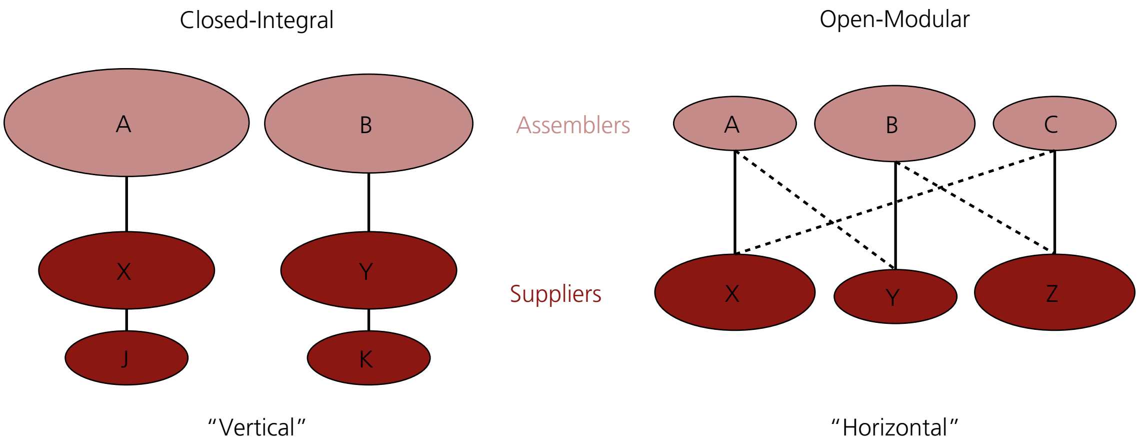
In an open-modular industry, manufacturers act primarily as assemblers and source components ("modules") produced by a large decentralized network of suppliers. This type of structure is typically found when a product exhibits high modularity, meaning it can be divided into several modules that are copied, 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 because of the high degree of product modularity (Ohara 2006). The open-modular structure typically results in increased competition and lower costs.

In a closed-integral 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 (Sugiyama 2003; Sinocars.com 2006). Figure 3.11 adapted from Ge and Fujimoto 2004 contrasts the two structures.

14 Includes LBH (Zhejiang) and Lantian (Tianjin).

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

Figure 3.11: Industry Structure Comparison, Closed-Integral versus Open-Modular



Source: Adapted from Ge and Fujimoto 2004.

The emergence of open-modular industries is a relatively recent phenomenon, and its effect on innovation has been the subject of much analysis (Sugiyama 2003; Sinocars.com 2006). They conclude that this structure leads to lower production costs than a closed-industry structure because of enhanced competition and cross-pollination of ideas. Evidence of this exists in the PRC's motorcycle industry and its ability to capture the lead market share position from the incumbent Japanese motorcycle industry. 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".

The force of technology improvement can also be partly attributed to the highly modular product structure of e-bikes. 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 it has gained more attention since the late 1990s because of globalization and increasing recognition of its importance for businesses managing global supply chains (Mo and Chihua 2007).

E-bikes meet the first criterion of modularity because most key functions of the vehicle are assigned to just one component (e.g., battery stores energy, motor delivers power). E-bikes also meet the second and third criteria of modularity: simple interfaces with minimal information exchange. For instance, the core modules of the drive-train 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.[16] Machining is not required at the assembly plant because components are prefabricated, and interfaces

[16] Based on site visits by the author to six E2W plants.

Figure 3.12: Electric Two-Wheeler Design Flexibility

Source: Authors.

exhibit greater tolerance of error. Designers also have more flexibility in positioning modules to enhance comfort, convenience, and styling, as seen in the models in Figure 3.12 (folding e-bike, standard e-bike, e-scooter).

Interface flexibility and simple information exchange between the interfaces of the e-bike are one reason for the wide variance in body style (e.g., e-bike versus e-scooter), module positioning, and module technology substitution (e.g., VRLA versus Li-ion). In contrast, motorcycle design has inherent limitations in module positioning and fuel flexibility.[17]

The highly modular nature of e-bikes 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, production volume increases and costs drop.

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 NiMH battery industries as each competes for a larger stake in the expanding e-bike market, both domestically and internationally.

Standardized technology with simple interfaces has lowered the barriers to entry into this industry, which is another reason for the large number of firms. Manufacturers of bicycles, appliances, toys, and motorcycles have all been successful in entering the e-bike business.[18]

From a user perspective, the modular industry facilitates uncomplicated maintenance of e-bikes. Each component is generally interchangeable with components made by other manufacturers. If a component fails on an e-bike, it is easily replaceable without requiring the purchase of proprietary replacement components. This results in a widely distributed maintenance network throughout most cities in the PRC.

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[17] Shanghai is the only successful market in the PRC of alternative fuel motorcycle use, using liquefied petroleum gas.

[18] During surveys of E2W manufacturers, one original equipment manufacturer who used to make only motorcycles started producing E2Ws when the market took off, stating, "It was easy for us to shift to producing E2Ws because the technology is much simpler."

It is expected that e-bike technology will continue to improve, in part because of the unique structure of the e-bike industry and the modular structure of e-bike products.

Force 2: Local Motorcycle Bans

The power of policy in the PRC has given e-bikes a strong advantage via the banning of gasoline-powered motorcycles in many large and medium-sized cities. This policy, driven by air quality concerns, has spread from 30 cities in 1998 to 148 by 2006 and effectively diminished motorcycle demand (Steinfeld 2004).

A recent survey on policy toward e-bikes and gasoline-powered motorcycles was completed for 33 cities with populations over 2 million. A total of 29 cities had either complete or partial bans on motorcycles. In comparison, four cities had either complete or partial bans on e-bikes. The cities' policies are summarized in Table 3.4.

Force 3: Local Policy Support for Electric Bikes

Besides banning motorcycles, cities have adopted other approaches to encouraging the use of E2Ws and the growth of the e-bike 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 (Weinert, Ma, et al. 2007). In 2006, Beijing reversed its intended ban against E2Ws, in part because of the worsening traffic congestion in the city. A testimony from one e-bike 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

Table 3.4: Motorcycle and Electric-Bike Bans in Large Cities

	Motorcycle		E-bike	
City	Complete ban	Partial ban	Complete ban	Partial ban
Beijing		X		
Changchun		X		
Changsha		X		
Changzhou	X		X	
Chengdu		X		
Chongqing		X		
Dalian	X			
Foshan	X			
Guangzhou	X		X	
Guiyang		X		
Hangzhou		X		
Harbin	X			
Huai'an				
Jinan	X			
Kunming		X		
Lanzhou		X		
Nanjing		X		
Ningbo	X			
Putian				
Qingdao		X		
Shanghai		X		
Shenyang		X		X
Shijiazhuang		X		
Suzhou	X			
Taiyuan	X			
Tangshan	X			
Tianjin		X		
Wuhan	X			X
Wuxi		X		
Xi'an	X			
Xiangfan				
Zaozhuang				
Zhengzhou	X			
Zibo				
TOTAL	**13**	**16**	**2**	**2**

Source: Authors.

the 34-year-old mother. "It takes only 10 minutes by electric bicycle, but a half-hour drive in the Beijing traffic."

National E2W standards for performance are seldom enforced at a local level, allowing manufacturers to answer a strong market demand for larger E2Ws with higher speed and more power. This incentive to produce models that violate the standard is not unique to the E2W industry and is thought to be due to the way power at a state level is distributed among local governments. Although supporting evidence on why this occurs is insufficient, some speculate it is because local governments which control quality inspections like to support local manufacturers to boost tax revenue (Weinert, Ma, et al. 2007). This support sometimes comes in the form of exemptions or minor fines for violating the standard.

Loose intellectual property protection in the e-bike 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 from large E2W companies surveyed by the authors complained that intellectual property rights are not well enforced. 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 exact duplication of a more famous company.

Force 4: Deteriorating Public Bus Transport

Despite huge investments, the quality and service level of bus public transport is worsening in many cities, causing greater demand for cheap motorized private transportation. For most low- and middle-income users (the predominant population served by public bus systems) e-bikes are the next best alternative. A survey in Shijiazhuang found the majority of E2W users shifted from bus public transport because it was too slow and over-crowded (Zegras and Gakenheimer 2006). 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 a bus because buses move slowly on congested corridors (Schipper and Ng 2007). However, changing from bus to E2W does not imply that traffic conditions overall will improve.[19]

There are several reasons that urban bus public transport is losing its competitiveness; the root causes can be traced to urbanization and rising income. Public transport systems have difficulty adding capacity fast enough to serve their rapidly growing low-income user base (mainly people from rural areas). Rising income is driving motorization in cities (Menon 2006), resulting in more private vehicles (two-wheelers and automobiles) on the road, increasing traffic congestion, and is making buses slower.[20] As buses become slower, it has the cyclic effect of shifting even more people to private transport. Third, cities expand and decentralize because of the increase in urban population and growing use of private vehicles (both motorized two-wheelers and automobiles). Decentralization increases the set of trip origins and destinations, an inherent challenge for public transport systems that are most profitable when serving high-density corridors. The trends of urbanization

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[19] In fact, the contrary may occur because of erratic driving of E2Ws, which is a reason Guangzhou has banned motorized two-wheelers in favor of public transit.

[20] Motorization increases with rising income, a pattern followed by every developed country because of demand for greater accessibility and safe, comfortable travel.

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 (Zhang 2007).[21]

Other Driving Forces

Electric two-wheelers 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 transport made up 70 million tons of oil equivalent (mtoe) in the PRC in 2006, it is expected to increase to 165 mtoe by 2020 (Meszler 2007). E2Ws' energy use per km is 20%–25% that of motorcycles over their life cycle. They have been recommended by the state as a means of saving energy and improving the environment (Weinert, Burke, et al. 2007).

The existing legacy of bicycle infrastructure pervasive throughout the PRC's cities is another factor driving the growth of e-bikes. Users rely on the nonmotorized-vehicle lane and parking infrastructure to improve travel speed, safety, and convenience. This extensive infrastructure, a legacy from 1949 policy decisions, may explain e-bikes' current success in the PRC 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 city's first extensive restructuring for cyclists since it first banned cycling in certain parts of the city center during the past decade (Ohmae, Sawai, et al. 2006).[22]

The practically nonexistent noise level of e-bikes could become an important driving factor for statutory regulations and consumer choice favoring e-bikes. Although the authors are not aware of any policies like this in the PRC, Shanghai measures noise levels on certain arterial roads.

Resisting Forces

The forces resisting a shift toward e-bikes include

- strong demand for motorcycles,
- e-bike bans, and
- increasing support for public transport.

Force 1: Strong Demand for Motorcycles

In most of Asia, motorcycles using the internal combustion engine and gasoline (and sometimes liquefied petroleum gas) 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 prices, motorcycle fuel economy and emissions control technology continue to improve through innovation in engine design and emission control technology (Jamerson and Benjamin 2007).

For the higher-income market segment, E2Ws using VRLA battery technology have difficulty competing with motorcycles because of inherent limitations in power, speed, refueling, and life span (*Shanghai Daily* 2005). In addition, their performance (range and life span) degrades

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[21] Based on urban population of 560 million in 2006 and a projected population of 600 million by 2030 (Schipper 2007).

[22] In Shanghai, liquefied petroleum gas scooters are allowed, so this policy will probably benefit them as well.

quickly in areas where temperatures are very high throughout the year or very low (Zegras and Gakenheimer 2006). This partially explains why they have failed to catch on in Southeast Asia and India, where bicycles and motorcycles dominate the roads. E-bikes with the performance characteristics of motorcycles could become generally more expensive than their gasoline counterparts. For the domestic PRC E2W market, the benefit–cost ratio of Li-ion batteries is not yet compelling enough to create a noticeable shift away from lead acid batteries.

Force 2: Bans on Electric Bikes

Several cities throughout the PRC have banned or restricted E2Ws in recent years, in addition to banning motorcycles. Some officially cited reasons for the bans include improving traffic flow, poor safety records, and reducing environmental pollution from worn-out batteries (Center for Electric Bicycle Products Quality Monitoring and Inspection 2006). As automobile ownership grows, it is reasonable to assume that pressure to improve traffic flow and allow automobiles to move faster 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.

Pressure for E2W bans may also increase because of the abundance of low-quality and unsafe products on the market, which can be traced back to loose enforcement of standards. Many users complain that e-bike brakes are insufficient for the weight and speed of the vehicle. Low-quality VRLA batteries have a short life and thus lead to greater lead waste. A sample of E2W products from 40 manufacturers in 2006 revealed that only 74% of them passed the quality standards. In a sample of E2W VRLA batteries from 35 manufacturers, only 77% of the batteries passed the quality standards (Zamiska and Spencer 2007). Thus, loose enforcement of standards is a double-edged sword for E2Ws. It allows manufacturers to sell products that violate the standard though they are highly desirable for customers; however, it also leads to more low-quality products on the market.

Lead pollution from production and recycling use of VRLA batteries could lead to greater environmental backlash against them. The lead mining, smelting, and recycling industries in the PRC are highly dispersed, and many are small scale, resulting in high loss rates because of poor management, weak regulation, and the use of outdated and inefficient technologies. It is estimated that 44%–70% of the lead from lead acid batteries in the PRC is released into the environment as waste. Groundwater and crop contamination from hazardous chemical and metals has already caused some local health problems throughout the country (Suzuki 2007).

In addition to those listed in Table 3.4, 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 the PRC's largest and most motorized cities, banned motorized two-wheelers to improve traffic safety and traffic flow.

