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Electric Two-Wheelers in China: Analysis of Environmental, Safety, and Mobility Impacts

by

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requirements for the degree of

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in

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in the

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of the

University of California, Berkeley

Committee in charge:

Professor Adib Kanafani, Co-Chair
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Professor Maximilian Auffhammer

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Abstract

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Chinese cities have a long legacy of bicycle use due to relatively low incomes, dense urban development, and short trip lengths. Because of tremendous economic growth, increased motorization, and spatial expansion of cities, trips are becoming longer and more difficult to make by bicycle. As a result, electric powered two-wheelers have risen in popularity over the past five years, with sales exceeding 16 million in 2006. Recently, policy makers have enacted bans on electric two-wheeler use, citing a poor safety record, a large contribution to congestion, and poor environmental performance. This study quantifies many of the safety and environmental impacts of electric two-wheelers and balances the negative externalities by quantifying benefits to users in terms of increased mobility and access to opportunities.

Touted by some as environmentally friendly vehicles, electric two-wheelers are capable of traveling 40-50 kilometers on a single charge and emit zero tailpipe emissions. However, they do have significant environmental impacts because they use lead acid batteries that are recharged with electricity that is predominantly generated from coal power plants, but they also have significant mobility benefits that are seldom considered. This research investigates the tremendous growth of electric two-wheelers in China and compares their environmental and safety impacts to those of alternative modes of transportation; such as traditional bicycles, public transportation, or personal cars. This research also analyzes the benefits of electric two-wheelers in terms of increased mobility and accessibility to opportunities due to their increased speed and range.

Electric two-wheelers tend to be more energy efficient and produce less air pollution per kilometer traveled than many other modes. Also, to the extent that they displace car trips, they improve the safety of the transportation system in Chinese cities. Electric two-wheelers provide much higher mobility and access to opportunities than all other low cost modes.

The impacts of electric two-wheelers on the transportation system are dependent upon local characteristics of the transportation system. Considering alternative transportation modes in two case studies (Shanghai and Kunming), banning electric two-wheelers will result in higher net energy use and greenhouse gas emissions. Moreover, the public health impacts from traditional air pollutants and road safety would likely be worse in a situation where electric two-wheelers are banned. The mobility and accessibility to the city will also deteriorate significantly for users of electric two-wheelers. However, allowing electric two-wheelers in a city results in significant increases in lead pollution over the lifecycle, compared to alternative modes. This research shows that while electric two-wheelers do have some problems that need to be addressed (namely excessive lead acid battery pollution); they provide large benefits and can be a successful strategy toward a sustainable transportation future.

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CHAPTER 1: INTRODUCTION

Chinese cities have been developing economically at a phenomenal rate for the past decade. With this has come an increase in urbanization and motorization, which has increased congestion and reduced urban air quality. China's transition to a more market based economy has effectively unbundled housing and employment, causing increased trip lengths. Additionally, growing employment and labor markets are prompting more multiple worker households and trip destinations throughout the urban area. Increases in income have led to increased consumption and thus increased demand of local and regional shopping destinations. As a result, residents in Chinese cities are spending more time and a higher portion of their income on transportation than ever before (Cherry 2005).

Chinese cities are investing heavily in advanced public transportation systems in order to improve the efficiency in their transportation system (Chang 2005). Many cities have coupled investment in public transportation with restrictions on bicycle and motorcycle use, presumably to improve the safety and efficiency of the transportation system and reduce conflicts between modes. While public transportation systems are the most efficient mode of transportation by many metrics, they do not provide door-to-door flexibility or the short travel times of personal transportation modes (such as bicycles) that Chinese residents are accustomed to. Because of these inherent limitations of public transit systems, bicycles are still widely used, despite annexed infrastructure and increased regulation.

As a result of these trends, industry has been developing modes that can provide low cost personal transportation that is fast, flexible and energy efficient. Particularly, electric bicycles and electric scooters have gained popularity and their use has become widespread in many Chinese cities. Electric bikes come in a range of styles and performance specifications, but the primary technology is the same. The vast majority of them utilize lead acid batteries to provide energy to a hub motor that is usually on the rear wheel. Most electric bikes fall into two categories: scooter style electric bikes (SSEBs) or bicycle style electric bikes (BSEBs) (Figure 1.1). SSEBs appear much like gas scooters complete with headlights, turn signals and horns; with large battery packs under the footboard. BSEBs resemble bicycles, with functioning pedals and usually smaller batteries and a lower power motor. Electric bikes are capable of speeds exceeding 20-30 km/hour and weigh between 40 and 60 kilograms.

Electric bikes are recharged by plugging into standard wall outlets. This is a great advantage because there is no need for dedicated refueling/recharging infrastructure. Most electric bikes have removable batteries and chargers so that they can be transported indoors and recharged during the day or night. With their increased popularity, many apartments or workplaces are retrofitting bicycle parking areas to accommodate electric bikes by providing electrical outlets. Batteries require 6-8 hours to charge. Charging electric bikes at night can increase the efficiency of the electric power generation network. By recharging batteries overnight, 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.

Electric bikes are very cheap and efficient to operate. The purchase price is 1600-2400 RMB or US$ 200-300. Considering an average SSEB with a 350W motor and a

48V 14Ah battery, the energy requirement is 1.3kWh/100km. Electricity rates in most of China are around 0.6 RMB/kWh, so the cost of operating an electric bike is 0.78RMB/100km or about $0.10/100km. The total average cost is about 0.10-0.12 RMB/km (Jamerson and Benjamin 2004), far cheaper than any other motorized mode; for instance user costs to ride the bus is around 0.5 RMB/km. Moreover, this cost is rarely realized by electric bike users. They often do not pay for the recharging because they recharge at a centralized parking lot. If they recharge the battery in their apartment, the cost is bundled into their electric utility bill and they do not see how much is from battery recharging. This results in difficulty regulating electric bike use through the cost of fuel (electricity). The main expense is the purchase of batteries, which is over half of the in-use cost (Jamerson and Benjamin 2004).

In 2005, over 10 million electric bikes were sold in China, which is about 3 times the amount of cars sold (Figure 1.2) (Jamerson and Benjamin 2004; National Bureau of Statistics 2005). Guo (2000) chronicles the emergence, development, and regulation of the electric motorcycle over the past 30 years, indicating that China is currently experiencing its third peak in electric motorcycle use. The author cites reasons for the current success such as better batteries, more government support, and more reliability. Recent laws passed by China's central government classify electric bikes as bicycles from an operational and regulatory perspective. Driver licenses and helmets are not required and they are allowed to operate in the bicycle lane (China Central Government 2004). Manufacturers are required to adhere to technical standards developed by the central government that stipulate a maximum weight of 45 kg and a maximum speed of

20 km/hour (China Central Government 1999). This standard precludes most SSEB's from development, but the standard is poorly enforced (Weinert, Ma et al. 2006).

Figure 1.1: Bicycle Style and Scooter Style Electric Bikes (image source: www.forever-bikes.com)

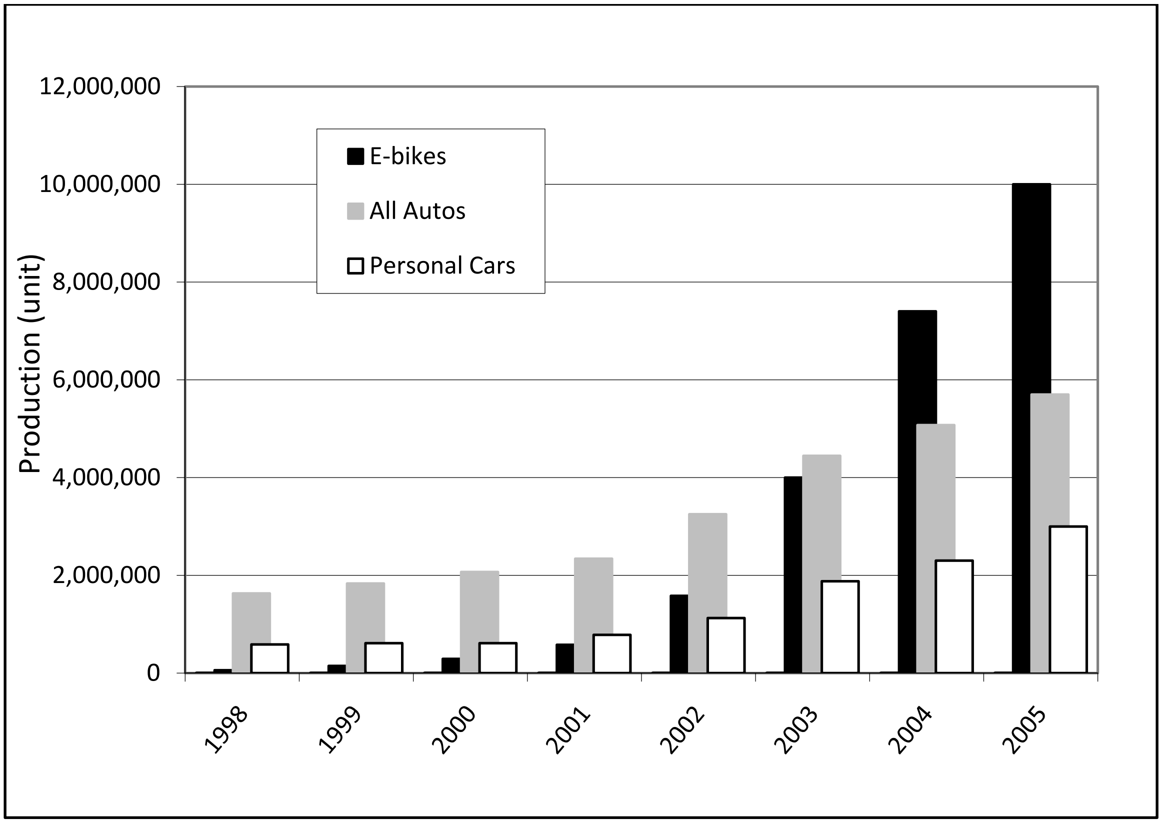

Figure 1.2: Production of E-bikes and Cars For Domestic Market in China

This mode of transportation has certain advantages over others, but also presents challenges to transportation planners and policy makers. As cities expand, many origins and destinations grow farther apart and become less accessible by bicycle. Public transportation in many cities is underdeveloped and inefficient. Buses often operate in mixed flow lanes and the average operating speed has decreased with increases in congestion. The result is that electric bicycles, operated in the bicycle lane, increase personal mobility in terms of reduced travel time and thus accessibility to goods, services, jobs, etc. Bicycle lanes are seldom congested and offer high levels of capacity to bicycle and electric motorcycle users. Using an electric motorcycle could be seen as a superior mode to a car in terms of travel time and cost savings, potentially resulting in lower car ownership. Additionally, electric motorcycles have zero local emissions and low noise levels.

Although electric vehicles produce no local emissions, they do require electrical energy, which in the case of China is almost exclusively generated by coal-fired power plants (National Bureau of Statistics 2005). Electric motorcycles require 0.9-1.3 kWh of electric energy per 100 km. Electric bikes will have different emission rates based on regional location and energy mix. Emissions from one point source (powerplant) are easier to manage and regulate than emissions from multiple sources (tail-pipes) and likely have lower public health effects because of their rural location.

Currently, most electric motorcycles are powered by lead-acid batteries and each battery has a lifespan of approximately 300 charges or 10,000 km. Generally, a battery lasts one to two years. Battery disposal and recycling is a serious environmental consideration, as improper disposal can lead to contamination of soil or groundwater and inefficient production and recycling processes can lead to high emissions of airborne lead pollution. The recycling process and the negative effects of lead-acid batteries in the developing world are well documented (Lave, Hendrickson et al. 1995; Yeh, Chiou et al. 1996; Suplido 2000; Cortes-Maramba, Panganiban et al. 2003; Mao, Lu et al. 2006). China currently does not have a well regulated and institutionalized disposal and recycling program for lead-acid batteries. This is a serious consideration when considering an appropriate policy for Chinese cities.

The growth of this mode has prompted local and national policy makers to question the impact of electric bikes on the transportation system and pursue policies to regulate them. Taiwan promoted and even subsidized electric bike use in the 1990's to provide a clean alternative to gas powered scooters (Taiwan EPA 1998; Chiu and Tzeng 1999). Despite this subsidy, electric bikes competed directly with gas scooters and the performance characteristics were not competitive enough to induce a large market shift. Although they were promoted in Taiwan, several cities in mainland China, notably Beijing and Fuzhou, have attempted to ban electric bikes altogether, citing lead pollution and safety issues (Beijing Traffic Development Research Center 2002; Weinert, Ma et al. 2006). These policies are being implemented with little information about who is using this mode and what impact it has on the transportation system. Taiwan attempted to shift from gas scooters to electric bikes, but little is known about who is riding electric bikes in China and from which modes they are shifting.

1.1 Research Objective:

Policy makers are making decisions based on perceived environmental and social costs, but little research has been done that carefully quantifies these costs and also looks at benefits that electric bikes provide to the urban transportation system. Little is known about the life cycle energy use and environmental impacts, safety impacts or accessibility effects experienced by electric bike users. Policy makers may cite environmental concerns regarding electric bikes, but they often do not consider the environmental impacts of alternative modes, if electric bikes became unavailable.

The research question addressed in this dissertation is: *Compared to the predominant alternative modes, bus and traditional bicycle--under what conditions do electric bikes provide a greater relative benefit in terms of mobility and accessibility improvements than relative costs in terms of energy use, environmental impacts and safety?*

Since many of these impacts are local in nature, two case studies are carried out in Kunming and Shanghai, two cities with very distinct differences, but similar electric bike use. Several research activities are carried out that address the primary research question.

1) Investigate electric bike user demographics, vehicle use characteristics, and factors that influence mode choice through a user survey. Calibrate a choice model that identifies factors that influence current mode choice.
2) Conduct a life cycle assessment (LCA) of electric bikes and compare energy use and emissions outcomes to those of alternative modes, namely bicycles and buses.

3) Identify safety impacts of electric bikes and develop mode shift scenarios that influence the overall safety of the transportation system.
4) Quantify mobility and accessibility changes in terms of origin to destination travel time differences and jobs access, compared to bus and bicycle use.

These activities represent the primary costs (emissions, energy use, and safety) and benefits (accessibility) of electric bikes in China. The metrics of these analyses reflect the difficulty in developing environmental, economic and equitable sustainable transportation policy. These metrics are not comparable in the sense that one could make direct comparisons which would result in an objective, deterministic policy solution. There will likely be trade-offs that will differ, depending on the goals of the policy maker. For instance, accessibility will be measured in terms of jobs access increase, as a proportion of increase compared to alternative modes. Emissions will be measured in terms of total pollutants or public health effects. While it is difficult to compare these metrics, they must both be considered in the decision making process, and the policy recommendation will differ, depending on the goals of the policy maker. This research quantifies these costs and benefits so that the decision making process is more informed and transparent.

1.2 Dissertation Organization

This dissertation is composed of nine chapters, including the introduction. The second chapter of this dissertation will build a research framework and discuss the methodology and data collection techniques for each of the research activities. It will review relevant literature on each of the topics and give introductions to the case study cities. The third chapter will discuss the user demographics and use characteristics of electric bike use in Kunming and Shanghai and discuss the development of a discrete choice model that predicts mode choice based on individual and mode specific variables. The fourth chapter identifies major contributors to the environmental impact of electric bikes and alternative modes (buses and bicycles). An LCA is conducted that accounts for the environmental impact of production, use and end-of-life phases of the life cycle. The life cycle impacts are compared across all three modes. Public health impacts are calculated from electric bike and bus emissions from the use phase of the life cycle. Chapter five discusses the safety data of electric bikes. Crash and fatality rates are compared across modes in different cities and regions and scenarios are developed in the event of modal shift. Chapter six synthesizes collaborative research conducted by Chinese partners on the effect of electric bikes on congestion. The seventh chapter discusses the results of mobility studies in Kunming and Shanghai and extends the results of those studies to accessibility gains. The eighth chapter summarizes the results of the analysis in the context of the Kunming and Shanghai case studies. The ninth chapter extends this analysis to a national context and develops a framework from which to analyze electric bike impacts in any city. It discusses some shortcomings of this study and future research directions are presented that improve on this methodology and extend this work to other modes and cities.

CHAPTER 2: RESEARCH FRAMEWORK, METHODOLOGY, AND DATA

Different cities or regions have different electricity use patterns, travel mode patterns, demographics and transportation regulations that influence the use of electric bikes. If a majority of electric bike users would otherwise be using bicycles, then the net environmental impact is negative. If electric bikes replace motorized vehicle use, then there is possibly a positive environmental benefit. One must weigh the environmental impacts against the economic benefits, which are realized through increased mobility. This research will develop a framework within which to analyze relative impacts of electric bikes in any Chinese city. Different Chinese cities have different data reporting practices and thus different ways to approach this analysis. Generally, this framework involves identifying the following:

Environmental Impacts:

- Number of electric bikes in a Chinese city and the approximate daily vehicle kilometers traveled (vkt)
- Safety impacts of a shift from alternative modes to electric bikes.
- Emissions generated by the production of an average electric bike, a bus, and a bicycle.
- Energy mix and subsequent emission factors for fossil fuel power plants serving a city where electric bikes are operated
- Human exposure of airborne emissions
- The amount of lead emitted into the environment during the production, recycling, and disposal processes of batteries

- Proportion of electric bike users that would otherwise use bicycles or transit if electric bikes were prohibited

Mobility and Accessibility Impacts:

- Difference in operating speed and thus travel time from origins and destinations between competing modes
- Change in accessibility to jobs, goods or services

2.1 Research Approach

The framework for analysis is outlined in Figure 2.1. One of the difficulties associated with conducting a full analysis of the costs and benefits of a new mode is to bound the research to include the most significant costs and benefits. This research will not include a full cost and benefit accounting, but will consider what are seen as the greatest impacts; those associated with vehicle life cycle emissions and energy use, safety impacts, and mobility and accessibility changes. These environmental and safety impacts are commonly cited by electric bike opponents, but opponents rarely acknowledge mobility and accessibility gains.

The research approach first involves identifying case cities, Shanghai and Kunming. These cities have given demand characteristics of electric bikes and alternative modes. They have city specific operating speeds for electric bikes, buses and bicycles. Each city also has somewhat static electricity mix. Given these inputs, primary costs and benefits can be calculated. Environmental production costs will be incurred in the provinces where electric bikes and their components are manufactured and will be constant across all cities where electric bikes are used. The costs imposed by operating electric vehicles will be distributed among the population affected by power plant emissions serving that particular city. Air emissions can be converted to population exposure and thus mortality and morbidity changes associated with electric bike use. The safety and mobility impacts will be experienced by users of electric bikes. Mobility changes can be expressed as changes in accessibility, given transportation network and land use data for a given city. In short, environmental externalities will be external to the electric bike user, and are social costs, while safety and mobility changes are internal to the user. The following sections will discuss the research approach of each component of the costs and benefits to be evaluated. A more thorough methodology section will be given in each of the respective chapters.

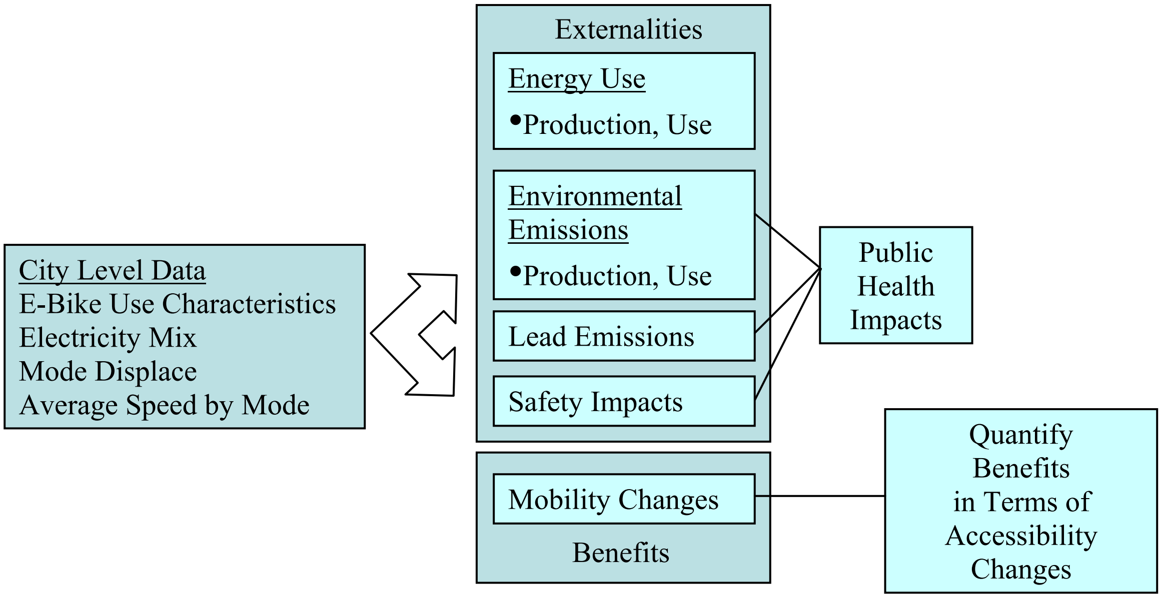

Figure 2.1: Framework of Analysis of Cost Effectiveness of Electric Bikes

2.1.1 Energy Use During Production

To identify the effects of the development of the electric bike market and industry in China and the effect of regulation in different cities, the entire life-cycle of the electric bike must be investigated. This includes identifying the production processes for each unit and identifying resource, energy use, and environmental impacts during production. The production function will likely vary between factories, but since most factories are located in Zhejiang or Jiangsu Province (near Shanghai) their access to resources should be similar.

When conducting a environmental life cycle analysis of a vehicle, five components of the vehicle's life should be considered (Sullivan, Williams et al. 1998).

1) Raw materials acquisition and processing
2) Part and Subassembly Manufacturing
3) Vehicle Assembly
4) Vehicle Use and Operation
5) Disposal

Sullivan and Williams et al. (1998) found that the vast majority of personal car's energy use (84%) is from operation. Raw material production and manufacturing account for 14% of energy use. In terms of air emissions, vehicle operation accounts for 87% of CO_2, 94% of CO, and 90% of NO_x. The material production and manufacturing components account for 65% of particulate emissions and 34% SO_2 emissions. This is primarily because the production and manufacturing components use the most electricity and thus coal emissions of the life cycle phases. Vehicle disposal uses very little energy, but is the greatest contributor to solid waste of all other stages of the vehicle's life. The authors do not consider infrastructure, building construction, transportation costs of distribution or secondary inputs into production processes. It is generally accepted that these inputs are very small in relation to the overall costs. This approach is used to determine the environmental impact of electric bike use in Chinese cities.

Electric bikes, buses and bicycles all have different fuel technologies. Buses are most closely related to the personal car example, with most of the environmental impacts occurring during the use phase. Alternatively, the production of a traditional bicycle accounts for nearly all of its environmental costs, so when comparing these two modes, the environmental costs of a bicycle should be very carefully measured.

Since electric bikes use electricity from a power plant, which more efficiently generates and transfers primary energy into movement than burning gasoline or diesel internal combustion engines, electric bikes have lower use phase environmental impacts. A greater proportion of an electric bike's environmental impact is imposed during the manufacturing phase.

An electric bike, like most vehicles, is made from hundreds of parts and components. Comprehensive component lists that include the weight and material of various components are supplied by industrial partners. The major parts/component manufacturers and processes that likely use energy and produce emissions are: batteries, motors, tires, steel frame welding and forging, and plastic manufacturing. While this is not an exhaustive list of the components, these produce the most pollution. These components are manufactured and shipped to a final assembly plant where the electric bike is finally produced. Aggregate environmental data on these processes are readily available in statistical yearbooks. These costs can be divided over the life of the vehicle to identify energy use per kilometer. Once primary, first-order production costs are calculated, sensitivity analysis can be conducted to evaluate the potential effects of the second-order costs that were omitted or estimated, such as distribution or infrastructure.

2.1.2 Energy Use During Vehicle Operation

During electric vehicles' operation, they emit zero local air pollution, but they do use electricity (about 0.9-1.3 kWh per 100 km). For example, consider an average SSEB with a 350W motor, a 48V/14Ah battery and 50km range.

Current=Power/Voltage=350W/48V≈7.3 A

Drain Time=14Ah/7.3A=1.9 hours

Energy=Power*Time=350W*1.9 h=672Wh

Energy/Range=672Wh/50km=13Wh/km

This energy use varies by different motor/battery combinations. The weighted average electricity use per kilometer can be calculated based on fleet composition in a city or nationwide.

2.1.3 Air Emissions from Electricity Generation

In China, About 75% of electricity is generated by coal-fired power plants. Much of China's power is generated locally by small, inefficient power plants, with a limited regional or national power grid and distribution network (Zhu, Zheng et al. 2005). There are currently 15 power grids that serve different parts of China. Cities throughout China are served by different proportions of power sources (coal, natural gas, hydro, wind and nuclear). For instance, the construction of the Three Gorges Dam provides a large amount of clean hydro power, although its capacity still comprises a small proportion of China’s overall capacity. In general the power generation capacity in northern China is almost exclusively coal powered because of abundant coal supply. The power generation capacity in southern China has much higher hydro-electric capacity. The wind, solar and nuclear power generation capacity in China is negligible.

The following graphs illustrate the emissions of primary pollutants from average existing coal-fired power plants, new coal-fired power plants, and gas turbine power plants.