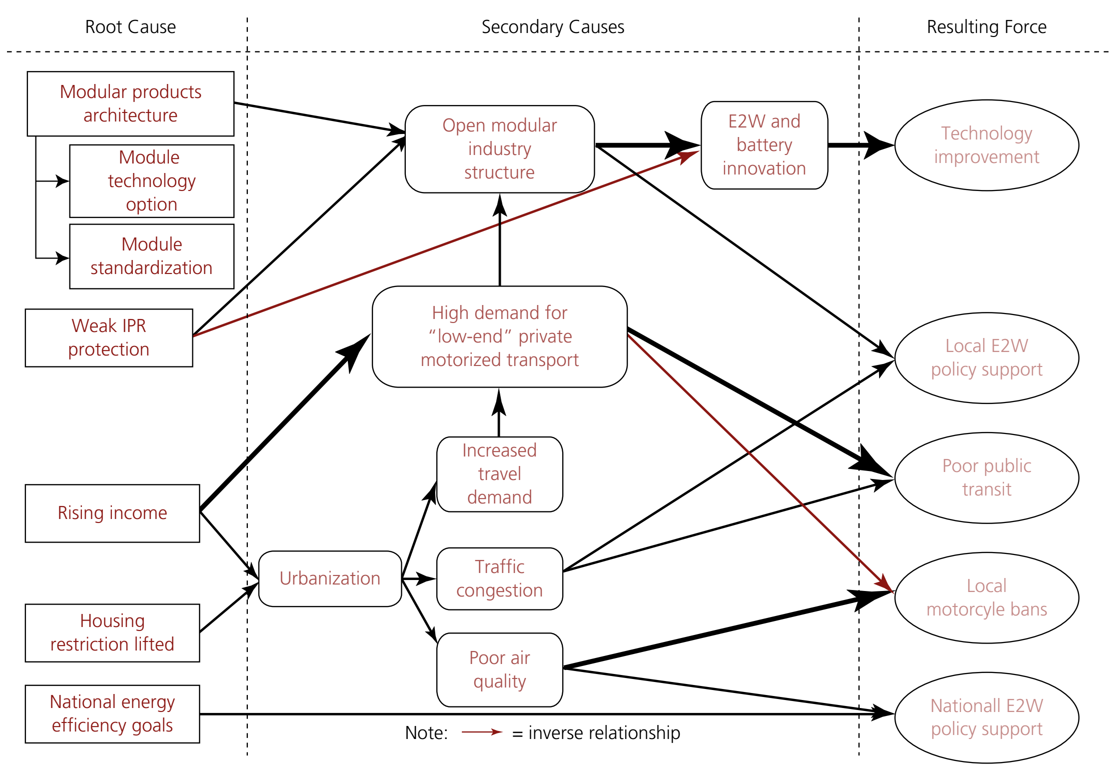
Force 3: Support for Public Bus Transport

Increasing financial and political support for public transport, especially bus rapid transit, could reduce the shift from buses to e-bikes discussed in section Modal Comparison of Environmental Impacts, p. 21. Bus rapid transit (BRT) has been gaining support in the PRC as a means to improve public transport performance by converting or constructing bus-only lanes, building stations, and using information technology (Neupert 2007). BRT can be a lower-cost alternative to light or heavy rail, which only the PRC's large wealthy cities have built (e.g., Shanghai, Beijing, Shenzhen, Guangzhou, 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 such as Dalian (14 km), Jinan (135 km planned), Shijiazhuang, Chengdu, Changzhou, and Shanghai have constructed, or have plans to construct, a BRT network. Successful demonstrations in these cities may lead to even greater support and more demonstrations throughout the PRC. Guangzhou and Shanghai have announced in their 5-year plans their intention to strongly enhance public transport service, both rail and bus transit.

Interrelatedness of Forces

The forces and their root causes listed in the previous section are interrelated in complex ways. For clarity, they are mapped into visual diagrams (Figures 3.13 and 3.14). 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, although these rankings are to some degree subjective.

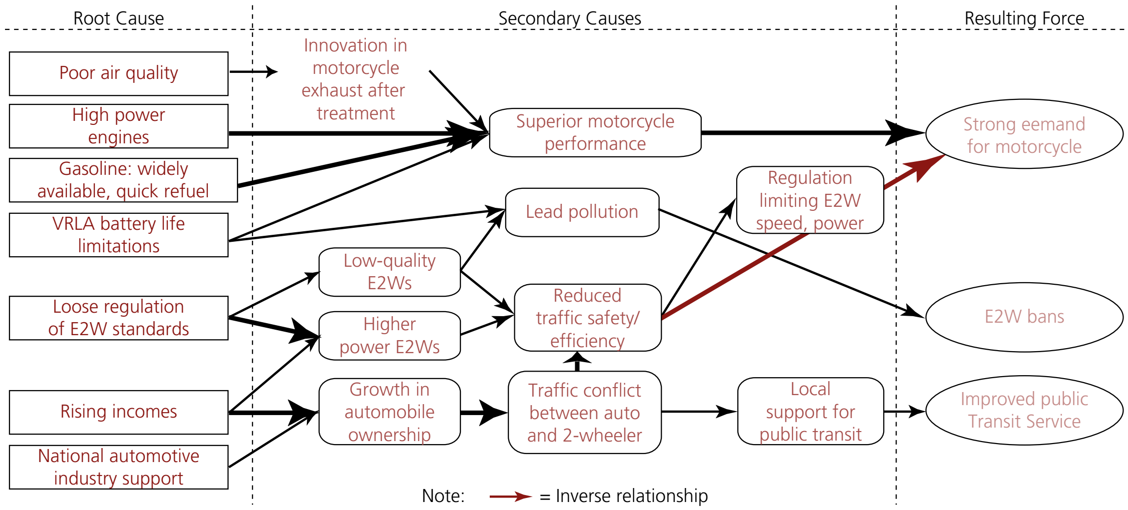
Figure 3.13: Forces Driving Electric Bike Market Growth



E2W = electric two-wheeler, IPR = intellectual property rights.

Source: Authors.

Figure 3.14: Forces Resisting Electric Bike Market Growth



E2W = electric two-wheeler, VRLA = valve-regulated lead acid.

Source: Authors.

Table 3.5: Rankings of Forces Driving and Resisting Electric Bike Growth

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

E2W = electric bike two-wheeler, L = low, M = medium, H = high.

Source: Authors.

Quantifying the Forces

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 therefore 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). The ratings are based on an understanding of the root causes for each force described in the previous sections. An improvement to this method would be to ask people within the e-bike industry or government officials to rank each factor and compile the results.

Table 3.5 shows that the forces driving a growth in e-bikes outweigh the forces resisting that growth by 19 to 12. Figure 3.15 presents the same analysis more graphically, by relative sizes of the "force fields".

Prospects of Electric Bikes in Other Southeast Asian Countries

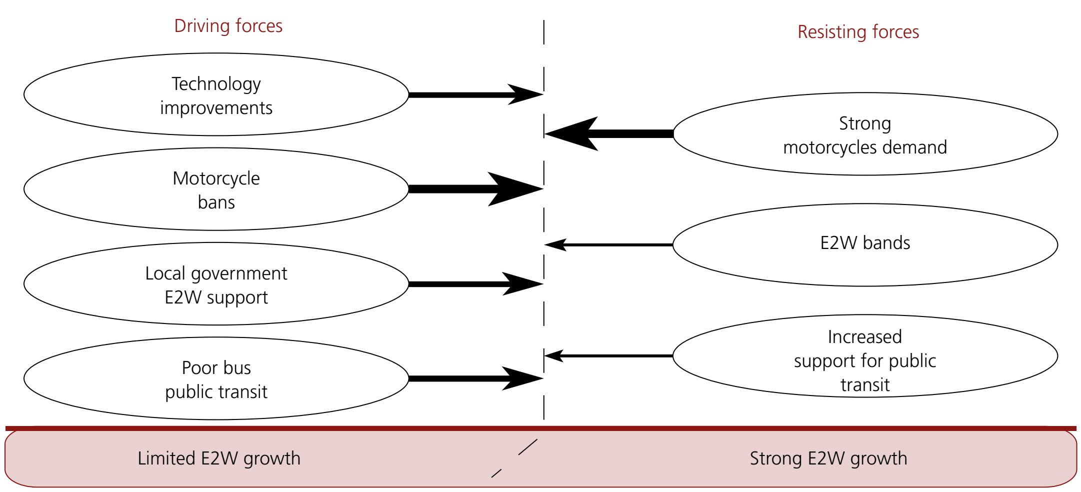
The overwhelming majority of the world's e-bikes (96%) are concentrated in the PRC. There are other small but growing e-bike markets in Japan, Europe, and more recently in India (Figure 3.16) (Schenker 2008).

After the PRC, the next largest e-bike market is Japan with annual sales of 270,000 bikes in 2006 and 13% average annual growth since 2000 (Weinert, Ma, et al. 2007). Pedelecs (a style of e-bike driven primarily by human power with battery assist) are the dominant type of e-bike. Most pedelec e-bikes use NiMH or Li-ion batteries. Battery capacity is 0.2–0.6 kWh, motor size is 150–250 W, and the price is $700–$2,000.

In Europe, the market is estimated at 190,000 bikes/yr in 2006 (Center for Electric Bicycle Products Quality Monitoring and Inspection 2006; Wang 2006). E-bikes in Europe are also mainly pedelec style. Sales in the Netherlands are the highest because of extensive bicycle infrastructure and a deep-rooted biking culture. Germany and Belgium are the next largest markets for pedelecs.

India's e-bike market is small, but some e-bike manufacturers are forecasting significant growth. A market survey by AC Nielsen in 2006 estimates the e-bike market in India at 200,000 units for 2007–2008 and later 490,000 units. The survey also found that the target buyers in India are bicycle users from 14 to 18 years old and users of gas-powered two-wheelers (G2Ws) who are 24 and older. An important aspect of the emerging Indian e-bike market is that most products are

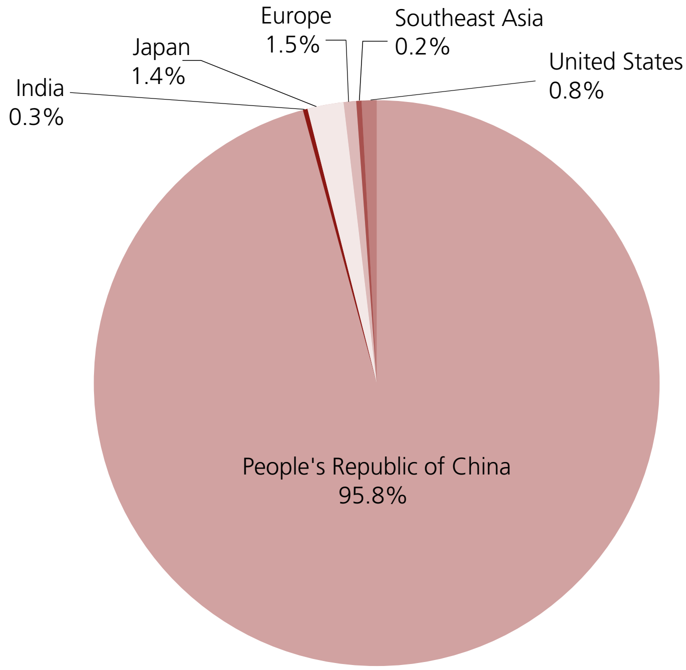
Figure 3.15: Force-Field Analysis of Forces Driving and Resisting Electric Bike Growth



E2W = e-bike two-wheeler.

Source: Authors.

Figure 3.16: Worldwide Electric Bike Sales, 2006



Source: Authors, derived from Schenker 2008.

PRC type with low-power motors that make them exempt from motor vehicle classification and consequent safety and emission standards. This helps keep costs low. E2Ws that match the performance of their gasoline counterparts may be too expensive and require compliance with regulations and thus may not be accepted. This may be an important factor influencing future growth of e-bikes in India.

In other developing countries of Southeast Asia such as Indonesia, Thailand, and Viet Nam, where two-wheelers are the dominant form of transport, e-bikes have not gained a significant market share. This may be attributed to lower incomes, the lack of regulation limiting the use of gas-powered two-wheelers, and limited bicycle infrastructure separating nonmotorized two-wheelers from motorized. G2Ws are the dominant mode in the larger cities of these countries.

In the United States, the very small e-bike market is limited mainly to recreational riders who rely on the assistance of the electric motor out of physical necessity. The e-bike is not a common commuter vehicle in most cities because commuting distances are long and bicycle infrastructure nonexistent.

The FFA framework can be used to describe the factors influencing future e-bike market growth in Southeast Asia.

Driving Forces

- Technology improvements in the PRC e-bike market may eventually make e-bikes more competitive with motorcycles in other Southeast Asian countries. The trend of e-bikes becoming larger, faster, and more powerful is one indication that this is plausible.

- Air quality concerns in urban areas and increasing pressure for carbon mitigation may eventually lead to regulations limiting gasoline motorcycle use (as in the PRC) or requiring better tailpipe emissions and fuels (as in Taipei,China). If other countries follow the example of the PRC, it is expected that the e-bike market would grow.

Resisting Forces

- There is a strong motorcycle culture in many Asian countries, including Viet Nam, Thailand, and Indonesia. Just like automobiles in the developed world, motorcycles serve as both transport tool and status symbol. There may be reluctance to accept a product that is slower, less powerful, and has less status appeal.
- High-power e-bikes of similar performance to G2Ws may require compliance with vehicle standards, increasing cost and making them less competitive with G2Ws.
- Limited bicycle/e-bike infrastructure in the form of dedicated nonmotorized vehicle lanes may limit the growth of an e-bike market because of the safety risk of mixing slower e-bikes with high-speed and heavy vehicles.

E-bikes are most likely to gain penetration into the market in regions where the driving forces are stronger than the resisting forces.

Conclusions

The e-bike market will continue to expand over the next several years as the PRC's lower income population trades bicycles and public transport for motorized two-wheelers. By 2030, however, modeling shows that the number of motorized two-wheelers will begin shrinking as the PRC's middle class trades e-bikes for automobiles. Future e-bike and motorcycle numbers are explored in three scenarios of "business as usual", "e-bikes thrive", and "e-bikes stagnate".