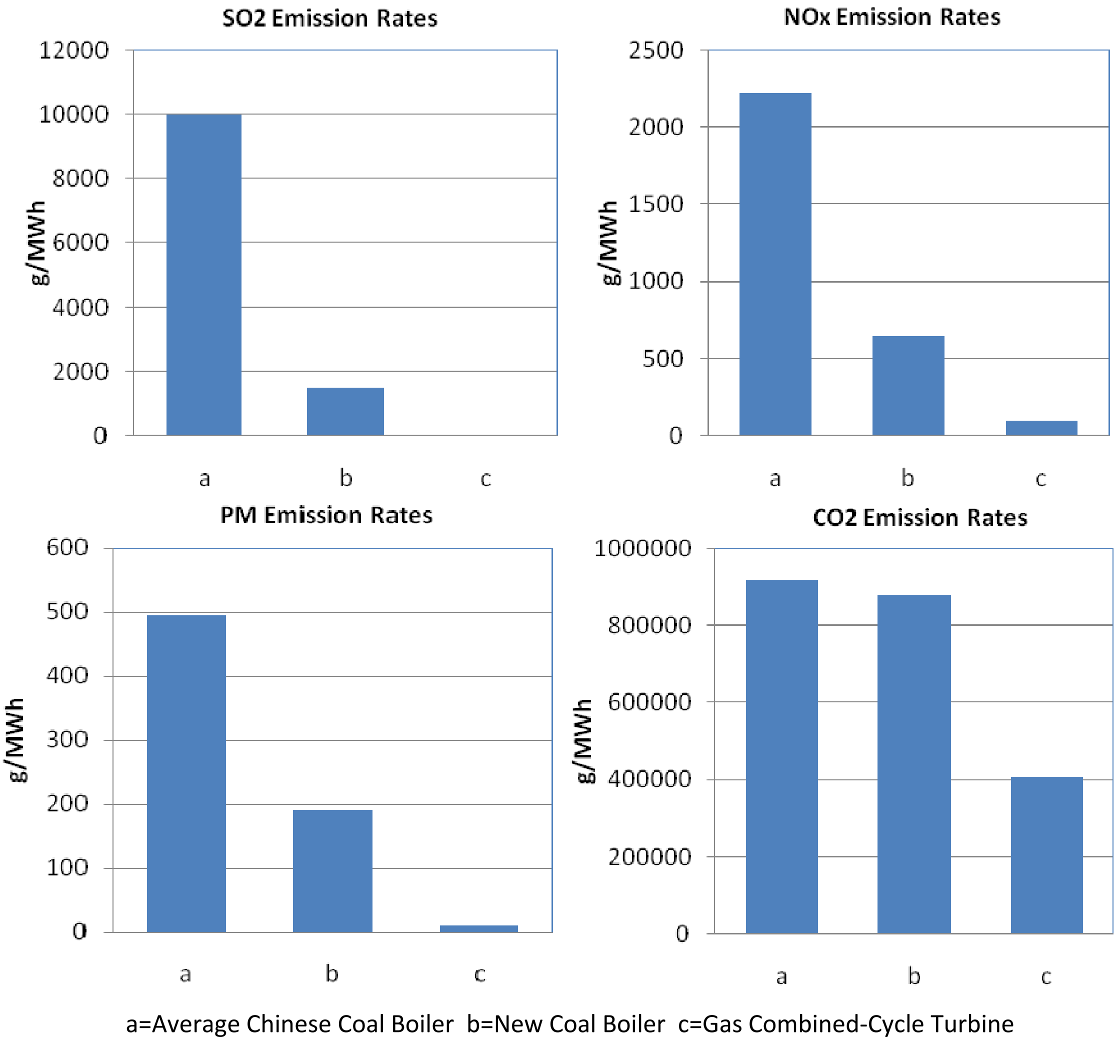

Figure 2.2: Emission Rates from Chinese Power Plants (Energy Foundation China 2005)

Once emissions rates have been determined per MWh, they can be converted to emissions rates per kilometer. In order to calculate the emissions per kilometer due to production, the electricity used per electric bike produced must be divided by the total lifespan of the vehicle. To calculate the emissions rate for the operation of the electric bike, the amount of electricity used per kilometer can be converted to emissions per kilometer.

Different emissions rates can be calculated using various energy mix combinations of hydro generation, coal generation, or gas generation. Additionally, there is a spectrum of technologies that must be considered on a case by case basis to accurately estimate the emissions per kilometer of electric bike use (Larson, Wu et al. 2003; Wang, Mauzerall et al. 2005).

The production emissions can be calculated using the average power plant emissions and energy mix in the East China power network sector, where most of the production facilities are located (Anhui, Zhejiang and Jiangsu Provinces and Shanghai Municipality). The emissions for operating the electric bike would be calculated using the average power plant emissions and energy mix of the sector in which the city is located.

2.1.4 Converting emissions into intake

Electric bike policy is highly dependent on the energy profile of a city or region and different scenarios of future electricity generation. In addition, the exposure of people to pollutants depends on proximity of power plants to population centers and meteorological conditions. Cities with urban power plants are more likely to expose higher populations to airborne toxics, while rural power plants will not have the same negative health impacts.

One of the techniques that has recently been developed to measure the exposure of people to pollutants is the intake fraction (Bennett, McKone et al. 2002; Marshall and Nazaroff 2004). The intake fraction is defined as the proportion of the pollutants that are emitted that are actually inhaled and can be calculated as follows:

$$iF = \frac{\sum_{i=1}^{N}(P_i \times C_i \times BR)}{Q}$$

Where P is population of zone i, C is pollutant concentration of zone i, BR is the average breathing rate or the volume of air inhaled per unit time of the population and Q is the total mass of pollutant emitted into the environment. The intake fraction is unit-less and can be a powerful tool to identify health impacts due to incremental changes in emissions such as pollution controls on power plants or added emissions due to electric bicycle use. It is also helpful to compare public health impacts of various alternative technologies without calculating public health end-points. That is, a technology that results in twice the intake fraction of an alternative will have twice the public health impacts.

2.1.5 Converting intake into health effects

Intake can be extended to public health impacts. Epidemiologists (Xu, Gao et al. 1994; Xu, Li et al. 1995; Wong, Ma et al. 2001; Pope III 2002; Brajer and Mead 2003; Chen, Hong et al. 2004) have developed dose response functions for different pollutants; primarily particulates, sulfur dioxide, and nitrogen dioxide, which are the most hazardous to human health. These researchers report relative risk factors, which are defined as a percent increase in mortality or morbidity per unit increase in pollutant. For instance, there is a 0.7% increase in mortality per $\mu g/m^3$ of $PM_{2.5}$ concentration increase, and 0.084% increase per $\mu g/m^3$ of PM_{10}. Similar numbers have been reported for morbidity, which result in increased hospital and doctor visits. Ultimately one would like to know the number of mortalities or sicknesses that are incurred as a result of increased pollution.

This is calculated using a concentration response function that was developed by the US EPA (1997).

$$\Delta C = C(e^{b\Delta P} - 1)$$

Where ΔC is the change in mortality or morbidity, C is the baseline mortality or morbidity rate, b is the response coefficient and ΔP is the change in pollution concentration level. Baseline mortality and morbidity rates are known for various cities or China in general. The change in pollutant concentration is modeled using pollutant transport models or back-calculated using the intake fraction methodology. The response coefficient, b, is related to the relative risk factor as follows (Brajer and Mead 2004).

b=ln(relative risk)/(change in pollutant)

Using this methodology, the total health effects of an increase in emissions and thus an increase in concentration of a pollutant or set of pollutants can be quantified in terms of additional lives lost as a direct result of increased power plant emissions.

Alternatively, if the net change of air emissions for different pollutants are determined and the relative public health impacts between each of those pollutants can be identified, then the direction of the public health impact can be estimated. For instance, if policy is enacted that doubles the amount of SO_2 and halves the amount of NO_X emitted from the transportation sector (controlling for exposure), then the public health impact of such a policy would be positive. Since NO_X has more severe public health impacts than

SO_2, halving its emissions would produce more public health benefit than the negative impact associated with doubling SO_2 emissions (Health Effects Institute 2004).

2.1.6 Lead Pollution from Battery Use

Perhaps the most significant environmental disadvantage electric bikes have is the use of lead acid batteries. According the Electric Bikes Worldwide Report (Jamerson and Benjamin 2004), 95% of all electric bicycles and scooters in China are powered by lead acid batteries. Chinese electric bikes use 24 or 36V, 7-12Ah batteries. The batteries weigh between 9 and 15 kilograms. Batteries typically have a lifespan of 300 charges, or about 10,000 kilometers. Electric bicycle manufacturers typically cite the lifespan of a battery is about 2 years, depending on use, maintenance, and recharging protocol. Recent developments have made Nickel Hydride and Lithium batteries more feasible for future uses, but the prospects for use of these batteries is uncertain and these types of batteries also have negative environmental implications.

Recent research has shown that equivalent of 70-100% of lead content of a battery is emitted into the environment in China through the mining, manufacturing, recycling and disposal processes (Mao, Lu et al. 2006). It is unclear what portion of this is emitted into the air, ground, or water. However, lead is classified as a hazardous material that decays slowly, so all emissions could eventually have public health effects.

The Center for Disease Control (CDC 1991) and the World Health Organization (WHO 1995) have identified the lead poisoning blood concentration threshold for children (10μg/dL), men (40 μg/dL) and women (30μg/dL). If a person's lead concentration exceeds this value, they are in danger of experiencing symptoms of lead poisoning. Lead poisoning manifests in many ways that are difficult to quantify. Children experience long term developmental disorders, low IQ, and physical growth impairments (Shen 2001). There have been a couple of studies in the context of battery recycling and manufacturing plants in Asia and their health effects on workers and people nearby. Suplido and Ong (2000) found that workers at battery recycling shops and children of workers in the Philippines had much higher lead levels than control groups (330% higher for adults and 400% higher for children). The blood lead concentration is five times the WHO guidelines for children. Cortes-Maramba et al. (2003) found that populations living within five kilometers of a large battery recycling plant (>14,000 batteries per year) experienced significantly higher blood lead concentrations than control groups living outside of the five kilometer radius (20% higher for adults and 30% higher for children). In terms of quantifying the health impacts, they identified that adults living within five kilometers of the plant had a 23.1% history of hospitalization, compared to 4.2% for the control. Likewise, 37.5% of the affected children have a history of hospitalization, compared to 11.8% of the control group.

The US EPA (1997) identified the public health impact of removing lead from fuel. The report identifies several quantifiable public health impacts of lead pollution, including mortality, lower IQ, hypertension and stroke. These effects are a function of the blood lead levels, not air concentration as in the previous section. Given absence of blood lead levels, approximations can be made based on studies made by Cortes-Maramba et al. (2003) or Suplido and Ong (2000).

For the near term, lead acid batteries will be the primary source of power for electric bikes and policy must be developed that encourages more environmentally benign batteries and establishes disposal and regulation policy. The negative environmental impacts can be quantified in terms of lead emissions during the production and recycling processes. Public health effects can be calculated using hospitalization rates near lead recycling plants or estimates of blood lead concentration increases and thus public health effects. These are imperfect measures without more advanced medical screening for specific cases, but could give an estimate of the effects of lead pollution.

2.1.7 Safety

Safety is a primary concern of Chinese government officials. In each of the last three years, China has exceeded 100,000 road fatalities, where most of the victims are vulnerable road users such as pedestrians or bicyclists (National Bureau of Statistics 2005). One of the motivations cited for regulating the use of gasoline powered motorcycles is safety. Beijing officials cited safety as one of the main reasons to ban electric bikes as well. The China Bicycle Association (electric bike advocates) countered, citing the crash rate (percent of vehicles involved in a crash per year) for electric bicycles is 0.17% and 1.6% for cars (Ribet 2005). The primary question is whether electric bicycles result in a decrease of safety of the entire transportation network, in terms of fatalities and injuries per person kilometer traveled, or if the incidence of fatalities is higher for electric bike users because they are vulnerable road users. For safety considerations, electric bikes' operating speed is limited so that they can safely operate in bicycle lanes. Moreover, if we assume that the traveler will take the trip regardless of mode, what are the safety implications of switching to an alternative mode, bicycle or transit?

2.1.8 Mobility and Accessibility Changes

The reason we tolerate environmental externalities as a society is because the benefits that activities provide outweigh their externalities. In the case of transportation, mobility is the primary benefit. Mobility can be defined as average operating speed or travel time between two points. Mobility by itself does not provide economic benefits, but it provides access to jobs, goods and services. Mobility differences between modes can serve as a proxy for accessibility differences between modes in a static, uniformly distributed built environment. That is, given an origin and a set of destinations, a mode with higher operating speed than an alternative can access proportionately more destinations. If origins and destinations are clustered, accessibility increases could be higher than simply the increase in speed.

Floating vehicle studies using a global positioning system (GPS) interfaced with a geographic information system (GIS) are conducted for bicycles and electric bikes in the city. These data give an accurate distribution of speed for each mode. They also indicate a spatial distribution of speeds throughout the urban area. This speed is used in conjunction with spatial distribution of jobs and housing using an accessibility index (Cervero 2005) to identify the difference in accessibility between modes.

2.2 Case Studies

China has 660 cities and three quarters of its urban population lives in small and medium sized cities by Chinese standards (0.5-4 million people) (Cherry 2005). However, many of the cities facing the greatest transportation challenges and which are looked to for best practices are China's megacities, notably Beijing, Shanghai and Guangzhou. To represent a large portion of the population and investigate differences between two sizes of cities, the authors decided to investigate Kunming, a medium sized city with an urban population of about 3 million and Shanghai, a megacity of 15 million.

2.2.1 Kunming

Kunming is the capital of Yunnan province in southwest China (Figure 2.3). It is a gateway for trade with Southeast Asia and also a major tourism destination. It has an urban population of 2.5 million, but the population of the metropolitan area exceeds 5 million. The per capita gross domestic product of urban residents was 31,700 RMB[1]/year in 2004 (China Data Online 2006). This is significantly lower than the national average of 37,000 RMB/year, which is indicative of western China's lagging economy, compared to coastal areas.

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[1] 8 RMB=1 USD

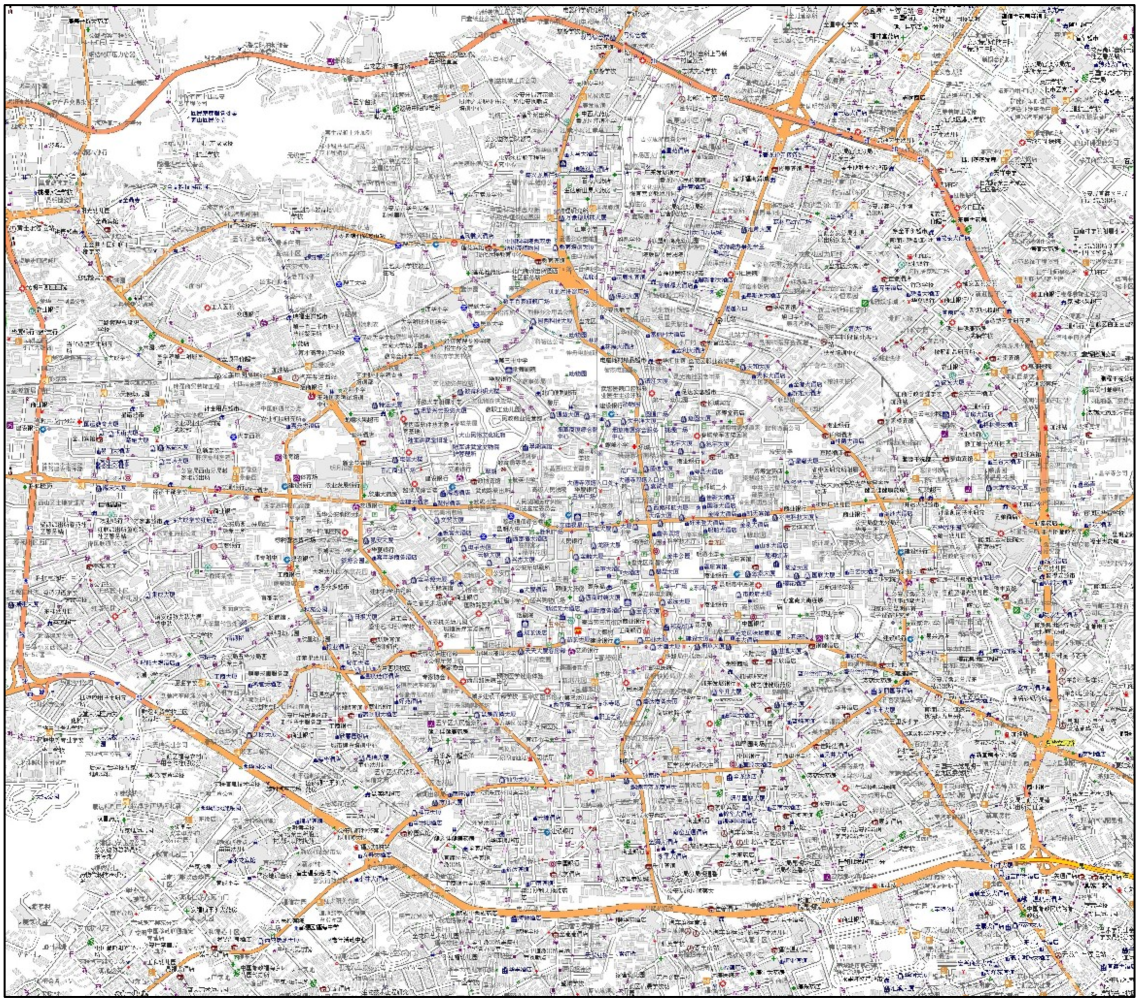

Figure 2.3: Map of Kunming

Although it has no urban rail transit system, Kunming was the first city in China to build a bus rapid transit system (Joos 2000; Kunming Urban Traffic Research Institute 2004). Its road network features three east-west arterials, four north-south arterials, and two ring roads. A third ring road is currently under construction. Motorcycles are prohibited within the first ring road and trucks and rural vehicles are prohibited within the second ring road (with some exceptions).

The municipal area of Kunming contains about 45 passenger vehicles/1000 people (National Bureau of Statistics 2005). The mode splits for all trips in Kunming are shown in figure 2.4 (Kunming University of Science and Technology 2003; Li 2006). Non-motorized modes, bicycle and walk trips, clearly dominate. The data presented in Figure 2.4 classifies electric bikes as a non-motorized mode, or a bicycle.

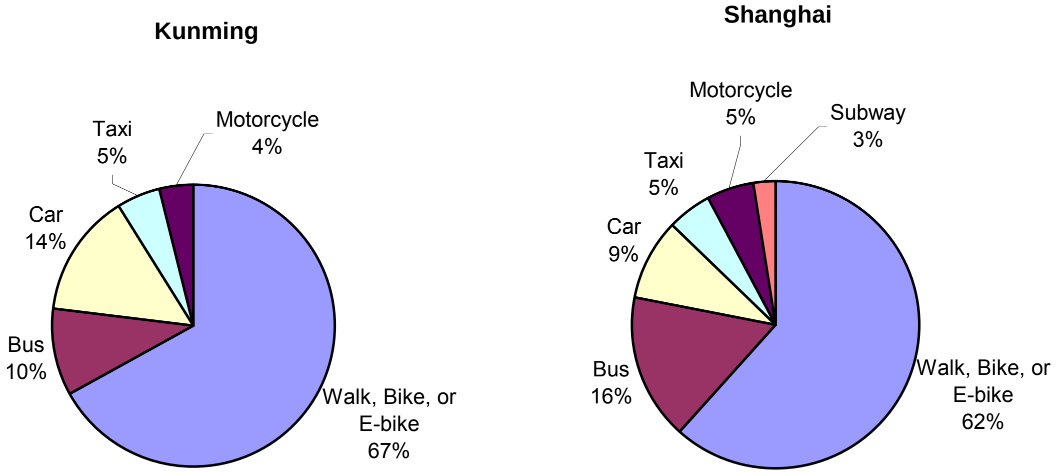

Figure 2.4: Mode splits for all trips in Kunming (2003) and Shanghai (2006)

2.2.2 Shanghai

Shanghai is one of China's megacities, and the municipality is one of the four municipalities that is classified on the prefecture level (Figure 2.5). With an official urban population of a 13 million in 2004, some estimate the entire municipal region to contain 20 million inhabitants. Shanghai's economy was boosted in the mid 1980's when the central government invested in and developed it as a major economic hub. Since then, Shanghai has become the industrial and economic center of China. The per capita GDP exceeded 57,000 RMB/year in 2004, making it one of the most productive regions in China.

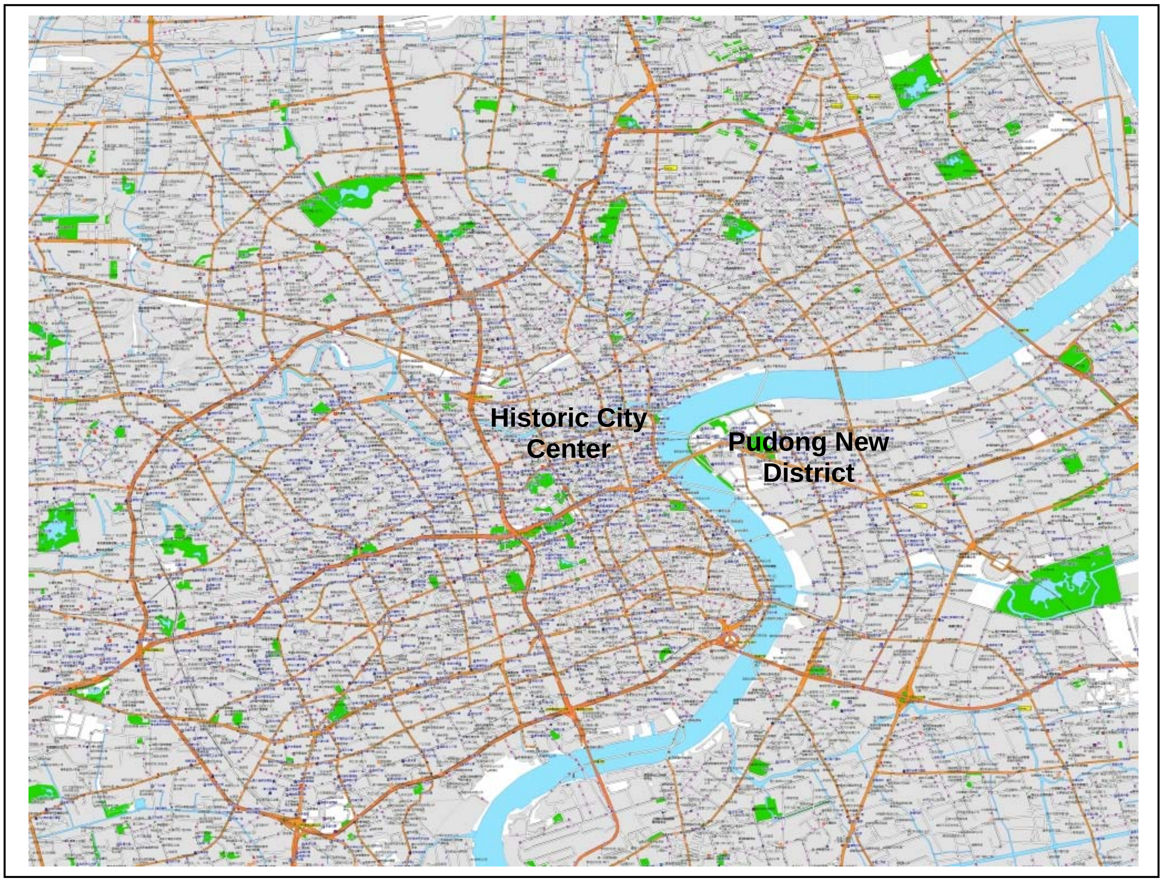

Figure 2.5: Map of Shanghai

Shanghai's transportation system consists of two major grade separated ring roads and a north-south and east-west elevated highway crossing the center city. The city center is composed of a highly dense historic road network. Pudong, on the east side of the Huangpu River is being developed as the new financial center of Shanghai, with a superblock arterial grid pattern in addition to new subway service. Pudong is connected to the west bank by tunnels, bridges, subways and ferries. Shanghai currently has four metro lines, primarily serving the historic city center, Pudong, and the northern and southern suburbs. Shanghai is undergoing a massive infrastructure development plan for the 2010 World Fair. This plan will expand the existing rail network to a total of 311 km, where 30% of the city and 50% of the population will be within a 600 meters of a station.

The recent mode split is displayed in figure 2.2. Motorcycles are also heavily restricted in Shanghai's city center. Shanghai's private car ownership rate is 47 passenger vehicles/1000 people, which is considerably lower than some Chinese cities because of rationed vehicle registrations and license distribution and high registration fees (National Bureau of Statistics 2005). When Shanghai's taxi fleet converted to LPG, the infrastructure became available for the growth of LPG scooters. As a result, Shanghai is the only city in China where LPG scooters have gained a significant share of the market. They are not restricted from the city center and are required to operate in the bicycle lane.

2.3 Data

Through partnerships with Tsinghua University, Tongji University, Kunming University of Science and Technology and electric bike industrial partners, primary and secondary data were collected to conduct the research outlined above. Secondary data sources, particularly for environmental impacts, and bus operations come from statistical yearbooks, electronic databases, and transit agencies. Primary data were collected, including interviews with electric bike manufacturers, public security bureaus, surveys of bicycle and electric bike users, and floating vehicle speed studies. Table 2.1 shows the main data collected and sources.

Table 2.1: Data, Units, and Sources

	Data	Units	Source
Local City Level Data for Case Study	Energy Mix (local power network)	%coal, %gas, %hydro	(National Bureau of Statistics 2005)
	Power Plant Emission Factors	µg pollutant/kWh by pollutant	(Energy Foundation China 2005)
	Power Plant Locations	latitude and longitude for GIS	(International Institute for Applied Systems Analysis, World Bank et al. 1999)
	Population distribution	GIS (population/county)	(All China Marketing Research Co. Ltd. 2003)
	Job distribution	GIS (population/county)	(All China Marketing Research Co. Ltd. 2003)
	Battery Recycling rates	% of batteries from virgin or recycled lead	(Mao, Lu et al. 2006)
	Crash Rates	fatality and injury per million veh km	Local Public Security Bureaus
	Average Speed by Mode	km/h by mode (bicycle, e-bike, bus)	GPS/GIS floating vehicle travel time study on major corridors, transit agencies
	Mode Shift	% of e-bike users who otherwise use bicycle/transit	travel survey
	Average e-bike and bicycle use per day	vkt per day	travel survey
Production Data	Electricity Use per e-bike and bicycle	kWh per year and vehicle production per year	Interview managers of major components of bicycles and electric bike
	Energy Mix (East China Power Network)	%coal, %gas, %hydro	(National Bureau of Statistics 2005)
	Energy Intensities of production processes	Tonne Coal Equivalent (tce)/ton product	(National Bureau of Statistics 2005),(Lawrence Berkeley National Laboratory 2004)
	Emission Factors (East China Power Network)	µg pollutant/kWh by pollutant	(Energy Foundation China 2005)
	Power Plant Locations (East China Power Network)	latitude and longitude for GIS	(International Institute for Applied Systems Analysis, World Bank et al. 1999)

Vehicle production processes and energy use are obtained from partnerships in the electric bike industry. Yearly power and resource usage can be divided by yearly output and a production function can be developed for each electric bike produced. Detailed material inventories are collected and the energy and emissions of those materials for each vehicle are calculated using statistical yearbook data. From these data, energy use and emissions during the production process can be estimated.

Emissions of Chinese power plants have been documented along with scenarios for future fuels and technologies. Greenhouse gas emissions and conventional pollutants such as CO, SO_2, NO_x, and particulates are considered because their public health effects and treatments vary. Provinces generate electricity from different power sources. The National Bureau of Statistics (2005) keeps yearbook data on the proportion of power generated by various means for all provinces and major cities in China. Using the combination of power generation mix and emissions from each type of power generation by province or city (or power network at a more aggregate level) can aid in the decision making process to determine how much electricity is used and the conventional and greenhouse gas emissions generated per kWh, which can be translated to emissions per vehicle kilometer traveled by region and growth scenario.