Based on force-field analysis, we conclude that driving forces outweigh the resisting forces for e-bikes. Improvement in e-bike and battery technology is a driving force that can be partially attributed to the open-modular industry structure of suppliers and assemblers; standardization has enhanced competition among battery technologies. Growing air quality and traffic problems in rapidly expanding cities has led to strong political support for e-bikes 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 transport 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 the growth of e-bikes. The superior performance of motorcycles is a powerful limiting factor, especially in areas where motorcycles are not banned and incomes are high. Urban bans on e-bikes might continue to spread, instigated partly by the increasing use of automobiles and the prevalence of low-quality e-bikes. Some large cities are also trying to promote public transport 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 transport.

One area not explored in this analysis is how city size impacts the success of e-bikes. In megacities like Guangzhou, public transport may be more effective than e-bikes at moving millions in an orderly, efficient way. In small to medium-sized cities like Suzhou, where commuting distances and resources for public transport are smaller, e-bikes may be preferred for providing low-cost, local-pollution-free mobility. Another concept worth exploration is integrating e-bikes with public transport to improve the efficiency of both. For example, rental e-bikes could be made available in business districts for users commuting into cities via public transport. This type of system would help overcome public transport's "first/last kilometer dilemma", allowing transit users an access mode to transit routes in increasingly expanding cities. E-bikes could also act as feeders from residential districts to trunk lines for bus and/or rail transit. This already occurs as evidenced by the many e-bikes parked at the Shanghai Metro's various terminal stations.

Electric Two-Wheeler Battery Technology Status

At the heart of electric bike (e-bike) technology is the rechargeable battery. The core rechargeable battery technology used in e-bikes is valve-regulated lead acid (VRLA) or "sealed", and lithium-ion (Li-ion). Advances in VRLA batteries and rising gasoline prices over the past decade have made e-bikes increasingly competitive with gasoline scooters in price and performance (Wang 1998). E-bikes using VRLA achieve low cost ($150–$300) and adequate range (30–70 kilometers [km] per 8-hour charge). The power system characteristics of e-bikes are shown in Table 4.1. Because most e-bikes use either VRLA or Li-ion batteries, this analysis will focus on these two battery types.

Methodology

The analysis relies on literature and data from surveying a variety of companies involved in battery production for e-bikes. The authors visited several battery factories making both lead acid and Li-ion batteries. Batteries from some of these manufacturers have been laboratory tested. In the Battery Transitions in the Electric Bike Market section (p. 55), results are presented from equipping an e-bike and e-scooter with a data logging system to measure energy use, power use, and overall efficiency.

Table 4.1: Electric Bike Power System Characteristics

Specifications	BSEB	SSEB
Total battery pack capacity (kWh)	0.4–0.6	0.8–1.0
Maximum current (A)	15	20–30
Voltage (V)	36	48
Modules/pack (typical)	3	4
Cells in series	18	24
Peak motor power (kW)	0.24	0.5–1.0
Maximum depth of discharge (%)	80	80

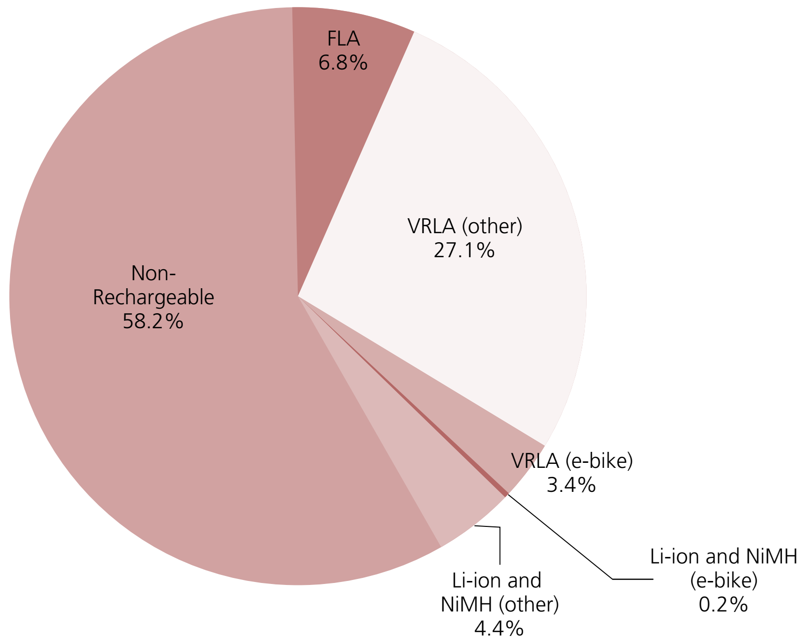
A = amp, BSEB = bicycle-style e-bike, kW = kilowatt, kWh = kilowatt-hour, SSEB = scooter-style e-bike, V = volt, % = percent.

Source: Authors.

Battery Industry in the People's Republic of China

The total battery market in the PRC was valued at $12.4 billion in 2006, 35% of which is for rechargeable lead acid batteries. Estimates on the production volume capacity of lead acid batteries range from 35 million to 67 million kilowatt-hours per year (kWh/yr), produced by more than 2,000 companies (Eckfeld, Manders, et al. 2003). Three hundred of these companies

Figure 4.1: The People's Republic of China's Battery Market by Battery Type



e-bike = electric bike, FLA = flooded lead acid, Li-ion = lithium-ion, NiMH = nickel-metal hydride, VRLA = valve-regulated lead acid.

Source: Eckfeld, Manders, et al. 2003.

specialize in e-bike batteries with an estimated annual production of 3.5 million to 9 million kWh/yr in 2005. Calculations based on the annual e-bike sales in 2006 and assumed after-market sales to the existing e-bike population indicate a much higher annual production of 15 million to 20 million kWh/yr.[23] Figure 4.1 shows the proportions of different battery types in the PRC.

VRLA batteries were first introduced into uninterruptible power supply (UPS) applications in the United States and Europe in the 1970s because of their low maintenance requirements and high reliability over traditional flooded lead acid. The rapid growth in telecommunications and computer networks throughout the world during the 1980s created a huge market for this battery type. The VRLA industry finally spread to the PRC in response to the telecommunications boom of the 1990s (Eckfeld, Manders, et al. 2003; Razelli 2003). Prior to that, the battery industry in the PRC produced mainly flooded lead acid batteries for agriculture and transport (e.g., trucks, train infrastructure). Between 1990 and 1996, sales of VRLA batteries grew from 60,000 to 730,000 kWh, primarily for telecommunications applications. In the late 1990s, production of small VRLA and flooded starting, lighting, ignition (SLI) batteries grew in response to the growing automobile, gasoline scooter, and e-bike markets (Eckfeld, Manders, et al. 2003).

[23] Assuming that average e-bike battery capacity is 0.53–0.67 kWh, there were 16 million new sales in 2006, and that of the estimated 20 million existing e-bike users, 40% replace their battery each year and 60% replace it every other year.

One of the main problems with the PRC's lead acid battery industry is that it is difficult for government to regulate production, quality, and environmental impacts. This is partly because of the large number of relatively small manufacturers spread throughout the country. This high degree of decentralization results in lower-quality batteries entering the market and batteries containing toxic performance-enhancing materials such as cadmium, as well as lead waste issues. In 2006, 23% of the e-bike battery companies inspected did not pass the minimum standards set by the national inspection bureau.[24] Considerable consolidation within the industry is expected, as occurred in the European battery industry during the 1990s (Gaines and Cuenca 2000).

The advanced battery market in the PRC makes up 15% of the total market, which includes batteries using lithium or nickel compounds. These companies primarily produce batteries for consumer electronics applications used throughout the world. The first Li-ion battery was commercialized by Sony in 1991 in Japan for use in consumer electronics. Few manufacturers in the PRC are making advanced batteries. From one manufacturer's perspective, Li-ion batteries are still dangerous and costly, and the market for lead acid batteries is still large and expanding.

Valve-Regulated Lead Acid Production

Most of the world's small VRLAs (less than 25 amp-hours [Ah]) are manufactured in Asia and exported around the world because of low labor costs, land cost, and loose environmental standards (Broussely 1999). The process for making large modules is roughly the same as making small modules. Manufacturing is labor-intensive yet exhibits low profit margins. Battery quality can be considerably different among manufacturers and is a key factor distinguishing top brands from the hundreds of smaller competitors. Differences from company to company are linked to factors such as differences in materials (alloy plate formula, electrolyte formula, absorptive glass mat, etc.) and manufacturing dust control, and quality inspection stations (Gaines and Cuenca 2000).

Lithium-Ion Production

Li-ion batteries, whether for electric vehicles, e-bikes, or consumer electronics, are all produced using similar processes (Ober 1999; Tse 2004). Hence, a single manufacturer can produce battery sizes for a wide range of applications (China Market Intelligence Center 2007). Li-ion batteries can be designed for high power or high energy depending on cell size, thickness of the electrode, and relative quantities of material used (Moseley 2004). High-power cells are generally smaller to dissipate the higher heat load. Both types use the same current collectors and separators. Lithium resources are abundant in the PRC. The PRC was the second-largest producer of lithium in the world as of 2000, and in 2004 produced 18,000 tons (Center for Electric Bicycle Products Quality Monitoring and Inspection 2006).

Batteries for Electric Bikes

The majority of the e-bikes in the PRC use VRLA batteries, although other more advanced batteries are starting to be used, including Li-ion

[24] Personal communication with the chief operating officer of Ritar Power.

and nickel-metal hydride (NiMH). Between 2005 and 2006, the share of e-bikes produced with Li-ion increased from 7% to 10% (0.8 million to 1.6 million) while the share of nickel-based battery types remained constant at 3% (Weinert, Ma, et al. 2007). Although the majority of advanced-battery e-bikes are probably exported to other countries (based on observations of e-bikes and dealerships around the PRC), Li-ion battery manufacturers and the e-bike companies they supply are reporting increasing domestic sales.[25] This section describes VRLA, Li-ion, and NiMH batteries for use in e-bikes and identifies the most important battery characteristics.

Valve-Regulated Lead Acid

VRLA battery packs typically consist of three to four 12 V modules (12, 14, or 20 Ah capacity) for a total voltage of 36 or 48 V and energy capacity of 0.4–1 kWh. In 2007, e-bikes with system voltage as high as 72 V were found on display at trade shows. VRLAs for e-bikes differ from SLI VRLAs used in automotive applications in that they can be deep-cycled. E-bike batteries are typically of the absorptive glass mat (AGM) type, meaning they use an absorbed sulfuric acid electrolyte in a porous separator, as opposed to a gelled silica/acid separator in gel-type VRLAs. Whereas standard SLI automotive batteries are typically discharged only 10%–15%, deep-cycle batteries for motive applications like e-bikes are discharged 80%–90% (Weinert, Ma et al. 2007). Battery makers claim the key distinguishing factors of their batteries are life span and stability (i.e., mean time before failure). Most domestic manufacturers do not report the defect rate of their products, but one study by a battery manufacturer reports a 3%–9% defect rate of e-bike batteries from three domestic manufacturers.

Lithium Ion

Li-ion battery packs for e-bikes typically range from 24 V to 36 V with capacity of 8–12 Ah. The market for Li-ion e-bikes in the PRC is still small. In Japan and Europe, however, Li-ion and NiMH are the dominant battery types, although annual e-bike sales in these regions are two orders of magnitude lower than in the PRC.

Nickel-Metal Hydride

NiMH battery packs for e-bikes also typically range between 24 V and 36 V with capacity of 8–12 Ah. Market share of NiMH battery e-bikes remained static between 2005 and 2006 at 3%, probably because of the rising price of nickel, falling cost of Li-ion batteries, and better energy and specific density of Li-ion compared with NiMH. Figure 4.2 shows the historic price of Li-ion and NiMH batteries in the consumer sector in Japan (Santini 2007).

In the automotive industry, NiMH is still the preferred battery type in hybrid cars because of its better safety characteristics over Li-ion. However, automakers including General Motors, Toyota, and Nissan have announced plans to switch from NiMH to Li-ion, possibly as early as 2010. This shift has already begun in the e-bike industry, probably because e-bike battery packs use fewer cells and are an order of magnitude smaller. This reduces the complexity of pack management and lowers the risk of a battery pack overheating or bursting.[26]

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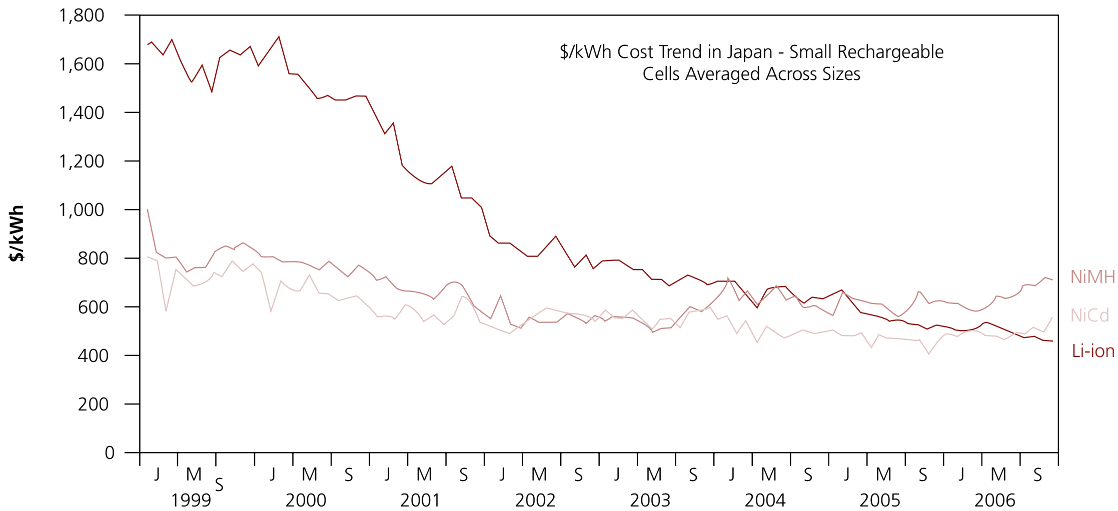
25 Includes LBH (Zhejiang) and Lantian (Tianjin).

26 Based on personal communication with Hannes Neupert, there have been safety incidents reported with Li-ion battery packs for e-bikes, some involving bursting and even fire.

Figure 4.2: Battery Costs in Japan for Consumer Applications



J = January, kWh = kilowatt-hour, Li-ion = lithium ion, M = May, NiCd = nickel-cadmium, NiMH = nickel-metal hydride, S = September.

Source: TIAX, based on Japan's Ministry of Economy, Trade and Industry (METI) data.

Electric Bike Battery Requirements

Ultimately, the battery type that succeeds will depend on several key criteria.

Cost: Battery cost is probably the most critical factor in battery choice, as evidenced by the market dominance of VRLA. Despite the significant advantages in energy density and life span of Li-ion, VRLA is much cheaper. The emphasis on cost may change as average income increases throughout the PRC.

Cycle Life: Lifetime of the battery is critical because it affects long-term operating costs. E-bike ownership can last several years depending on use. However, most users find they need to replace their battery after 1–2 years because of serious performance degradation (London Metal Exchange 2006). Battery cycle life is explained in greater on page 53.

Weight: Vehicle range is one of the most critical metrics for e-bike users because of the long recharge times. Range depends on stored energy capacity, which for a given specific energy (watt-hour per kilogram [Wh/kg]) determines battery weight. Weight for VRLA e-bike batteries typically ranges from 12 kg for the bicycle style to 26 kg for the large scooter style, which corresponds to a range of 2,540 kilometers (km). Long-range e-bikes on the market using two bicycle-style e-bike (BSEB) battery packs claim ranges up to 80 km. There may be practical battery weight limitations based on e-bike volume limitations and user ability to remove the battery for recharging, although the dominant limitation is most likely cost.[27] In terms of required minimum battery range, surveys of e-bike users in three medium-sized to large cities show that the average commuting distance is 9.3 km/day.

[27] Surveys show that many users remove the battery from their E2W and carry it into their home or office for recharging, although some users roll the entire vehicle inside if there is an elevator or find a convenient place to recharge on ground level.

Charging Safety: In terms of risk of damage to self and property, the recharging process for VRLA batteries is considerably more flexible and tolerant of mistakes than it is for Li-ion batteries. As evidenced by the worldwide Sony battery recall of 2006, Li-ion batteries still entail danger, which is amplified as cell size increases.

Temperature Effects: E-bike batteries are used over a wide range of temperatures, from winter lows of –40° Celsius (C) in the PRC's northeast to summer highs of 40° C in the southwest. A battery's performance at extreme temperatures will affect range and lifetime and is thus an important factor.

Electric Bike Battery Performance and Price

Advances in VRLA technology over the past decade have made e-bikes affordable, efficient, and practical. Li-ion technology has also improved to the point that Li-ion e-bikes are now marketed in the PRC, in addition to being exported throughout the world. The technical performance and price of VRLA, Li-ion, and NiMH batteries from local manufacturers are compared in this section.

Valve-Regulated Lead Acid Battery Performance and Price

The key performance characteristics and price of VRLA (AGM type) batteries from several manufacturers for two popular e-bike battery module sizes (20 and 12 Ah) are shown in Table 4.1. VRLA costs for 12 V, 12 Ah modules from three PRC and one Japanese brand are compared in Table 4.2. The batteries tested are specifically designed for motive power, not SLI applications, which have different characteristics when deep-discharged.

Lead price increases in 2007 have caused the VRLA battery price (65%–75% lead by weight) to jump by 50% since the time of this analysis

Table 4.2: Valve-Regulated Lead AcidModule Characteristics

Manufacturer	Capacity (Ah) (2hr)[a]	Weight (kg)	Volume (L)	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Cost ($/kWh) (2006$)
Ritar	12	4.4	1.39	33	104	86.4
Tian Neng	12	4.1	1.39	35	104	80.5
Chaowei	10	4.1	1.39	29	86	81.9
Panasonic	12	3.8	1.39	38	104	104.3
Sunbright	10	4.1	1.39	29	86	–
Huafu	12	4.2	1.39	34	104	–
AVERAGE				**33**	**97**	**$88**
Ritar	20	7.2	2.37	33	101	–
Chaowei	20	10.0	3.63	24	66	–
Panasonic	20	6.6	2.30	36	104	–
Sunbright	20	7.0	2.31	34	104	–
Huafu	20	6.8	2.40	35	100	–
AVERAGE				**33**	**95**	

– = no data available, Ah = amp-hour, kg = kilogram, kWh = kilowatt-hour, L = liter, Wh = watt-hour, $ = US dollar.

Note: Information obtained from company websites. Price is the purchase price from a retailer.

[a] A "2hr" rate is a commonly used metric for testing battery capacity. It represents the discharge rate used to completely discharge the battery in 2 hours.

Source: Authors.

Table 4.3: Performance of Valve-Regulated Lead-Acid Battery Modules (C/2.4 discharge rate)

Company	Mass (kg)	Capacity (Ah)	Specific Energy (Wh/kg)	Resistance (mΩ)	Max power at 9.6V (W/kg)
1	4.24	12.0	34.2	20	272
2	4.05	12.2	36.8	22	258
3	4.27	12.1	34.3	27	200
4	4.00	11.5	35.0	30	192
Average	**4.14**	**12.0**	**35.1**	**25**	**231**

Ah = amp-hour, kg = kilogram, mΩ = milliohm, V = volt, Wh = watt-hour.

Source: Authors.

(Huang and Xiao 2006). The prices of $88/kWh should be adjusted to $130/kWh. These prices were verified by several e-bike vendors in late 2007. The spike in the cost of lead has reportedly been caused by the rapid rise in demand in the PRC and a mine problem in Australia (Suzuki 2007). E-bikes reportedly account for 13.1% of the PRC's lead demand, or 4% of world demand (Neupert 2007).

To verify performance, 12 V, 12 Ah modules from four large e-bike battery suppliers were obtained and tested with an Arbin BT2043 device. Current and power levels were chosen based on the typical demands of an e-bike. Table 4.3 shows the results. The discharge characteristics are given in Ah, Wh/kg, and W/kg at 9.6 V. The results exceed the manufacturers' stated claims on energy density and are considered quite good for VRLAs of such small cell size.

Cycle Life

Manufacturers report cycle life of between 400 and 550 cycles, although independent testing of four brands by an anonymous manufacturer revealed cycle life of 300–400 cycles. Most e-bike manufacturers provide only 1- to 1.5-year warranties on the battery, which corresponds to roughly 110–170 cycles, assuming 9.3 km/day average driving distance (see section Electric Bike Battery Requirements, p. 51) and 30 km battery capacity. The large difference in manufacturer claims versus real-world cycle life under warranty may be due to poor battery and charger quality and wide ambient temperature variations that batteries experience. In Shanghai, for example, temperatures can vary from below freezing to above 35° C over the year. Manufacturer testing is probably done at an ideal constant temperature. One of the principal advantages of Li-ion batteries compared with VRLA is their longer lifetime.

Defect Rate

The industry average defect ratio is 5% for e-bike batteries while only 0.10% for other types of lead acid batteries.[28] The main reason for this large difference is the extreme variation

[28] Data are based on a comparative study of battery performance from large e-bike battery suppliers, conducted by one battery manufacturer in 2006.

in charging and discharging experienced in e-bikes compared with other applications. Foreign-brand lead acid batteries had fewer defects than local ones. High defect levels would also explain the low battery cycle life that has been reported in a previous section. According to interviews with one battery company, improving battery lifetime and stability is the key area of research.

Lithium-Ion Performance and Price

Li-ion battery performance and price from various local and international manufactures are compared in Table 4.4. Prices range from $510 to $760 per kWh. Data from another local Li-ion battery manufacturer quote costs of $300–$600/kWh (retail price is not provided) (Anderman 2003). The stated cycle life of Li-ion batteries from three manufacturers is 600–800 cycles. The actual warranty on their batteries is 2 years.

Table 4.4: Characteristics of Lithium-Ion Modules

Manufacturer	Capacity (Ah) (2hr)	Weight (kg)	Volume (L)	Specific energy (Wh/kg)	Energy density (Wh/L)	Power density (W/kg)	Price ($/kWh) (2006$)
Xingheng—high power	15.0	0.88	0.43	63	128	1,261	–
Xingheng—high power	7.5	0.41	0.16	68	173	1,805	–
AVERAGE—high power					**151**	**1,533**	
Xingheng—high energy	30.0	1.00	0.45	111	249	111	510
Xingheng—high energy	10.0	0.37	0.15	100	241	200	530
Lantian	60.0	1.80	0.78	123	286	–	–
Lantian	18.0	0.60	0.31	111	215	–	–
Lantian	4.7	0.14	0.052	124	333	–	–
Citic Guoan MGL	50.0	1.95	0.95	97	201	–	–
Citic Guoan MGL	30.0	1.10	0.66	104	173	–	–
Citic Guoan MGL	10.0	0.47	0.19	81	198	–	–
Zhengke	11.0	–	–				510
Zhenlong (ZJ)—high energy	10.0 (37V)	–	–	–	–	–	480
Panasonic	–	–	–				*760*
AVERAGE—high energy				**106**	**237**	***156***	***$560***

Ah = amp-hour, kg = kilogram, kWh = kilowatt-hour, L = liter, Wh = watt-hour.

Source: Authors.

Battery Transitions in the Electric Bike Market

Moving away from VRLA batteries is critical for improving the environmental impact of e-bikes. It appears the transition from VRLA to Li-ion batteries in e-bikes is progressing. It also appears that most manufacturers are bypassing NiMH in favor of Li-ion, based on the products displayed at the Nanjing e-bike exhibition in late 2007. To quantify the relative advantages of each battery type, the three battery types are compared on a single e-bike using the battery performance and cost data from the previous sections. The batteries are sized for an average 48 V scooter-style bike with a 60 km range (0.90 kWh) and 350 W motor. This type of e-bike was chosen since it is a popular model for a three-person family. It sets a practical upper bound to battery size in an e-bike and is comparable in performance to a 30-cubic centimeter engine displacement (cc) gasoline scooter. An e-bike energy consumption of 0.014 kWh/km and an average travel distance of 15 km/day were assumed in making the battery comparisons.

These results suggest that the cost differential between the battery types dominates all other factors. Even with currently high lead prices and low recharge cycles, VRLA batteries are still the most cost-effective option. On the other hand, the 18 kg mass difference between lead acid and Li-ion is significant since a 26 kg battery is most likely unmanageable for the majority of e-bike users. If users' only option to recharge is to carry the battery indoors, they may be inclined to use NiMH or Li-ion. The shorter life of NiMH batteries may not justify the higher cost to some users. Li-ion batteries are expensive, too, but their lifetime cost is only 1.6 times as high as that of VRLA batteries. Therefore, with some price reductions, Li-ion could be cost-effective in the future, especially with regulatory pressure to reduce the weight of e-bikes.

Table 4.5: Comparison of Battery Types

Results	VRLA	NiMH	Li-ion
Cost ($)	130	270	500
Mass (kg)	26	14	8
Lifetime (yr)	1.5 (3 ideal)	2.0 (4 ideal)	4.5 (9 ideal)
Volume (L)	10	4	5
Maximum Theoretical Power (kW)	6.2	–	2.9
Recharging Safety	high	High	Low
Temperature Effects	moderate	High	moderate
Assumptions	**VRLA**	**NiMH**	**Li-ion**
Specific Energy (Wh/kg)	35	65	110
Energy Density (Wh/L)	86	235	170
Power Density (W/kg)	240	–	350
Cost ($/kWh)	130	300	560
Cycle Life (recharges)	300	400	800
Life-Cycle Cost ($/kWh/recharge)	0.43	0.75	0.70

– = data not available, kg = kilogram, kWh = kilowatt-hour, L = liter, Li-ion = lithium-ion, NiMH = nickel-metal hydride, Wh = watt-hour, yr = year.

Source: Authors.

Performance Test of Electric Bikes

Two e-bikes of different weight (39 and 57 kg) and rated power (300 and 450 W) were tested to determine their energy use characteristics. Both Li-ion and lead acid batteries were tested in the smaller e-bike. The e-bikes were tested for steady-state energy use at top speed (20 to 23 km/hr), low speed (14 km/hr), and accelerating. Results show increased energy use for the heavier, more powerful e-bike, mostly for accelerating, and a decreased energy use for Li-ion batteries, mostly for steady state, suggesting that weight affects acceleration energy primarily and battery efficiency affects steady-state efficiency primarily. A data set was built by developing a city driving cycle to mimic worst-case, real-world energy consumption; it consisted of four full-throttle accelerations per km and a maintained speed of 20 km/hr. The small e-bike with Li-ion batteries used 13 Wh/km or 0.13 liters (L/)100 km gasoline equivalent, an improvement of 7% over the lead acid batteries, and the medium e-bike with lead acid batteries used 16 Wh/km or 0.16 liters/ 100 km gasoline equivalent.

Experimental Setup

Two e-bikes were tested for this report, a small e-bike and a medium e-bike. Additionally, a Li-ion battery pack was tested along with the standard lead acid battery pack for the small e-bike. The specifications for the two bikes and batteries are given in Table 4.6.

Table 4.6: Electric Bike and Battery Specifications

	Small e-bike	Medium e-bike
Weight (kg)	39	57
Rated Power (W)	300	450
Peak Power (W)	700	1,000
Top Speed (km/hr)	20	23
Batteries (V, Ah, kg)	36, 14, 11 lead acid 36, 10, 5 lithium-ion	36, 14, 11 lead acid
Range (km)	36 lead acid 35 lithium-ion	35 lead acid
Suspension	Front	Front and rear
Tire Size	20″ x 1.75″	22″ x 2″

Ah = amp-hour, e-bike = electric bike, hr = hour, kg = kilogram, km = kilometer, V = volt, W = watt.