Energy and emissions data should be considered for each of the alternative modes available to the user. This includes both production and operating pollution. Since this research will consider the primary shift from bicycle and bus to electric bicycle, I explicitly investigate the production cost of traditional bicycles and buses, using the same methodology as that used to calculate electric bike impacts.

Lead loss rates are quantified in Mao et al. (2006) Formulations proposed by other researchers to quantify the effects on public health, such as the increase in hospitalization as a function of distance to a recycling plant (Cortes-Maramba, Panganiban et al. 2003), can be generalized in the Chinese case; considering various changes in recycling, disposal and battery technology.

Safety records are collected, but data is often reported in aggregate number of fatalities. Estimates of exposure are extrapolated by converting these totals into a rate (fatalities/million vkt), using survey data for annual vehicle kilometers traveled by mode. From these data, estimates of safety impacts can be determined by considering shifts between modes.

Many of the factors that are required for the above analysis require information on electric bike use characteristics, particularly average trip length and number of trips, and thus daily VKT. Additionally, information on alternative mode choice is required to evaluate the impact of electric bike regulation. These metrics are identified through a travel survey conducted in Shanghai and Kunming (see Appendix A). This survey includes questions related to:

1) Demographic information
2) Origins and Destinations of all daily trips
3) Trip purposes
4) Average travel time and costs of trips
5) Other modes available
6) Alternative mode if current mode were unavailable

Spatial distribution of jobs and housing is provided in GIS format from academic partners in China. These data are average residential and job density in a census tract in Shanghai and residential and job points in Kunming. Both maps represent the same information. Bus routes and headways are attained from bus agencies. Bicycle and electric bike travel times are collected using a GIS/GPS based floating vehicle speed study. These data feed into the accessibility analysis. Specific descriptions of data collected are included in the subsequent chapters.

CHAPTER 3: USE CHARACTERISTICS AND MODE CHOICE BEHAVIOR

In order to understand characteristics of users of electric bikes and other modes in the choice set, a survey of two-wheeled vehicle users was conducted in a Chinese megacity-Shanghai and in a medium sized city-Kunming. This chapter discusses the results of two surveys of electric bike, traditional bicycle, and liquefied petroleum gas (LPG) scooter users carried out in these two cities. The first section presents transportation and demographic information on both cities. This is followed by a discussion on the survey methodology and sampling approach. The results of the survey and descriptive statistics of electric bike users in these cities are then discussed. Next structural models that predict mode choice based on user and mode characteristics and stated preference responses are presented. The final section of this chapter discusses conclusions and policy inferences.

3.1 Survey Methodology

Two surveys were conducted in Kunming and Shanghai in early April 2006 and late May 2006, respectively. See Appendix A for a sample survey form. The surveys targeted electric bike and bicycle users. In the case of Shanghai, LPG scooter users were also surveyed. The survey contained two parts, a travel diary for the previous day's travel, which asks information about trip origins and destinations, travel times and alternative modes. The second part asks household and individual demographic and attitudinal questions. The surveys for all modes and both cities are identical, except for a few location and mode specific differences. Conducting a random household survey in China is logistically and institutionally difficult. As a result, targeted intercept surveys were conducted at locations that contain a representative sample of urban two-wheel vehicle users, specifically centralized parking facilities of major activity centers and trip generators throughout the urban area. These activity centers contain employment, social activities, and shopping that serve all demographic groups. In both cities, university students were hired from local universities to conduct the survey.

3.1.1 Location

In Kunming, surveyors were stationed at five major trip generators in the city center and around the 1st ring road. These locations included major shopping centers that cater to all demographics of users as well as centralized bike parking facilities surrounding a large pedestrian mall in the center of the city that contains shopping, entertainment, and employment. Importantly, most of the survey sites were within the gas motorcycle restricted zone.

A similar approach was taken in Shanghai. Surveyors were positioned at six major trip generators throughout the city, including locations in city center, Pudong, and residential districts. Additionally, several of the survey sites were also near subway stations, so some respondents utilized two-wheeled vehicles to access the subway. Again, locations were chosen that served all demographics. Shopping centers often have a major "anchor" store and dozens of other smaller stores surrounding the anchor, all served by a centralized bike parking lot. Often the bike parking lot has capacity to store thousands of bikes.

3.1.2 Sampling

Since bicycle parking is rarely free, most bike parking lots have a single entrance or exit point, where parkers can pay the attendant. Surveyors were instructed to position themselves at the entrance of the parking lot and ask every adult entering, regardless of age or gender, if they would participate in the survey. If people arrived while completing a survey, they would skip those individuals and ask the first person arriving after he or she returned to the gate. This sampling method minimized bias. Surveyors conducted the survey during the middle of the week, from Tuesday to Friday, so that the previous day travel diary would represent a "typical" weekday (Monday to Thursday) and during the periods of heaviest activity, from mid- morning to evening. After the survey was completed, survey respondents were offered a small gift (parking fee payment) as a token of appreciation. In Shanghai, 696 responses were collected and in Kunming, 502 responses were collected.

3.2 Survey Results

3.2.1 Descriptive Statistics

Overall, people who use bicycles, electric bikes, and LPG scooters come from similar populations. There are some differences between household characteristics, particularly wage, household income, and education. Table 3.1 shows the household demographics of bicycle, electric bike and LPG scooter users in Shanghai and Kunming.

Table 3.1: Demographics of Two-Wheel Vehicles Users in Kunming and Shanghai

Shanghai

		Mean value of:				
	Gender (% F)	Age **	Education (index)[1] ***	HH Income (RMB)[2]*	Wage (RMB)*	HH Size
Bicycle	41%	35.3 (14.7)	2.424 (1.235)	52626 (29756)	2080 (1722)	3.49 (1.13)
Electric Bike	41%	36.4 (12.8)	2.352 (1.111)	59209 (29418)	2563 (1862)	3.70 (1.27)
LPG Scooter	29%	38.2 (11.1)	2.623 (1.131)	66000 (29572)	3270 (1779)	3.56 (1.23)

Kunming

		Mean value of:				
	Gender (%F)	Age	Education (index)*	HH Income (RMB)*	Wage (RMB)*	HH Size
Bicycle	50%	34.2 (12.0)	2.293 (1.010)	29761 (16774)	1652 (1022)	3.47 (1.41)
Electric Bike	51%	33.1 (9.6)	2.551 (1.003)	37734 (19411)	1905 (1101)	3.47 (1.22)

Note: t-statistics were calculated to identify differences between samples
* P<0.05 all modes different **P<0.05 bike-lpg different ***P<0.05 ebike-lpg different
Note: Standard deviation in parenthesis
[1] In calculating the index, the following ordinal values were used: less than high school (1), high school (2), some college (3), college degree (4), and graduate study (5)
[2] Stated yearly income of all workers in the household
[3] Monthly wage of individual survey respondent

The Shanghai survey included LPG scooter users, which were significantly different than bicycle and electric bike users on most metrics. However, bicycle and electric bike users are significantly different only in wages and household income. The majority of bike, electric bike and LPG scooter users are male, in the mid 30s. There is no statistical difference between the education of bicycle and electric bike users although LPG scooter users have significantly higher education than electric bike users. Household income and wage are significantly different across all modes, with LPG scooter users having higher incomes than electric bike users and bike users as expected.

Kunming does not have LPG scooters and there was a much more notable and significant difference between the demographics of bike and electric bike users, particularly education and income. There was about a 50% gender split for both modes and users were in their mid 30’s on average. The education and income metrics were all significantly higher for electric bike users than bicycle users

Household vehicle ownership rates of survey respondents are shown in Table 3.2. As expected, the household ownership of vehicles who were responding to the survey were significantly higher than those who were not (i.e. bicycle ownership of bicycle respondents is much higher than bicycle ownership of non-bicycle respondents). Surprisingly, in Shanghai there is no statistically significant difference in car and motorcycle ownership between modes, despite progressively higher incomes of electric bike and LPG scooter users. This is most likely due to Shanghai’s restrictions on automobile registration and ownership. Owners of LPG scooters have more electric bikes in their household than bicycle users.

In Kunming, electric bike users have more than twice the amount of cars available to the household than bicycle users, which is likely the effect of higher incomes. The car ownership of electric bike households is 75 vehicles per 1000 people, which is about the same as the city average.

Table 3.2: Household Vehicle Ownership Levels

Shanghai					
Surveyed User:	Average number of vehicles in the household:				
	Car	Motorcycle	Bicycle**	Electric Bike*	LPG Scooter***
Bicycle	0.140 (0.378)	0.234 (0.487)	1.504 (0.886)	0.187 (0.409)	0.259 (0.493)
Electric Bike	0.155 (0.363)	0.163 (0.402)	0.737 (0.807)	1.060 (0.573)	0.223 (0.463)
LPG Scooter	0.156 (0.380)	0.228 (0.425)	0.731 (0.749)	0.269 (0.458)	0.946 (0.562)
Kunming					
Surveyed User:	Average number of vehicles in the household:				
	Car*	Motorcycle	Bicycle*	Electric Bike*	
Bicycle	0.111 (0.359)	0.151 (0.386)	1.452 (0.988)	0.432 (0.039)	
Electric Bike	0.257 (0.544)	0.178 (0.462)	0.782 (0.913)	1.234 (0.028)	

Note: t-statistics were calculated to identify differences between samples
*P<0.05 all modes different, **P<0.05 bike and others different, ***P<0.05 LPG and others different
Note: Standard deviation in parenthesis

3.2.2 Travel Behavior

Differences in mode share have significant impact on travel demand, road capacity, environmental impacts and in the long term, urban form. As travelers choose faster modes, trip length and frequency will likely increase, creating more demand on the transportation infrastructure. Faster speeds also promote the spatial separation of land uses. Alternatively, people may choose modes like electric bikes to provide “easier” mobility, not necessarily to travel faster or more or access more destinations.

The surveys asked travelers to list characteristics of their previous day’s travel by bicycle, electric bike, or LPG scooter. Questions were asked related to trip purpose, modal choice set, primary alternative mode, previously used modes, trip length, and travel time. Table 3.3 shows the characteristics of travel by each mode.

Table 3.3: Travel Characteristics, Surveyed weekday (April-May 2006)

Shanghai

	Number of Trips[1]	Average Trip Lengths (km):			Average trip:		
		Total Trips[2]*	Work Trips***	Other Trips	Travel Time (min)[3]	Speed (kph)[4]*	Weekday VKT[5]
Bicycle	2.06	4.29 (4.39)	4.94 (4.86)	4.07 (4.21)	26.31 (22.35)	11.38 (7.07)	8.84
Electric Bike	2.00	4.83 (4.25)	5.66 (4.37)	4.50 (4.16)	25.56 (18.75)	13.04 (7.25)	9.66
LPG Scooter	2.06	6.64 (5.96)	7.78 (6.77)	6.16 (5.53)	28.75 (19.81)	14.57 (7.94)	13.68

Kunming

	Number of Trips	Average Trip Lengths (km):			Average trip:		
		Total Trips*	Work Trips	Other Trips	Travel Time (min)	Speed (kph)*	Weekday VKT
Bicycle	2.23	3.38 (1.91)	3.54 (1.79)	3.28 (1.97)	22.95 (12.29)	10.45 (5.74)	7.54
Electric Bike	2.54	3.63 (2.08)	3.75 (2.06)	3.55 (2.09)	20.28 (11.29)	11.85 (5.90)	9.22

Note: t-statistics were calculated to identify differences between samples
* P<0.05 all modes different **P<0.05 bike and others different ***P<0.05 LPG and others different
Note: Standard deviation in parenthesis
Note: All distances in kilometers

[1] Trip number is defined as a one way trip, so a trip to work and back would constitute two trips. The number of trips should be at least two for any travel diary that had any trips. A few of the respondents reported no trips on the previous day.

[2] Estimated network distance from stated origin and destination

[3] Stated total travel time of trip estimated by respondent

[4] Average Speed is calculated as the measured trip length divided by the stated travel time of trip

[5] Total VKT (vehicle kilometers traveled) is total trip length times the number of trips.

The trip length is calculated as the network distance between stated origins and destinations. The trip lengths increased, corresponding to increases in speed, with LPG scooters taking the longest trips and bicyclists taking shorter trips. In Shanghai, the work trip length is about 20% longer than the length of other trips. In Kunming, the work trip length is not statistically longer than other trips. This could be because of Kunming's compact development and relatively short commute distance, compared to Shanghai.

When considering economic productivity, the total number of vehicle hours spent traveling (VHT) is an important metric to understand how much productive time people lose while commuting. The travel time from origin to destination is *stated* for each trip and interestingly, there is no significant difference in *perceived* travel time between modes (implying increased speed). This is consistent with time budget theory stating people are willing to accept thresholds of travel time and people will choose origins and destinations based on the maximum travel time they are willing to accept, not necessarily based on distance. This question is problematic because people often know and report door-to-door travel time. This includes access and egress time, which would have the effect of underestimating on-vehicle speed of faster modes. Also, people often round to the nearest 5-minutes and given the short trip distances, estimates of speed from stated travel time could be biased. Even with these considerations, the stated speeds of electric bikes are higher than bicycles by 15% and 10% in Shanghai and Kunming, respectively. LPG scooters in Shanghai are 12% faster than electric bikes. A floating vehicle travel time study conducted in Shanghai and Kunming compared bicycle and electric bike speeds and showed a 30-35% increase in average speed of electric bikes over bicycles.