Source: Authors.

The two e-bikes have rear hub motors and identical stock battery capacity. (A version of the medium e-bike is available with higher battery capacity and more power but is not used in this report.) The main differences are the strength and weight of the frame, suspension, and wheels, giving the medium e-bike a larger carrying capacity and more durability, and the motor power. Figures 4.3 and 4.4 show the e-bikes tested.

To calculate energy use, three measurements were taken from the e-bikes during testing: the battery voltage (V_{batt}), current to the motor (C_{motor}), and vehicle speed (S_{veh}). The following equation shows how the energy use was calculated.

$$energy \quad use = \sum_{time} \frac{V_{batt} * C_{motor}}{S_{veh}}$$

A data acquisition system was developed and employed on the e-bikes to record the three measurements during testing. The complete system with sensors, data logger, and signal conditioning is shown in Figure 4.5.

A Hobo data logger was used to record the data. The Hobo records a voltage measurement

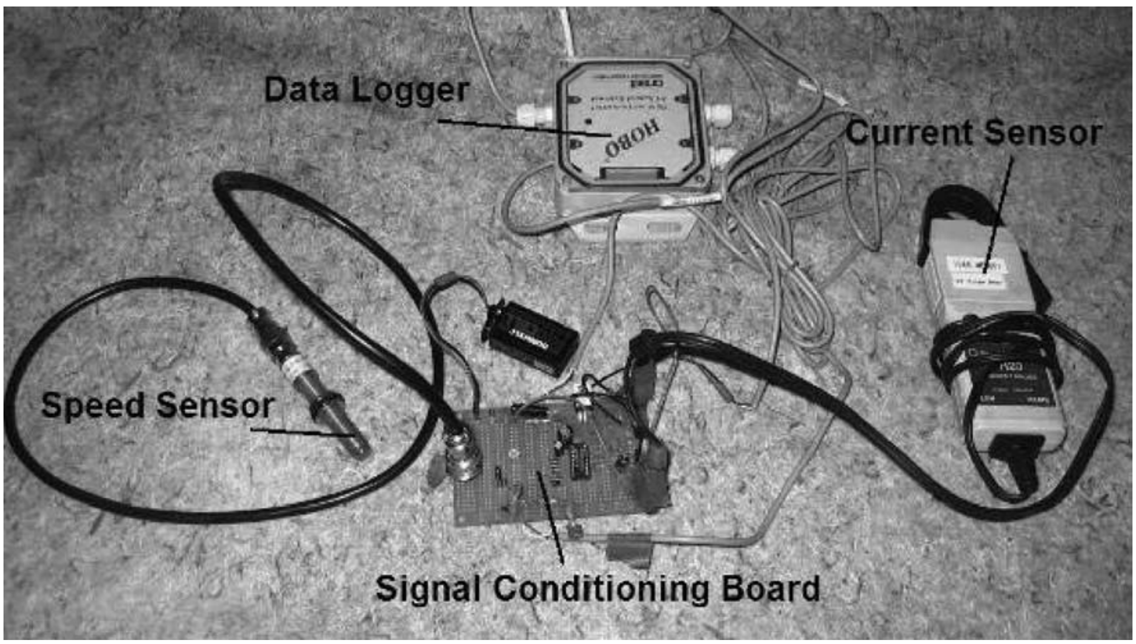
Figure 4.3: Small Electric Bike

Source: Authors.

Figure 4.4: Medium Electric Bike

Source: Authors.

Figure 4.5: Data Acquisition System



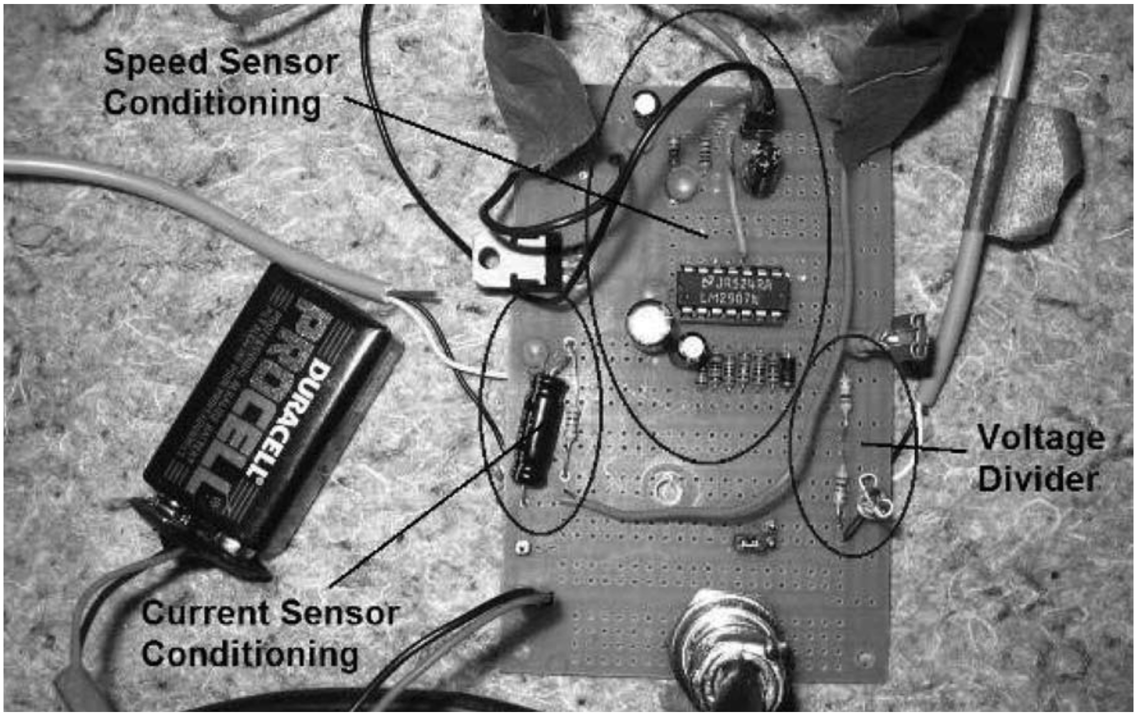
Source: Authors.

between 0 and 2.5 V every half second. Signal conditioning was necessary to transform the measurements into readable voltage signals for the Hobo (Figure 4.6).

To measure the battery voltage, a voltage divider consisting of two resistors was used. Leads from the battery were connected across the 100 kilo-ohm (kΩ) and 1 kΩ resistors in series. The voltage measurement to the Hobo was measured across the 1 kΩ resistor. Precise resistor measurements give a reduction of 103 times for the battery voltage.

The current was measured using a sensor that outputs 1 millivolt per amp (mV/A) for up to 30 amps (Figure 4.7). The current sensor has its own 9 V power source.

Figure 4.6: Signal Conditioning Board



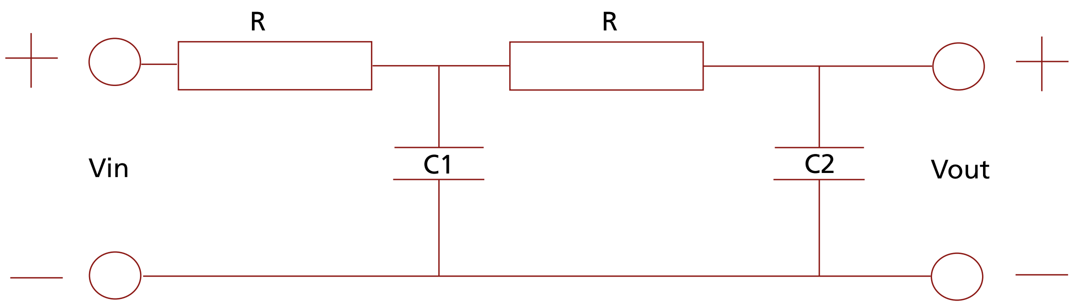
Source: Authors.

Figure 4.7: Current Measuring Device Clamped on the Battery's Hot Wire

Source: Authors.

The voltage from the current sensor was averaged over time by a resistor–capacitor (RC) filter to ensure accurate data was recorded by the Hobo. Without the filter, the current data would be unrepresentative of that half second. The Hobo would read either full current or no current because the controller uses pulse width modulation to control the power to the motor.

Figure 4.8: Resistor–Capacitor Circuit Schematic Used to Level the Current Signal Measurement



C = capacitor, R = resistor, Vin = volt in, Vout = volt out.

Source: Authors.

Figure 4.8 shows a schematic of the filter. The resistors are each 100 kΩ. C1 is .01 microfarad (μf) and C2 is .001 microfarad (μf).

The speed sensor and corresponding signal conditioning circuit were developed by a student at Tongji University in the PRC. A magnet on the wheel triggers a switch in the speed sensor The switching creates a frequency, which is converted into a voltage with an LM2907 IC chip. A 9V battery powers the chip.

Testing Procedures

Testing began with the completion of the data acquisition equipment. For all tests the tires were inflated to the maximum recommended tire pressure of 45 pounds per square inch (psi). The rider for the tests weighs 80 kg. A half-kilometer stretch of a perceptibly level and smooth asphalt road was used. Wind was minor to nonexistent. All tests were performed equally in each direction to negate the effects of grade or wind. Outside temperature was between 15° and 20° C.

First, a test was done to calibrate the speed sensor. Each e-bike was timed at top speed over a 50-meter (m) distance with a hand-held stopwatch. The average speed of the bike over the 50 m was compared with the average voltage from the speed sensor for the corresponding period and thus provided a coefficient to convert the recorded speed data to meter per second (m/s).

The energy use tests consisted of a top-speed, steady-state run at full throttle, a low-speed, steady-state run at 14 km/h, and accelerations from stopped to top speed with full throttle. These tests were done as electric power only for all bicycle and battery configurations as well as electric power plus pedal assist for the small e-bike, and with the lights on for the medium-sized e-bike. Pedaling was done at a comfortable pace and as consistently as possible. The lights did not work on the small e-bike, and the pedals were essentially useless on the medium e-bike, making those tests not viable. Table 4.7 illustrates which modes the e-bikes were tested in.

Table 4.7: Tests Performed for Each Electric Bike and Battery Type

	No pedaling, lights off	Pedaling, lights off	No pedaling, lights on
Small e-bike with lead acid	X	X	
Small e-bike with Li-ion	X	X	
Medium e-bike with lead acid	X		X

Li-ion = lithium-ion.

Source: Authors.

Table 4.8 shows an example of the data output and energy use calculation.

The imported data are in the first four columns on the left. The rest of the columns are calculated. Both the current and the speed measurements have small offsets from the power sources running the sensors. To calculate the current, the no-load offset is subtracted from V1, which is then multiplied by 10. The speed is multiplied by the speed calibration constant after subtracting the offset. V4 is multiplied by the voltage divider constant to get the battery voltage. The power is calculated by multiplying the voltage by the current. The charge is an integration of the current. Power is integrated to get the energy. Distance is an integration of the speed. Finally, energy use is the quotient of the energy and the distance. Figure 4.9 shows the energy use data for one of the test runs after being calculated in Excel.

The data were carefully selected for each of the tests—top speed, low speed, and acceleration—and separated into data sets to calculate the energy use. Figure 4.10 shows the selected data for a top-speed test run. Notice that the Wh/km energy use reaches an asymptote. The actual Wh/km energy use value used in the analysis comes from the last value in the data set.

A city-cycle data set was constructed from top-speed, steady-state data and acceleration data to estimate the energy use of the e-bikes in an urban environment. The e-bike city cycle consists

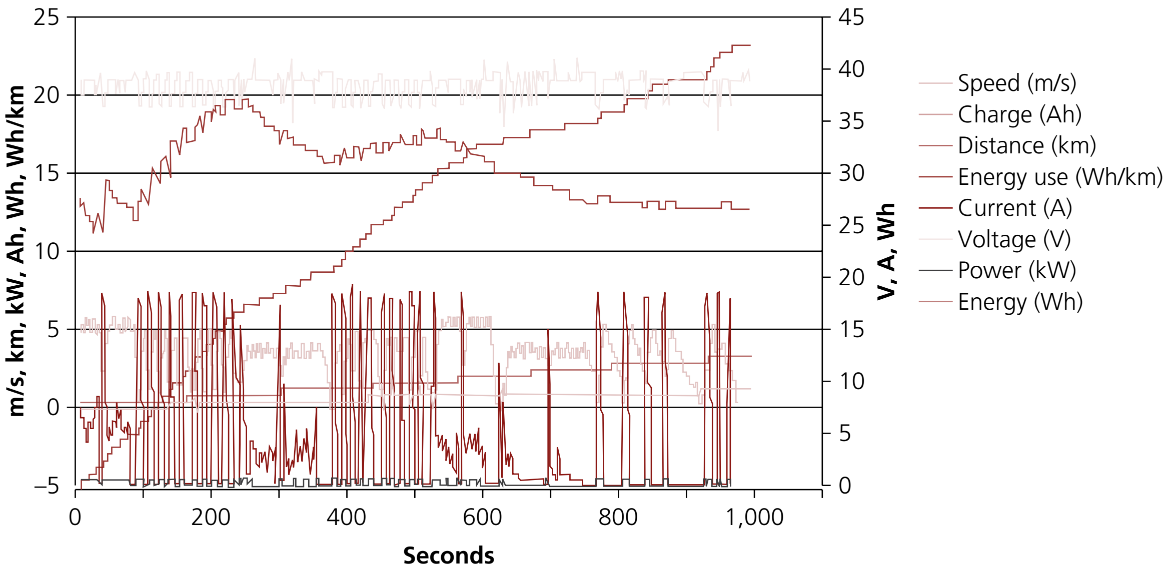
Table 4.8: Sample of Data Calculations in Microsoft Excel

Time	Voltage (V) (*1)	Voltage (V) (*3)	Voltage (V) (*4)	Time	Current	speed	Voltage	Power	Charge	Energy	Distance	Energy use
	Current	Speed	voltage	(sec)	(A)	(m/s)	(V)	(kW)	(Ah)	(Wh)	(km)	(Wh/km)
36:00.5	0.718	0.435	0.366	0	6.74	5.3	37.5	0.252	0.00	0.04	0.00	13.28
36:01.0	0.728	0.415	0.366	0.5	6.84	5.0	37.5	0.257	0.00	0.07	0.01	13.70
36:01.5	0.747	0.405	0.376	1	7.03	4.9	38.6	0.271	0.00	0.11	0.01	14.22
36:02.0	0.688	0.444	0.376	1.5	6.44	5.4	38.6	0.249	0.00	0.14	0.01	13.84
36:02.5	0.63	0.425	0.376	2	5.86	5.2	38.6	0.226	0.00	0.17	0.01	13.50
36:03.0	0.679	0.415	0.376	2.5	6.35	5.0	38.6	0.245	0.01	0.21	0.02	13.50
36:03.5	0.649	0.444	0.366	3	6.05	5.4	37.5	0.227	0.01	0.24	0.02	13.23

A = amp, Ah = amp-hour, km = kilometer, kW = kilowatt, m/s = meter per second, sec = second, V = volt, Wh = watt-hour.

Source: Authors.

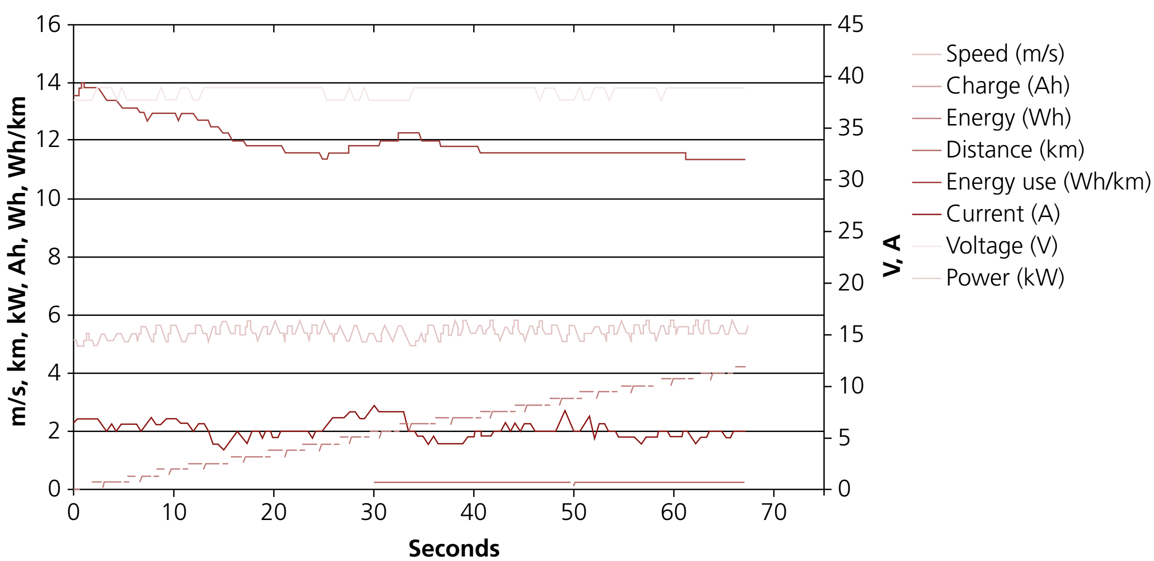
Figure 4.9: Sample Data after Energy Use Calculations



A = amp, Ah = amp-hour, km = kilometer, kW = kilowatt, m/s = meter per second, V = volt, Wh = watt-hour.

Source: Authors.

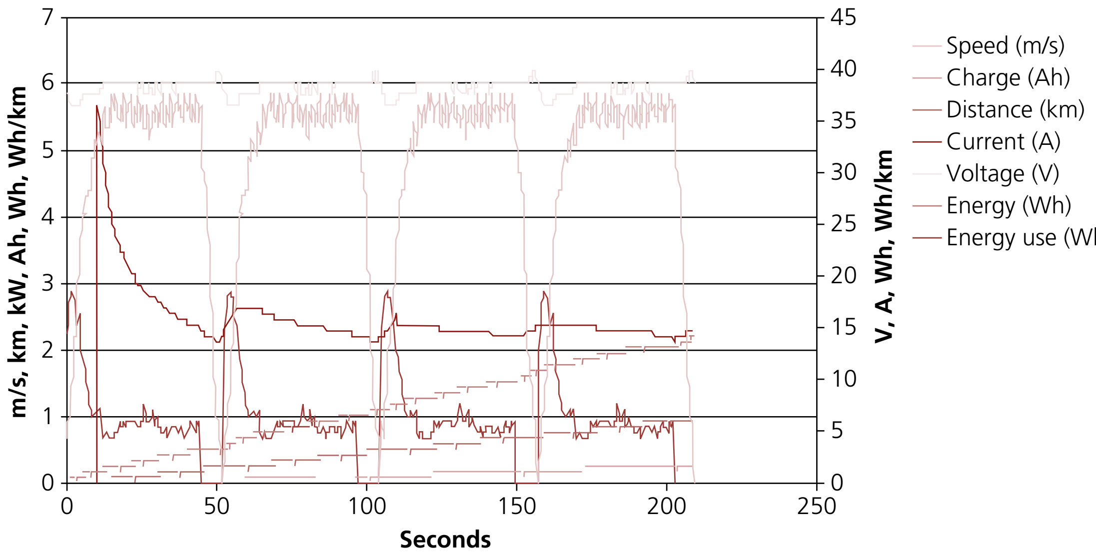
Figure 4.10: Sample of Top-Speed Test Data



A = amp, Ah = amp-hour, km = kilometer, kW = kilowatt, m/s = meter per second, V = volt, Wh = watt-hour.

Source: Authors.

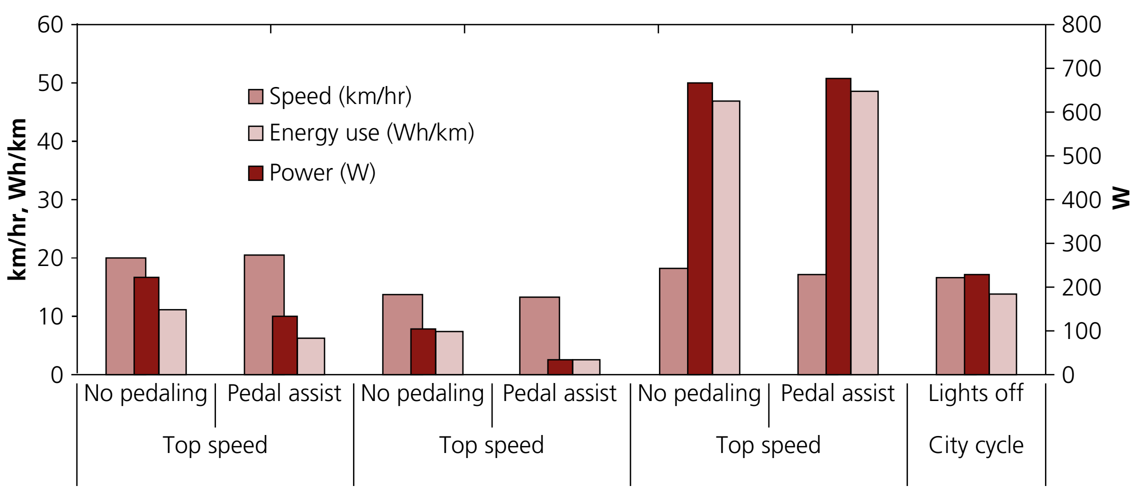
Figure 4.11: Electric Bike City-Cycle Data on Energy Use



A = amp, Ah = amp-hour, km = kilometer, kW = kilowatt, m/s = meter per second, sec = second, V = volt, Wh = watt-hour.

Source: Authors.

Figure 4.12: Energy Used by Small Electric Bike with Lead Acid Batteries



km/hr = kilometer per hour, Wh/km = watt-hour per kilometer.

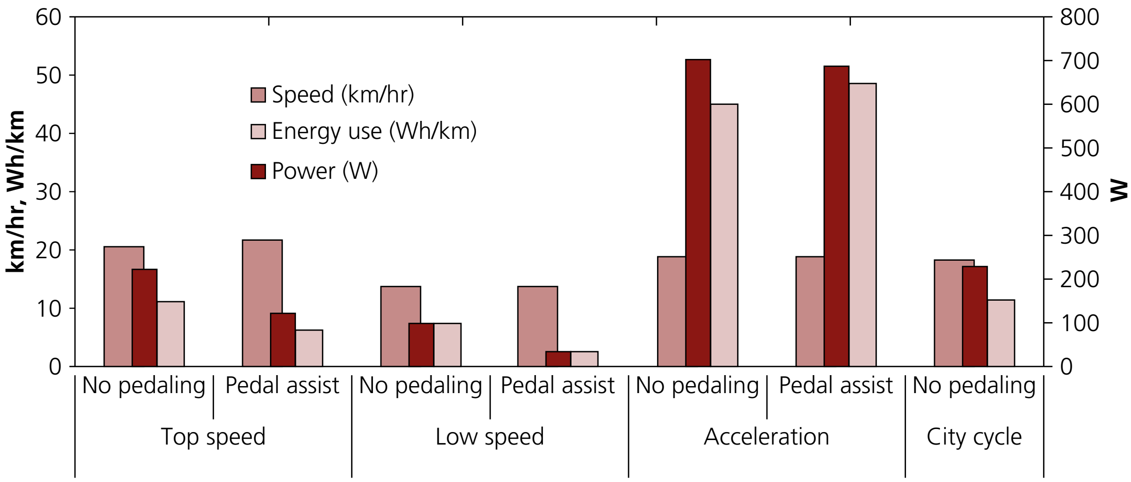
Source: Authors.

of four full accelerations to top speed per km without pedaling or lights. This is as hard as the e-bikes can be driven and gives a worst-case scenario for energy use. Figure 4.11 shows the e-bike city cycle constructed from actual data.

Test Results

The speed, power, and energy use for each of the six modes with each of the three e-bike/battery combinations are compared.

Figure 4.13: Energy Used by Small Electric Bike with Lithium-ion Batteries



km/hr = kilometer per hour, Wh/km = watt-hour per kilometer.

Source: Authors.

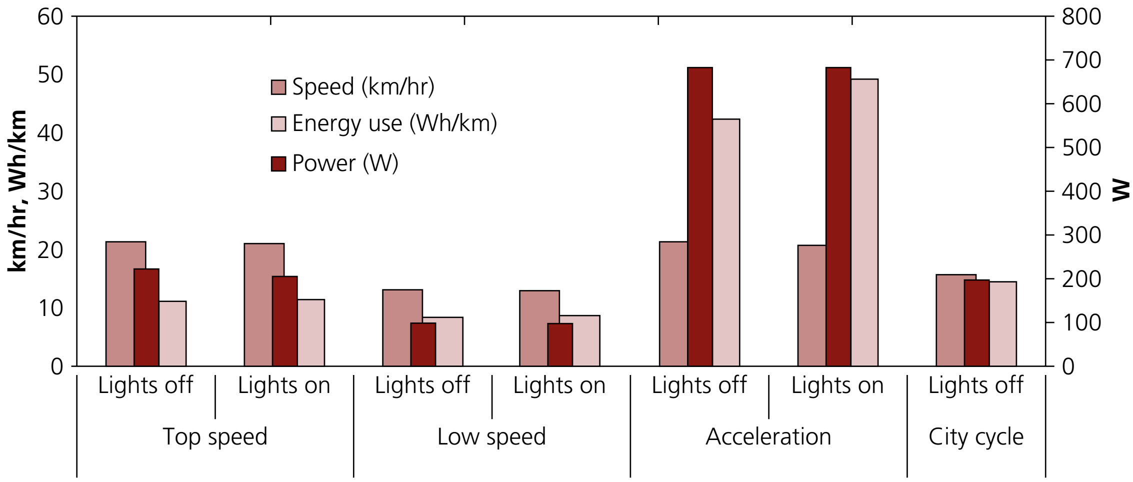
Figure 4.12 shows the results for the small e-bike with lead acid batteries. The peak power (from the acceleration test) is 674 W, and the top speed is 20 km/hr without pedaling. Pedaling increases the top speed marginally, by 1 km/hr, and reduces the energy use considerably, from 11 Wh/km to 7 Wh/km. Pedaling also improves the energy use for the low speed test from 8 to 3 Wh/km but not for the acceleration test, in which the energy use increases from 47 to 49 Wh/km. This may seem contradictory, but in fact the energy per acceleration is decreased from 1.2 to 0.9 Wh by pedaling. The city cycle uses a little more energy than the top-speed runs at 13.8 Wh/km, or 0.14 L/100 km of gasoline equivalent energy use.

Replacing the lead acid batteries in the small e-bike with more expensive Li-ion batteries improved the performance to a small degree (Figure 4.13). The effects of pedaling and different test modes remain. For the city cycle, the energy use is 13 Wh/km, or about 0.13 L/100 km equivalent gasoline energy use.

Results for the medium-sized electric bike show a pattern similar to the small e-bike's with respect to the top speed, low speed, and acceleration tests, but the numbers are generally larger (Figure 4.14). The lights use about 15 W, which is reflected in the power and energy use of top speed and low speed tests, and more considerably in the energy use of the acceleration test. For the city cycle, the energy use is 16 Wh/km, or about 0.16 L/100 km equivalent gasoline energy use.