Perhaps the most important metrics related to externalities generated by two-wheeled vehicles is the daily vehicle kilometers traveled (VKT) and vehicle hours traveled (VHT). Daily VKT is usually associated with roadway capacity needs, pollution, energy use and safety. As expected, the VKT of electric bikes is 9% and 22% higher than bicycles in Shanghai and Kunming, respectively. The daily VKT of LPG scooters is 41% higher than electric bikes in Shanghai. This increase in VKT could be an indication that travelers of higher speed modes choose to travel farther or more to access more destinations. It could also be a result of self selection, that is, people who were already traveling far on a previous mode switched to electric bikes or LPG scooters because of their distant travel, i.e. they are not traveling any farther than before, just faster.

Interestingly, the average lengths of all trips are significantly different among all modes, but the average trip length of work trips between electric bikes and bicycles in both cities is not significantly different. This indicates that most of the additional VKT is due to traveling farther for non-work trips, or discretionary trips. Work trip length of LPG scooters is significantly higher than bicycles and electric bikes in Shanghai. Trip purpose by mode and city is shown in Figure 3.1, with work trips constituting the overwhelming majority on all modes in both cities.

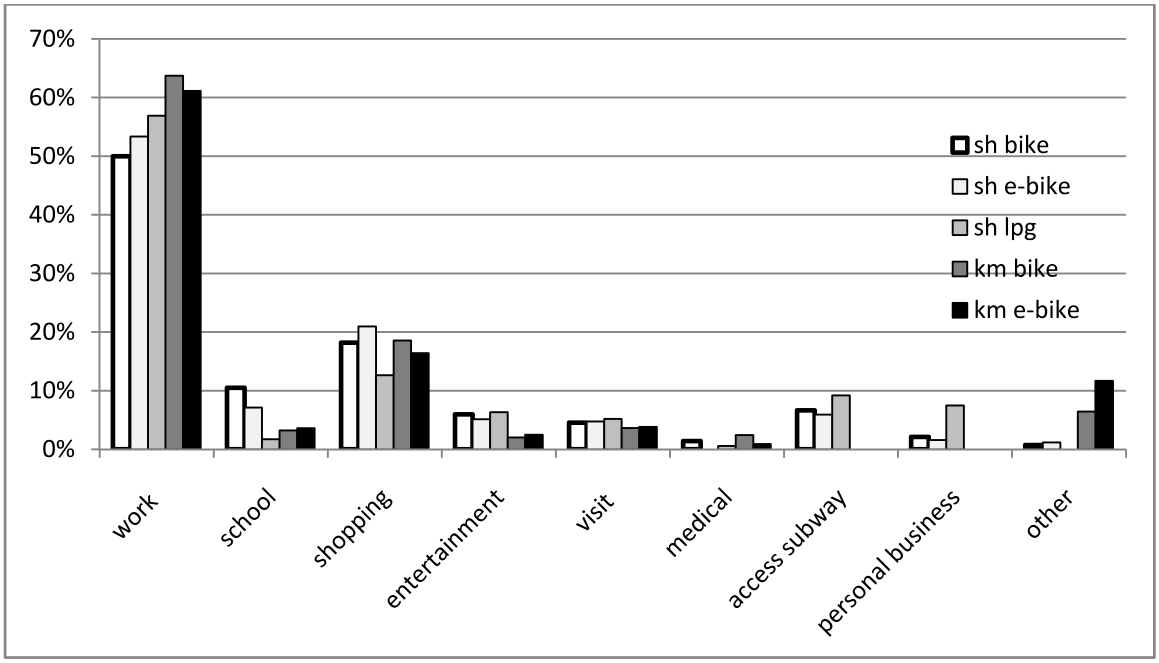

Figure 3.1: Trip Purpose by Mode and City

In order to identify relative impacts of different mode choices, alternative modes must be estimated. Respondents were asked what mode they would take in the absence (or regulation) of their current mode for each trip. Overwhelming, people responded that they would take a bus as the alternative mode, followed by bicycle and walking (Figure 3.2 and 3.3). Of electric bike users, bus is the best alternative for about 55% of trips in Shanghai and 58% of trips in Kunming and bicycle is the best alternative for about 12%

of trips in Shanghai and 21% of trips in Kunming. LPG scooter users are the least likely to choose a bus and most likely to choose a taxi, which is representative of their higher incomes.

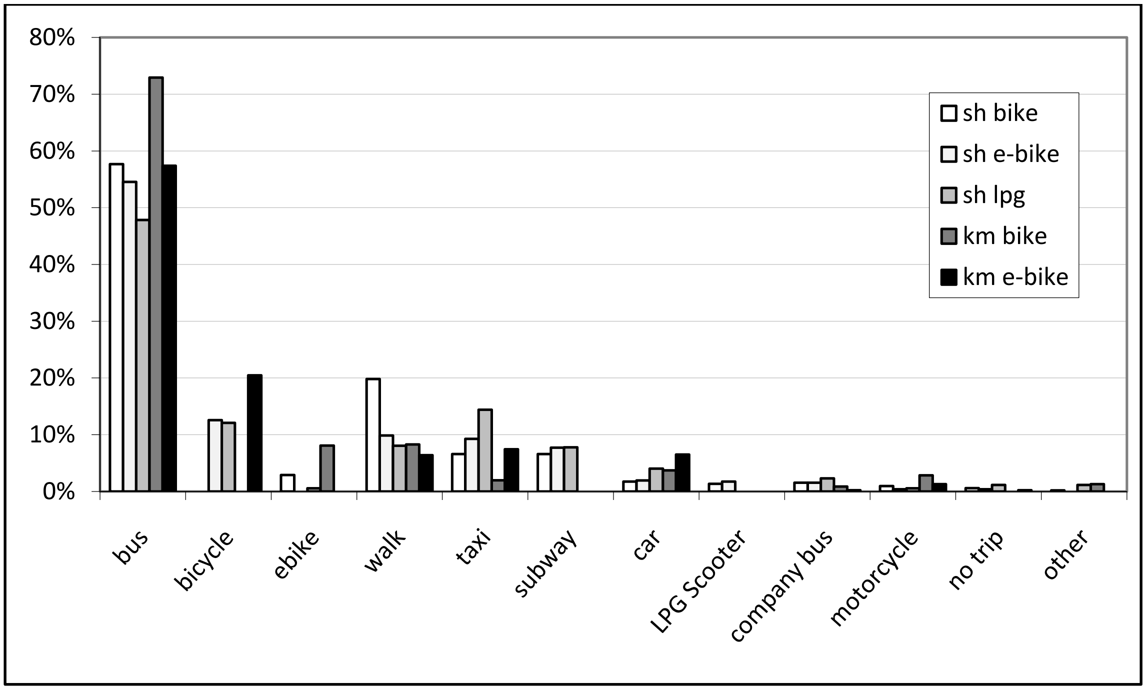

Figure 3.2: What Mode Would You Take Otherwise?

When asked what mode they used before they used their current mode, the most frequent response again was bus. Interestingly, a large portion of electric bike users used to use bicycles for their current trip, but would use bus now if they could not use electric bikes. This implies that a large group of travelers shifted from bicycle to electric bike in place of shifting from bicycle to bus. In most cases, over 50% of the travelers rode the bus before using an electric bike.

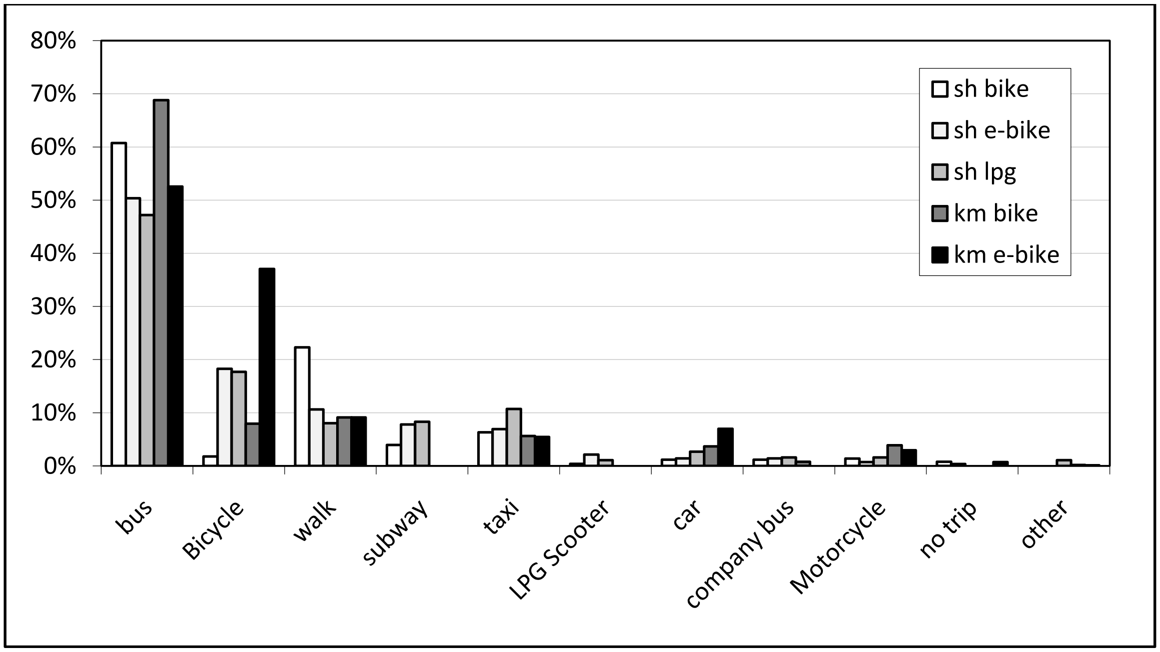

Figure 3.3: What Mode Did You Previously Use?

Knowing the alternative mode is essential when developing policy regarding the regulation of electric bikes or LPG scooters. If banning electric bikes causes a significant increase in bus ridership during peak hours, service expansion may be required resulting in significant public investment. Alternatively, if most people used to and would otherwise use non-motorized modes, little public investment would be required and energy and emission impacts would be significantly reduced.

3.2.3 User Attitudes

Several attitudinal questions were asked in this survey; particularly to find out the reasons people use different two-wheeled modes and what how people perceive electric bikes. When electric bike and LPG scooter users were asked why they chose the mode, most people responded that high speed was a primary reason. Also respondents cited that these motorized modes require less effort than alternative modes, such as bus or bicycle.

Identifying factors that influence attitudes can help explain mode choice. The distribution of responses is shown in Figure 3.4.

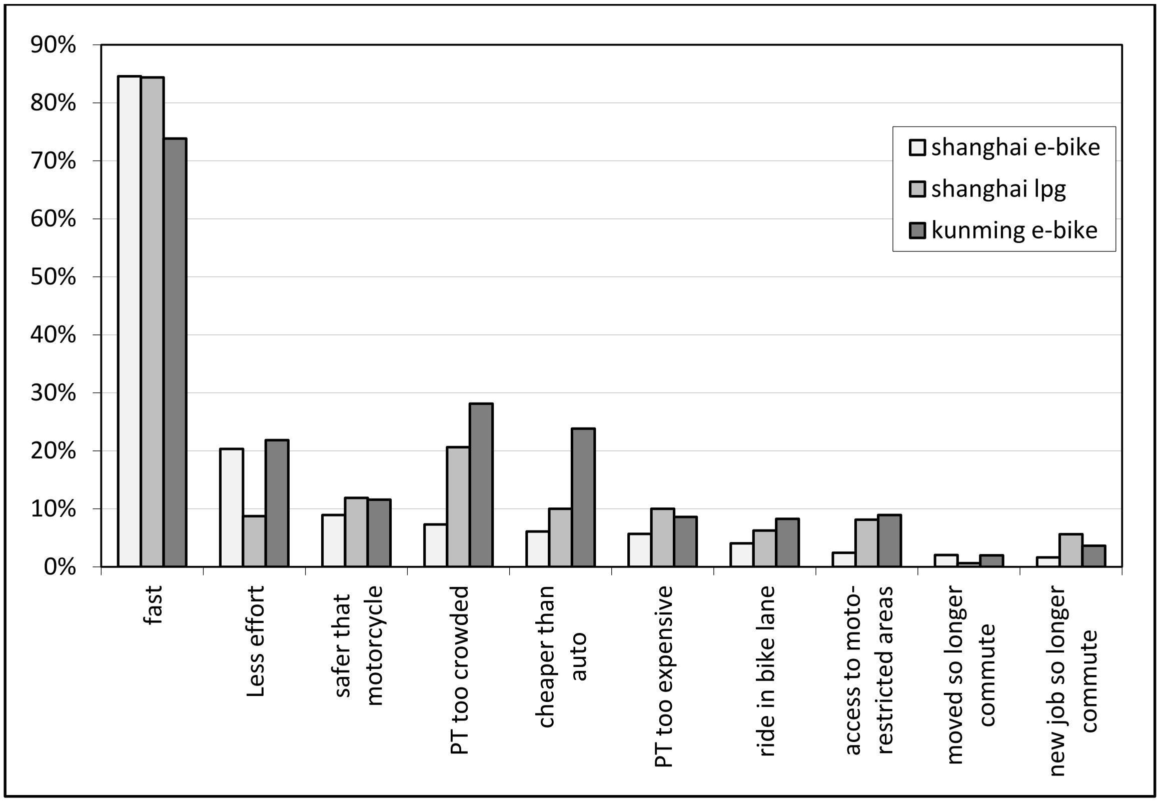

Figure 3.4: Why Did You Choose This Mode?

In order to find out how other users of the bicycle lane perceive electric bikes, respondents were asked if electric bikes should be allowed and developed as a viable mode in the city. Surprisingly, 70% of Kunming bicycle riders and 77% of Shanghai bicycle riders think that electric bikes should be developed more. Over 85% of electric bike and LPG scooter riders think that electric bikes should be developed more. This shows that electric bikes are popular in the bike lane and even bicyclists do not have a poor opinion of them.

3.3 Factors that Influence Two-Wheel Vehicle Choice

In order to gain a better understanding of the factors that influence electric bike use discrete choice models were specified on the survey responses to predict electric bike use based on demographic factors (such as income, age, and gender) and alternative specific characteristics (such as travel time and cost of alternative modes). Two research questions are presented:

1) What factors influence the trip mode choice between electric bikes and bicycles?
2) Given that a user has chosen electric bikes, what factors influence their best stated alternative?

These questions can be represented by the mode choice hierarchy represented in Figure 3.5.

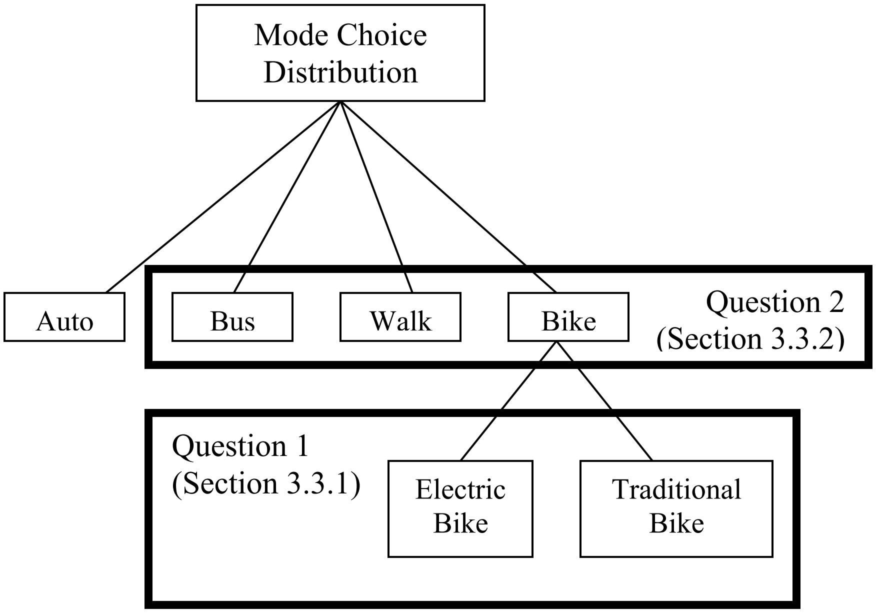

Figure 3.5: Modeling Hierarchy for Discrete Choice Models

In order to answer these questions, discrete choice models were specified on the survey responses. A logit modeling framework was used. In general, the logit model predicts a discrete, unordered outcome (*y*) by a series of explanatory variables (*X*). The general functional form of the logit model is:

$$P_{ni} = \frac{e^{\beta x_{ni}}}{\sum_j e^{\beta x_{nj}}}$$

Where P_{ni} is the probability of individual *n* choosing alternative *i*, and x_{nj} is the vector of observed demographic and alternative based explanatory variables for all alternatives *j*. One of the assumptions of the logit model is independence from irrelevant alternatives (IIA). This assumption allows analysts to model subsets of the choice set. For a thorough discussion of discrete choice modeling techniques and assumptions used in this section see (McFadden 1974; Ben-Akiva and Lerman 1985; Train 2002).

3.3.1 Choice Between Bicycle and Electric Bike

The initial hypothesis was that electric bikes are an intermediate mode on China’s motorization pathway. That is, bicycle riders will evolve into electric bikes and then into other personal motorized modes, particularly cars. The survey discussed above was used to develop a binomial logistic regression of the probability of choosing an electric bike instead of a bicycle. The data were adjusted to represent linked trips into a single home-based trip tour. A tour is defined as a series of trips that begins and ends at home. For example, a trip from home, to work, to the grocery store then back home is defined as three trips linked into a single tour. Each observation in the model is a tour. This removed potential bias from the model in two ways: 1) the level to which individuals were sampled more than once was minimized. For example people make more than 2 trips per day, but most people only make one trip chain, to work and back. The individual specific parameters are therefore independent between choice situations (trips). This reduced the need to correct for this dependence with a mixed logit approach (Train 1998). 2) The dependence between trip links is included within the trip. For example, if a person chose to ride an electric bike to work, the probability of choosing an electric bike to travel home is very high, and not independent of his/her choice to choose an electric bike for the previous trip. Combining all linked trips into a trip tour assumes that the individual makes choice decisions based on the entire trip tour, not just the first link.

The results of the logistic regression are shown in Table 3.4. The bicycle is the base unit of comparison, so the coefficients (β) measure the change in electric bike use relative to choosing a bicycle. Variables related to vehicle performance, user demographics and attitudes entered the model.

Table 3.4: Logit Model for Predicting Probability of Electric Bike Mode Choice

Number of obs = 669
Log likelihood = -170.329 Pseudo R2 = 0.566

Variable	β	Std Error	Z	P>z	Odds Ratio	Std Error
Difference in Travel time for trip tour between bicycle and e-bike (minutes)[a]	0.027	0.013	2.03	0.043	1.028	0.013
Number of e-bikes in household	3.736	0.311	12.00	0.000	41.919	12.550
Number of bikes in household	-0.756	0.203	-3.73	0.000	0.470	0.080
Number of Cars in Household	0.700	0.291	2.41	0.016	2.014	0.703
Pro-ebike attitude (1 if pro-ebike, 0 otherwise)[b]	1.144	0.343	3.34	0.001	3.140	1.137
Perceive mode as low effort (1 if low-effort, 0 otherwise)[c]	1.469	0.490	3.00	0.003	4.347	2.147
Age	0.267	0.065	4.11	0.000	1.306	0.094
Age^2	-0.004	0.001	-3.97	0.000	0.996	0.001
Gender*Age (1 male, 0 female)	-0.077	0.030	-2.54	0.011	0.926	0.028
Gender*Age^2 (1 male, 0 female)	0.002	0.001	2.39	0.017	1.002	0.001
CONSTANT	-3.488	1.206	-4.95	0.000		

[a] This is the total network distance of the trip tour divided by the empirically measured average speed of each mode using a GPS floating vehicle study (Cherry 2006), it does not use the travel time reported by respondents.

[b] Respondents answered a question asking if they think that electric bikes should be encouraged in the city. If they answered favorably, they were coded into the dataset as “pro-ebike”

[c] Respondents stated that one of the reasons they chose a particular mode is because of the low effort required

This model shows that household ownership of various vehicles increases or decreases the probability of choosing that mode. As expected, ownership of an electric bike greatly increases the probability of choosing an electric bike. Bicycle ownership decreases the probability of choosing an electric bike. Car ownership also increases the probability of choosing an electric bike. This could be an indication that electric bikes act as “second cars” for families with multiple wage earners, or that household members are accustomed to personal motorized mobility and thus more likely to use an electric bike instead of a bicycle. It could also be a proxy for household income or value of time. As expected, the respondents who share the attitude that electric bikes should be encouraged and those who value low effort when making mode choices are more likely to choose electric bikes. The older the person is, the more likely they are to choose an electric bike up to a certain point, and then they are more likely to choose a bicycle. This is probably a result of the oldest members of the population unwilling to adopt new technology. Gender enters into the model when interacted with age. The sign on the two interaction variables indicates that the concave curve of electric bike choice as a function of age is flatter for men – that is, across all age categories, men are generally less likely to opt for electric bikes then women. Finally, the longer the trip or the larger the travel time difference, the greater the likelihood of choosing an electric bike.

Factors of note that did not enter the model (due to statistical insignificance) are gender alone, city (dummy variable), household income, household size, level of education, trip purpose and monetary trip cost. These are important findings, particularly the non-appearance of a fixed-effect city variable and monetary cost variable. The failure of the relationships of difference between cities suggests the results could be generalizable to other similar Chinese cities, regardless of local GDP. Also, bicycle and electric bikes users do not pay a large out-of-pocket marginal cost when making a trip or tour. The major cost of operating a bicycle is largely a one time purchase price and the cost of operating an electric bike is paid monthly through electricity bills and when batteries are replaced, normally every year or two.

Electric bikes were oversampled to gain an adequate number of electric bike responses, while not requiring an overly large sample of bicycles. Of the final sample of 669 trip tours that entered the model, 183 were bicycle trips and 486 were electric bike trips. The true ratio of bicycles to electric bikes is about 4.5:1 in Shanghai and Kunming. Choice based sampling causes biased estimates of the alternative specific constants and is corrected by the following equation (Train 2002):

$$\alpha_j^* = E(\hat{\alpha}_j) + \ln(A_j / S_j)$$

Where α^*_j is the true constant and $E(\alpha_j)$ is the biased estimated constant. The true population proportion for alternative j is A_j and the sampled proportion is S_j. The constant presented in Table 3.4 represents this adjustment.

3.3.2 Choice of Alternative Mode

A very relevant question to determine environmental impacts of electric bike policy is determining the alternative mode in the absence of electric bikes through regulation. If electric bikes are banned, the implications of environment costs and mobility benefits are very dependent on the alternative mode. A fixed-effects logit model was specified to understand factors that influence a traveler's choice of a low cost alternative mode. Again, trips were categorized into trip-chains and the entire trip chain was modeled as an independent observation. The problem of over-sampled individuals was reduced using this technique. In this case, the three low-cost modes, bus (60%), bicycle (16%), and walk (6%), with the highest response rate among electric bike users for specific trip chains were included in the choice set. The model is shown in Table 3.5. Walk trips were set as the base case, so the coefficients (β) measure the change in bus or bicycle use relative to choosing to walk. The cost of the trip did not enter significantly into this model primarily because the marginal cost difference observed by users is small for all modes.

Table 3.5: Logit Model for Predicting Probability of Current Electric Bike Users Switching to Bus, Bicycle, or Walk if Electric Bikes Became Unavailable

Number of obs = 423
Log likelihood = -298.29 Pseudo R2 = 0.3396

Variable	β	Std Error	Z	P>z	Odds Ratio	Std Error
Alternative Specific Constant-Bus	1.628	0.352	4.62	0.000	5.094	1.794
Alternative Specific Constant-Bicycle	-3.034	1.542	-1.97	0.049	0.048	0.074
Trip Chain Travel Time (min)[a]	-0.042	0.010	-4.07	0.000	0.959	0.010
Age of Bicycle Choosers	0.173	0.086	2.01	0.044	1.189	0.102
Age^2 of Bicycle Choosers	-0.003	0.001	-2.27	0.023	0.997	0.001
Perceive Public Transit is Crowed (1 if PT Crowded, 0 otherwise)-Bus Choosers[b]	2.172	1.028	2.11	0.035	8.774	9.016
Perceive Public Transit is Crowded (1 if PT Crowded, 0 otherwise)-Bicycle Choosers[b]	2.306	1.055	2.19	0.029	10.033	10.581
Pro-ebike attitude (1 if pro-ebike, 0 otherwise)-Bus Choosers[c]	0.655	0.332	1.97	0.049	1.925	0.640

[a] For the bike option, travel time was estimated as the total network distance of the trip tour divided by the empirically measured average speed of bicycle mode using a GPS floating vehicle study (Cherry 2006) . Walk times assume 6.5 km/hr walk speed. Public transit agencies provide data on bus travel times that include access and egress time, wait time, transfer time and in-vehicle time for the bus option.

[b] Respondents stated that one of the reasons they chose electric bike is because they perceive public transit to be too crowded.

[c] Respondents answered a question asking if they think that electric bikes should be encouraged in the city. If they answered favorably, they were coded into the dataset as "pro-ebike"

As expected, travel time enters into the model with a negative sign, indicating the greater the travel time of a particular mode, the lower the probability of choosing that mode. Age of prospective bus riders does not significantly enter into the equation, indicating age does not influence the choice between walking and bus riding. Age of bicycle users is significantly positive, while age^2 is negative, indicating that people are more likely to use a bicycle (instead of walk or bus) as they age, up to a point and older individuals become less likely to choose to bicycle. Interestingly, travelers who share the opinion that public transit is too crowded are more likely to take the bus than walk, and slightly more likely to take a bus than ride a bicycle (although this difference is statistically insignificant). Finally, electric bike users who have a pro-ebike attitude are more likely to take the bus in the absence of electric bikes than walk or ride a bicycle.

Unfortunately, this model does not accommodate predictions based on most demographic variables. For the most part, demographic variables, including education, gender, wage, household income, household size, and vehicle ownership were not significantly different from each other across the three choices, with the exception of age affecting bicycle use. The factors that have the greatest influence on mode choice are travel time and attitudinal variables. If policy makers want to influence choice, they should focus on decreasing the travel time of the desired choice.

3.4 Conclusion and Policy Inferences

Electric bike use has grown at extraordinary rates over the past few years and little is known about who uses electric bikes and how electric bike users make mode choices. Policy makers in different cities are treating electric bikes differently. Some cities have embraced them as a low cost form of high mobility, complementing other transportation options. Other cities have pointed to environmental and safety problems and heavily restricted their use or banned them.