Figures 4.15, 4.16, 4.17, and 4.18 put the e-bikes and batteries in a direct comparison. The medium e-bike's top speed is 23 km/hr, beating the small e-bike with Li-ion batteries by 2 km/hr and the small e-bike with lead acid batteries by 3 km/hr (Figure 4.15). The energy use at top speed is nearly identical, however, between the small and medium e-bike with lead acid batteries. The Li-ion batteries improve the efficiency by 7% with a lower average power over the lead acid batteries in the small e-bike.

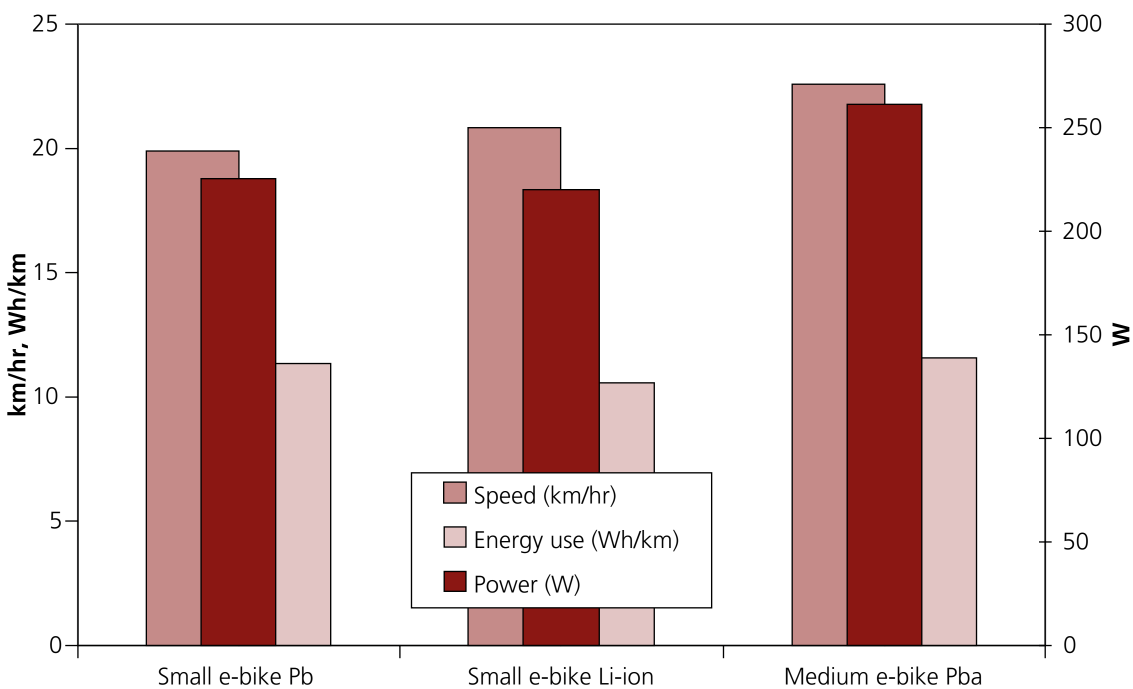
Figure 4.14: Energy Used by Medium Electric Bike



km/hr = kilometer per hour, Wh/km = watt-hour per kilometer.

Source: Authors.

Figure 4.15: Energy Used by Small and Medium Electric Bikes at Top Speed

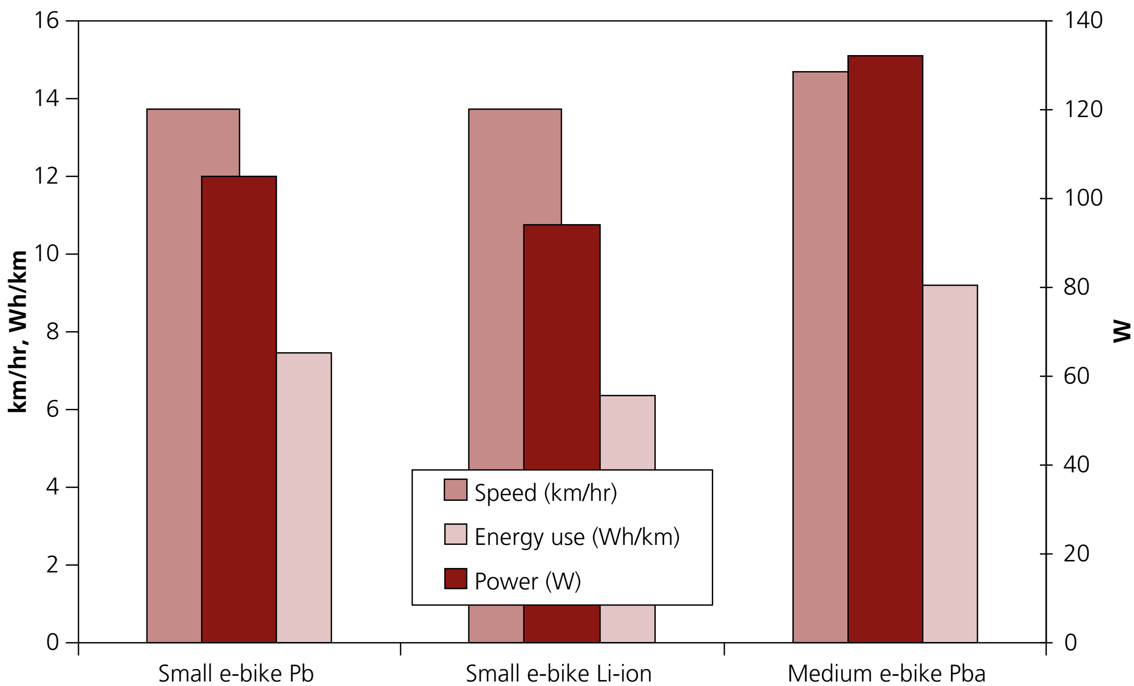


e-bike = electric bike, km/hr = kilometer per hour, Li-ion = Lithium-ion, Pba = lead acid, Wh/km = watt-hour per kilometer,.

Note: Electric power only, no lights.

Source: Authors.

Figure 4.16: Energy Used by Small and Medium Electric Bikes at Low Speed



e-bike = electric bike, km/hr = kilometer per hour, Li-ion = Lithium-ion, Pba = lead acid, Wh/km = watt-hour per kilometer.

Note: Electric power only, no lights.

Source: Authors.

The results for the low-speed test reflect the same energy use trends as the top- speed test, with the small e-bike with Li-ion batteries being the most efficient at 6.8 Wh/km (Figure 4.16). Here, however, the medium e-bike uses 9% more energy per kilometer than the small e-bike with lead acid batteries. The speeds are intended to be equal, but the medium e-bike is about 1 km/hr faster than the small e-bike in this test.

For the acceleration test, it is more important to look at the energy per acceleration than the energy per km (Figure 4.17). The small e-bike with Li-ion batteries uses 1.1 Wh/acceleration compared with 1.2 Wh/acceleration with lead acid batteries and 2.0 Wh/acceleration for the medium e-bike. (The comparison is not entirely fair because the medium e-bike reaches a higher speed.)

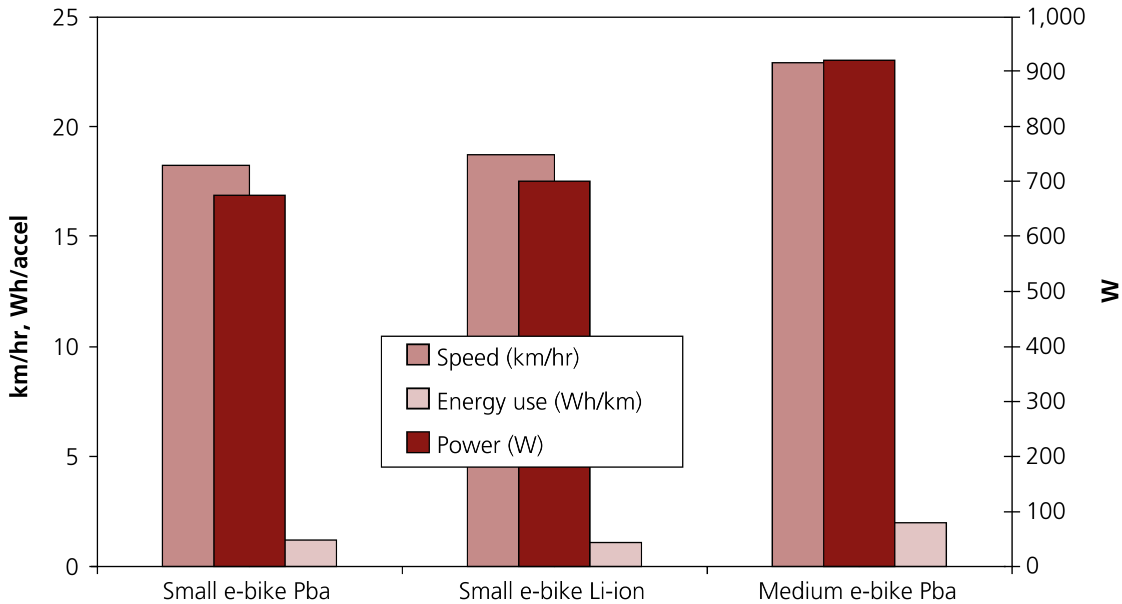
Finally, the results for the city-drive cycle are similar to the top-speed and low-speed steady-state tests, in which the small e-bike with Li-ion batteries is the most efficient at 13 Wh/km, and the medium e-bike is the least efficient at 16 Wh/km (Figure 4.18). The average speed for all three e-bike scenarios is similar (a difference of less than 1%).

Test Conclusions

Our tests confirm that an increase in weight and motor power increases the energy use, and that the Li-ion battery improves efficiency.

A 13% increase in the vehicle weight including the rider and a 27% increase in the peak motor power for the medium e-bike lead to a 13% increase in energy use for the city-drive cycle but

Figure 4.17: Energy Used by Small and Medium Electric Bikes in Acceleration

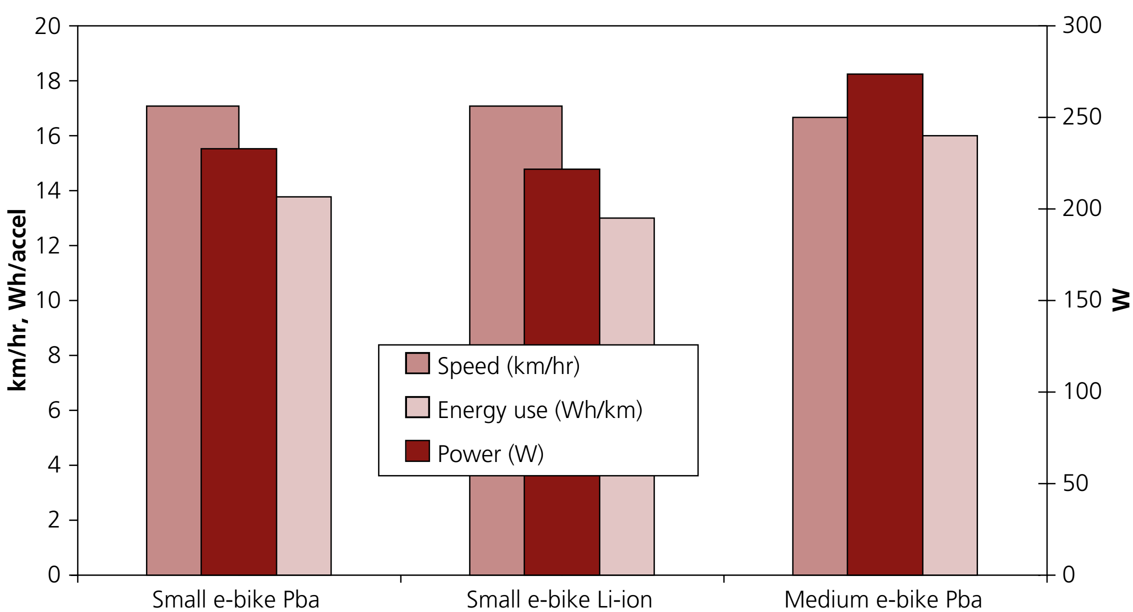


e-bike = electric bike, km/hr = kilometer per hour, Li-ion = Lithium-ion, Pba = lead acid, Wh/accel = watt-hour per acceleration, Wh/km = watt-hour per kilometer,.

Note: Electric power only, no lights.

Source: Authors.

Figure 4.18: Energy Used by Small and Medium Electric Bikes in City Cycle



e-bike = electric bike, km/hr = kilometer per hour, Li-ion = Lithium-ion, Pba = lead acid, W = watt, Wh/km = watt-hour per kilometer.

Note: Electric power only, no lights.

Source: Authors.

only a 2% increase in energy use for steady-state top speed. This suggests that rolling resistance plays a small role in energy use compared with accelerating inertia.

Switching to Li-ion batteries improves energy use by 6% for the city cycle and by 7% for steady-state top speed. Li-ion batteries are more efficient than lead acid because they have less internal resistance. They are also lighter. The pack used in the tests is 4 kg compared with 11 kg for the lead acid battery. It is not clear the extent to which the efficiency gains for acceleration are from battery performance or from weight reduction, but the energy use difference between the two lead acid e-bikes of different sizes is small for steady state and large for accelerations. Therefore, we believe that battery efficiency is the most relevant part of the energy use improvements. It would be interesting to test the Li-ion battery with extra weight on the e-bike.

To calculate the true energy use of e-bikes requires including the energy efficiency of the battery charger. Typical battery chargers get 82%–90% efficiency. We've assumed 85% efficiency. Using this value, the total "plug to wheel" energy use of the e-bikes under the city cycle is between 1.5 and 1.8 kWh/100 km.

Japanese and European Markets

After the PRC, the next largest e-bike markets are Japan and Europe. E-bikes in these markets are different from PRC e-bikes in that these bikes are typically the pedal-assist type or "pedelec". The user typically pedals but is assisted by a small electric motor when extra power is desired (e.g., acceleration, uphill climbs). According to the Industrial Technology Research Institute, 40% of e-bikes in Japan and 35% in Europe use Li-ion batteries. It is unclear how many use NiMH, but there are few lead acid battery e-bikes in those areas. Battery capacities range from 0.2 to 0.6 kWh, motor sizes range from 150 to 250 W, and prices range from $700 to $2,000.

Electric Bike Market Growth and Opportunities for Battery Improvements

The growing e-bike market will lead to further advancements in battery technology and a gradual transition to more advanced battery technologies. In turn, this battery advancement will expand the market for e-bikes in the PRC and throughout the world, especially in developing countries with high two-wheeler use. Research and development, adjustments in manufacturing, and response to the demands of in-service use will work together to yield improvements in battery performance and cost.

The materials and the manufacturing process for large and small cells for Li-ion batteries are similar, so any discoveries and improvements that apply to electronics use will also apply to e-bikes, and vice versa (Huang and Xiao 2006). Only the demands of e-bike use, however, will drive the operational learning progress for large-format battery cell technology. The key areas for technological improvements are safe charging and discharging, cell degradation over time, operation in extreme environments (low and high temperatures), and cell variability within a battery pack and its effects on lifetime. Cell variability is a key issue with VRLA cells. Safety and cost are the key issues with Li-ion cells.

Cell Variability

VRLA batteries exhibit considerable scatter in performance (i.e., no two modules have exactly the same electrical characteristics). This results from slight variations in the properties of materials and the electrodes used to assemble the cells due to the imprecise, labor-intensive manufacturing process (Wu 2007). When connecting several modules in series, as in the case of a 36 V (three module) or 48 V (four module) e-bike battery pack, there is often significant variability in the module voltage. This causes accelerated aging since the weakest module of the pack ages more rapidly (Yang 2007).

Safety

For Li-ion batteries, safety risks such as battery overheating, combustion, and explosive disassembly increase with the amount of energy contained within the cell/battery pack. Lithium colbatate ($LiCoO_2$) is commonly used for small cell Li-ion batteries but is considered unsafe for large-format batteries (Gaines and Cuenca 2000). New cathode materials such as lithium iron phosphate ($LiFePO_4$) are being introduced into Li-ion batteries for e-bikes, resulting in significant safety improvements (Huang and Xiao 2006). Hot-box heating and overcharge testing reveal safety advantages of $LiFePO_4$ over both lithium manganese oxide ($LiMn_2O_4$) and $LiCoO_2$.

Cost

Li-ion battery technology is still relatively new (12 years), so there are potentially many opportunities for cost reductions. Material substitution could make a large impact since 75% of the total battery cost is due to materials (Jamerson and Benjamin 2004). Research and development efforts are focused on using more inexpensive and chemically stable materials such as $LiFePO_4$ and $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ for the cathode. Table 4.9 presents the cost, energy density, and cycle-life differences between the commonly used $LiCoO_2$ cathode and these two alternative materials. For $LiFePO_4$, energy density is sacrificed for lower cost and longer life, along with the safety advantages mentioned above.

Some Li-ion battery companies are expecting 100% growth in sales in the next year and predict that the market for Li-ion battery e-bikes will grow to 20% of total annual e-bike sales in the next 5 years.

Conclusions

There has been a rapid transition to e-bikes and scooters in the PRC, with the market reaching nearly 16 million per year in 2006. This e-bike growth has been partly because of improvements in rechargeable valve-regulated lead acid battery

Table 4.9: Performance Characteristics of Various Cathode Materials for Li-ion Batteries

Cathode Material	$LiCoO_2$	$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$	$LiFePO_4$
Energy density (Wh/kg)	180	170	130
Cycle life (cycles)	400	400	1000
Price ($/kg)	30	22	12

kg = kilogram, $LiCoO_2$ = lithium colbatate, $LiFePO_4$ = lithium iron phosphate. Wh = watt-hour, $ = US dollar.

Source: Authors.

technology in the PRC. Further growth in the market and a transition from VRLA to lithium-ion batteries will lead to greater improvements in performance and cost.

VRLA and Li-ion battery technology for e-bikes has been assessed. For VRLA, a specific energy of 34 Wh/kg and a cost of $130/kWh were determined for a number of international brands. Li-ion batteries in the PRC on average have specific energy of 106 Wh/kg and a cost of $560/kWh. One NiMH manufacturer quoted a cost of $300/kWh for a NiMH battery pack. This price difference is lowered over the life cycle because of Li-ion batteries' longer life, thereby bringing the average cost per kilometer down but not completely closing the price gap with VRLA batteries. A widespread shift from VRLA to Li-ion batteries seems improbable for the mass market in the near term, given the cost premium relative to the performance advantages of Li-ion batteries.[29] However, as Li-ion battery technology gains more real-world use in e-bike and other applications, it may become more competitive. Unpredictable fluctuations in lead and lithium prices may also alter economic competitiveness. Cell variability is a key problem area to be addressed with VRLA technology. For Li-ion technology, safety and cost are the key problem areas, which are already being addressed through the use of new materials such as $LiFePO_4$. For NiMH, the key issues are material cost (nickel) and temperature effects in hot weather.

[29] The longer lifetime of Li-ion batteries relative to VRLA would justify the extra cost to a rational buyer, but there are many practical reasons consumers are reluctant to pay a high up-front battery cost. These include unknown quality of a relatively new product, distrust in battery quality based on VRLA experience, and a high rate of e-bike and battery theft in some areas. These are the authors' speculations based on knowledge of the market and conversations with e-bike owners.

Conclusions and Policy Recommendations

The electric bike (e-bike) market is expanding at an amazing rate in the People's Republic of China (PRC). E-bikes serve the enormous low-income populations who are currently using bicycles and public transport, providing an alternative transport option that has much of the mobility benefits of a personal car but is cheaper to own and operate and emits a fraction of the greenhouse gases and conventional pollutants. E-bikes are touted as a clean form of transport and do not emit any local pollution, but they do increase demand on electricity, boost power plant emissions, and introduce a large amount of lead into the environment. The operation of e-bikes produces a high proportion of sulfur dioxide (SO_2) air pollution in the life cycle, largely because of an electricity supply network that primarily consists of coal power plants. E-bikes produce fewer greenhouse gases and are more energy efficient than buses or motorcycles, indicating that they can be a component toward a sustainable transportation future, although their impact on congestion compared with buses and subsequent fuel use and emission implications need to be considered. Electricity generation in the PRC is primarily from coal power plants, but electricity can be produced with renewable resources, making e-bikes more efficient. Moreover, with proper planning, e-bikes can be integrated to support public transport systems as efficient and low-cost feeders.

When developing environmental policy on e-bikes, it is important to perform a comparative analysis with other modes of transport that are in e-bike riders' set of choices. The authors' previous work shows that the majority of e-bike users are former bus or bicycle riders (depending on the city) and would use a bus or bicycle in the absence of an e-bike. The e-bike performs well in terms of environmental impacts compared with the bus and motorcycles. E-bike SO_2 emissions are considerably higher (because of high sulfur coal), but other pollutants are lower than, or on the same order of magnitude as, bus emissions. When calculating emissions from electricity generation, it is important to consider the region in which policy is being developed and the influence of energy mix on the emission rates of e-bikes. Generally, provinces in the south have lower emission rates than provinces in the north because of their reliance on cleaner power generation, such as hydropower.

By far, the biggest environmental reservation associated with e-bikes is lead pollution. The lead emissions from battery use reported in this report are not tailpipe emissions for any mode but rather emissions from the production, recycling, and disposal processes of batteries, spread over the life cycle of the vehicle. Lead emissions per passenger-kilometer are several orders of magnitude higher for e-bikes than for buses primarily because buses use fewer (although heavier) batteries during their life cycle and get much more passenger mileage from each battery.

Since lead acid batteries are used for most modes of transport and many industrial sectors, the environmental regulation of lead producers and battery manufacturers will have broad impacts through many sectors. Lead mines, the source of some 50% of solid lead waste, must be regulated to ensure that lead compounds in mine tailings are contained. Battery manufacturers must be regulated, or given economic incentive, to improve manufacturing processes and protect environmental and occupational health. The PRC currently is drafting strict legislation to regulate the size and environmental performance of the battery-producing sector, which will improve the environmental performance of the battery production processes over time. Because of the high value of lead in the batteries, recycling rates are high. However, much of this recycling, or secondary smelting, capacity is in the informal and unregulated sector, where loss rates during battery breaking and lead smelting can approach 50% of the lead in the battery (United Nations Environment Programme 2004). These informal activities are the most dangerous to those recycling the batteries and those in the surrounding areas.

Several economic models for used battery take-back incentives have been successfully implemented in industrialized countries, including taxation, deposit-refund, and purchase discount schemes. One or more of these incentives could be implemented to ensure that batteries are recovered, broken, and recycled by environmentally responsible and certified recyclers. Still, improving production and recycling of lead acid batteries improves all modes' environmental performance, and e-bikes will still emit more environmental lead relative to other modes.

Lead acid batteries are not necessary for e-bike operation. Commercially available alternative technologies, such as nickel-metal hydride and lithium-ion (Li-ion) batteries, are much more expensive but they also have much higher energy densities, so battery weight can be reduced by more than half. A Li-ion battery that is equivalent (in power) to lead acid would cost about four times that of a lead acid battery. However, it is likely to have two to three times the life span, so while the actual life-cycle cost is still higher, it begins nearing that of lead acid batteries. Since batteries are one of the highest operating cost components of e-bikes, market adoption of Li-ion batteries will be slow among the generally lower-income e-bike riders who might not be able to afford higher up-front costs, given uncertainty in battery life span or lack of experience with Li-ion technology. These advanced battery technologies also contain chemicals and metals that are harmful to the environment and require a similarly responsible take-back and recycling mechanism in place before mass adoption.

E-bike market growth scenarios were presented based on empirical data observed from motorcycle adoption throughout Asia. This model suggests that the e-bike fleet could quickly approach 50 million, which some reports suggest has already happened. One reason for this growth is the modularity of e-bikes, allowing hundreds of companies to enter the market and assemble e-bikes under their brand. This has reduced prices and made e-bikes affordable to the large low-income population in the PRC.

One could argue that the PRC is a special case and is likely to see different trends of even greater growth, since the large number of nonmotorized and two-wheel-dependent travelers (over 500 million) provides a huge market for e-bikes. In any case, e-bike growth will remain strong for the coming years as the PRC's residents require more mobility and congestion hinders car and bus travel. This growth could lead to greater efficiencies in battery production, lowering the cost of all types of batteries. Ultimately, regulation of lead acid batteries would hasten the transition to cleaner battery technologies, reducing the environmental load of the millions of lead acid batteries entering the e-bike market yearly.

As cities expand, the propensity to use e-bikes instead of bicycles will grow. However, high-quality public transport systems provide high levels of range and mobility that can be complemented by bicycle and e-bike travel. E-bikes can provide very environmentally efficient transport for short distances to access transit stations. Depending on load factors, they can be much more environmentally friendly and cost-effective than feeder bus service and provide better service. To facilitate this positive relationship, dedicated e-bike infrastructure, such as low-speed and low-conflict rights-of-way and secure parking, should be developed to feed high-capacity public transport systems. This could expand the reach and efficiency of public transport in cities. Local policy makers, planners, and engineers have a strong role in encouraging synergistic relationships between personal two-wheelers and public transport modes.

The policy decision to integrate e-bikes into the transport system is beyond the scope of this study. There are other pressing concerns associated with promoting e-bikes, including their contributions to congestion, road hazards, disorganized development, erosion of public transport ridership, and galvanizing of commuters' inclination toward private mobility—possibly hastening automobile ownership. These areas require further research. Recent studies have begun to address concerns with e-bike safety (Lin, He, et al. 2008; Ni 2008). Chengdu recently announced comprehensive and differentiated regulation to integrate e-bikes and scooters to the urban transport system, in part to address safety issues (CHR Metals 2008).

Transport policy in cities must distinguish e-bikes from the general bicycle population to effectively monitor and regulate their use. Nonrestrictive licensing schemes have been implemented in many cities but are unenforced and have low levels of compliance, making it difficult to quantify growth and subsequent infrastructure requirements. Moreover, three-wheel e-bikes are popular in many cities and provide a host of challenges and opportunities to the transportation system. In the absence of reliable estimates of demand for these vehicles, it is difficult to know the impact they have on the transport system.

From an environmental perspective, if the e-bike industry shifted to alternative battery technology or substantially improved efficiencies of lead production on a national scale, then a switch to any other mode, except for a move to bicycles, would probably be more environmentally detrimental. If lead acid batteries could be replaced and e-bikes remained lightweight and low speed so that they could be safely integrated into the road network, then e-bikes would be perhaps the most environmentally sustainable motorized mode available in the PRC.

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Electric Bikes in the People's Republic of China
Impact on the Environment and Prospects for Growth

Electric bikes (e-bikes) provide low-cost, convenient, and relatively energy-efficient transportation to an estimated 40 million–50 million people in the People's Republic of China (PRC), quickly becoming one of the dominant travel modes in the country. As e-bike use grows, concerns are rising about lead pollution from their batteries and emissions from their use of grid electricity, primarily generated by coal power plants. This report analyzes the environmental performance of e-bikes relative to other competing modes, their market potential, and the viability of alternative battery technologies. It also frames the role of e-bikes in the PRC's transportation system and recommends policy for decision makers in the PRC's central and municipal governments.

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Asian Development Bank
6 ADB Avenue, Mandaluyong City
1550 Metro Manila, Philippines
www.adb.org
ISBN 978-971-561-793-2
Publication Stock No. RPT090040

ISBN 978-971-561-793-2

Printed in the Philippines