In order to develop environmentally sustainable and equitable policy regarding electric bikes, a policy maker has to understand what populations are using electric bikes, how they are using electric bikes and what they would choose in the absence of electric bikes. This research has identified characteristics of electric bike users in two different cities in China, Kunming and Shanghai. Although there are significant socio-demographic differences between these two cities, electric bike use characteristics are similar between them. Electric bike users are generally more educated than bicycle users and have higher incomes. Commuters do not use electric bikes in the same way as bicycles. Electric bike users take more and longer trips in an average weekday than bicycle users and LPG scooter users take much longer trips. The result is increased daily VKT and thus energy use and air pollution, compared to bicycles.

User attitudes also affect the reason people choose electric bikes. Users primarily cite speed, effort, safety, and crowded transit as reasons to choose electric bikes. Interestingly, most bicycle riders do not have a poor opinion of sharing the lane with electric bikes and would recommend developing electric bikes as a mode in the city.

User attitudes, demographics and vehicle performance are all significant factors that influence mode choice in the logit models specified above. The model specified in Table 3.4 predicts the choice between electric bike and bicycle use, based on survey responses in Kunming and Shanghai. Demographic factors such as wage, age, gender and household vehicle ownership all influence mode choice. One of the more significant factors that can be controlled by policy makers through regulation is the difference in travel-time between the two modes. As expected, the higher the travel time difference, the higher the likelihood of choosing an electric bike. Travel time differences are linked to speed, which is a function of congestion levels in the bike lane, network (traffic signal) density, and electric bike performance. Electric bikes are loosely regulated to a maximum speed of 20 km/hr, in which manufacturers rarely comply. As electric bikes become faster, the travel time differential will change and more people will shift from bicycles.

Speed is likely the factor that policy makers have most control over that has the greatest influence on mode choice, either through performance regulation or traffic control. In the cities studied, electric bike users spent a larger portion of their travel time stopped at signals than bicycles, as expected because of their higher free-flow speeds. A way to increase electric bike use would be to consider control strategies that limit the number of stops for both modes, through signal coordination or grade separated intersection crossings, thus increasing the travel time advantage of electric bikes.

Travel time of a trip also significantly influences alternative mode choice. Electric bike users would switch to a bus for most trips if electric bikes were banned from cities. Some cities have made an effort to reduce two-wheeled vehicle traffic by providing high quality transit. Signal priority and exclusive right of way for buses will increase ridership by decreasing travel time.

Factors that influence mode choice are important inputs into policy analysis when attempting to influence travel behavior. This chapter sheds light on this topic so that policy makers can make more informed decisions regarding the regulation or promotion of electric bike use in their cities. The findings of this analysis will help identify the significance of mode specific impacts that will be investigated in the following chapters.

CHAPTER 4: ENVIRONMENTAL IMPACTS OF ELECTRIC BIKE USE

The growth of electric bikes has caused concern for government officials, transportation engineers and city planners who are attempting to promote development of sustainable and efficient transportation in their cities. The environmental impacts of electric bikes are unclear and the benefits they provide to the transportation system are ambiguous. It is clear that they emit zero tail pipe emissions at their point of use and that their overall energy efficiency is higher and emissions per kilometer are lower than gasoline scooters and cars; but most electric bike users might not otherwise use cars or gasoline scooters. The environmental costs of this mode are largely related the alternative mode, should the electric bike be prohibited or restricted. Taiwan promoted and subsidized electric bikes in the 1990's (Chiu and Tzeng 1999) in order to induce a shift away from dirtier gasoline scooters. This chapter presents analysis of the environmental costs of electric bikes and alternative modes and can help inform policy that will affect millions of users.

This chapter begins by discussing the production processes and some of its energy use and environmental characteristics. The following section discusses the environmental impacts of electric bike use and attempt to quantify the largest sources of energy use and pollution. Environmental impact analysis is conducted for dominant alternative modes as a unit of comparison. Exposure differences of urban versus non-urban pollution sources are identified to serve as a proxy for public health effects of air pollution.

4.1 Energy Use and Emissions of Electric Bike Life Cycle

4.1.1 Production Processes

There are hundreds of electric bike manufacturing companies in China, ranging from small assembly factories to large component makers and assembly factories. In order to understand the production processes, five electric bike factories in Shanghai, Jiangsu, and Zhejiang provinces were visited. These factories ranged in production output from 12,000 bikes/year to over 150,000/year. Production capability ranged from simple e-bike assembly (e-bikes are assembled from components produced by other companies off-site), while others produced some main components in-house such as the motor, controller, and frame.

Assembly of an e-bike typically requires one main assembly line where the frame is passed through various stages of assembly until fully assembled. E-bike assembly lines have the capacity to produce one e-bike every 5 minutes. Individual components and processes of the e-bike are produced and performed off-line, such as assembling wiring systems, brake systems and painting.

Through interviews with factory owners and publicly reported statistics on energy use and emissions from the manufacture of raw materials, estimates are made regarding the environmental implications of the production process of electric bikes. To avoid the intensive work of calculating the environmental effect of each process in a factory, the overall energy use of all processes is obtained and included in the energy use calculation. Other estimates of energy use and emissions are made using the weight of raw materials required to produce an electric bike and the energy and pollution intensities of producing those materials in China. Some data are omitted because of lack of availability or the expectation that their impacts are small compared to other impacts.

There are few energy intensive processes associated with the assembly of an electric bike. Almost all energy use is in the form of electricity required to run the machinery of the factory. Perhaps the most energy intensive processes of the assembly process are steel frame construction and painting (large dryers are required). One of the larger e-bike manufacturers in China reports that in 2005[2], they produced 180,000 electric bikes and used 1,278,545 kWh of electricity, or 7.1kWh per bike. The processes included in this value are 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 scale electric bike battery manufacturer was also interviewed regarding energy consumption. The total energy consumption per 12V electric bike battery is approximately 2 kWh, so a 36V battery would require 6kWh and a 48V battery would require 8kWh[3].

The energy required by the assembly process is very small compared to the energy requirements of the raw material manufacturing, such as steel, plastic, and rubber. Table 4.1 is an inventory of electric bike components, the material they are composed of, the weight, and the energy required to produce those products. National statistics and literature on Chinese steel and lead industries are used to calculate the amount of energy used per unit weight of a product are then used to estimate the energy use of the manufacture of a component (Price, Phylipsen et al. 2001; National Bureau of Statistics

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[2] Interview with electric bike factory owner 3-4-2006

[3] Phone interview with electric bike battery factory manager 3-4-2006

2003; National Bureau of Statistics 2004; National Bureau of Statistics 2005; China Data Online 2006; Mao, Lu et al. 2006).

Table 4.1: Material Inventory, Emissions and Energy Use-Electric Bike

Weight of Electric Bike Materials (kg/bike)				
	BSEB		**SSEB**	
Total Steel	18.15	46.1%	26.18	46.5%
Total Plastic	5.67	14.4%	15.22	27.0%
Total Lead	10.28	26.1%	14.70	26.1%
Total Fluid	2.94	7.5%	4.20	7.5%
Total Copper	2.55	6.5%	3.46	6.1%
Total Rubber	1.14	2.9%	1.22	2.2%
Total Aluminum	0.52	1.3%	0.58	1.0%
Total Glass	0.00	0.0%	0.16	0.3%
Total Weight	41.25		65.73	
Associated Energy and Emissions of Manufacturing Processes				
Energy Use (tonne SCE)	0.179		0.261	
Energy Use (kWh)	1456		2127	
Air Pollution (SO2) (kg)	1.563		2.198	
Air Pollution (PM) (kg)	5.824		8.173	
Greenhouse Gas (tonne CO_2eq)	0.603		0.875	
Waste Water (kg)	1488		2092	
Solid Waste (kg)	4.463		7.139	

The weight of each material was estimated using weights of typical components of each style of electric bikes. These components were categorized into materials in which there are readily available data on energy use and emissions.

Several assumptions and omissions were made to develop Table 4.1. This table includes energy and environmental impacts due to the mining and production of ferrous and non-ferrous 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 transportation impacts. The values presented in Table 4.1 should be considered lower bounds. The solid waste only includes solid waste of the production process, not end-of-life waste, which will be discussed later. The numbers above also include the manufacture of replacement parts, specifically five sets of batteries, three sets of tires and two motors over the lifespan of the electric bike[4].

4.1.2 End-of-Life

Because of the relatively recent appearance of electric bikes in the transportation system, little is known about the fate of electric bikes that have become obsolete or non-operational. Many of the earliest models of electric bikes were simply modified bicycles, so if components failed, the electric bike could still operate as a standard bicycle. More recent models would be inoperable if vital components failed. In order to calculate the end of life solid waste, the recyclable components of the electric bike needs to be reduced from the total weight. Additionally, replacement parts must be considered; five batteries, three sets of tires and two motors.

Steel, which is the heaviest component of electric bikes has a high recycling rate, 79.9% in 2002 (National Bureau of Statistics 2003). This is the recycling rate of the entire steel industry, and might not reflect the actual recycling rate of the steel in electric bikes. Likewise the entire copper industry has a recycling rate of 88.5% in 2002. If these materials are recycled and the other materials, including replacement parts of the electric bike enter the waste stream, BSEBs and SSEBs produce 17 and 30 kilograms of solid waste, respectively. This does not include lead waste from batteries, which will be discussed in detail in the following section.

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[4] Personal communication with electric bike manufacturers and their estimation of component reliability

4.1.3 Lead Acid Batteries

Lead acid battery pollution is the most cited reason for regulation of electric bikes by policy makers. Approximately 95% of electric bikes in China are powered by lead acid batteries (Jamerson and Benjamin 2004). Based on interviews with manufacturers and service facilities, the life span of an electric bike battery is considered to be one to two years or up to 10,000 kilometers. BSEBs typically use 36V battery systems, on average weighing 14 kilograms. SSEBs typically use 48V battery systems weighing 18 kilograms. The lead content of electric batteries is 70% of the total weight, so BSEB and SSEB batteries contain 10.3 and 14.7 kilograms of lead, respectively.

This is perhaps the most problematic issue for electric bikes and is the same problem that influenced the demise of electric car development in the United States in the early 1990's (Lave, Hendrickson et al. 1995). Because of the relatively short lifespan of electric bike batteries, an electric 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: 1) Mining and smelting lead ore 2) Battery manufacturing 3) Recycling used lead and 4) Non-recycled lead entering 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 and Hendrickson (1995) cite that, in the USA, 4% (0.04 tons lost per ton of battery produced) of the lead produced is lost using virgin production processes, 1% is lost during the battery manufacturing process and 2% is lost during the recycling process. 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%.

China's lead acid battery system is very different from industrialized countries. Mao et al. (2006) investigated the Chinese lead acid battery system. They found that 27.5% of the lead content of a battery is lost during the mining, concentrating, smelting and recycling process. This value can be broken down into two components, emissions of concentration and primary refining of virgin ore and secondary refining of recycled scrap, which have emission rates of 31.2% and 19.7%, respectively. In addition to these losses, 4.8% is lost during the manufacturing process. The reasons for these very high loss rates are mostly due to poor ore quality and a high proportion of lead refined at small scale factories using outdated technology. The official recycling rate of lead in China's lead acid battery industry is 31.2%. Mao et al. (2006) estimate that the actual number is approximately double that, 62% because of informal, small scale recyclers. This value feeds into the proportion of recycled lead in each battery. The authors indicate that lead in a battery is made up of 22% recycled lead and 78% virgin lead.

Mao et al. uses data from 1999, before electric bike batteries were a significant share of the market. Several of the values (specifically recycling rate) are estimates and could have changed since electric bikes entered the market. In 2004, electric bike batteries constituted 8% of the market, with car and motorcycle batteries comprising 74% of the total battery market (Unknown 2006). Because electric bikes use batteries quickly, some informal recycling and collection practices have developed. In most cases, an electric bike customer can exchange an exhausted battery for ¼ the price of a new battery, or around 60 RMB (US$7.50), which is a significant amount of money in most Chinese cities. The dead batteries are then collected from service centers and sent to lead recycling factories. This institution could increase the average recycling rate of all lead acid batteries. Interviews with factory owners estimate that 85-100% of electric bike batteries are recycled[5].

The values in Table 4.2 are generated using the loss rates presented above. Lead is lost to the environment in three processes. Lead is lost during production in process I, during battery manufacture in process II, and by disposal (lack of recycling) in process III. 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 due to 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 loss rates from previous time periods and increased demand). Mao et al. (2006) estimate 22% recycled content of lead acid batteries, which could be considered a minimum. The manufacture loss is constant, regardless of source material and the recycling rate is estimated based on the official and estimated values.

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[5] Interview with factory owners and managers May 15-18, 2006

Table 4.2: Electric Bike Lead Emissions

		BSEB	SSEB
	Battery Weight (lead content) kg	10.3	14.7
I	**Lead Production Loss (% Recycled Material)**		
	0%	3.21	4.59
	(Mao, Lu et al. 2006) 22%	2.95	4.21
	44%	2.69	3.84
	60%	2.50	3.57
II	**Manufacture Loss**	0.49	0.71
	(Mao, Lu et al. 2006) 4.8%		
III	**End-Of-Life Loss (Recycling Rate)**		
	0%	10.30	14.70
	(Mao, Lu et al. 2006) official 31%	7.11	10.14
	(Mao, Lu et al. 2006) estimate 62%	3.91	5.59
	(E-bike manufactures) 85%	1.55	2.21
	100%	0.00	0.00
	Scenarios (Production, Manufacture, EOL)		
	Scenario A (0%, 4.8%, 0%)	14.01	19.99
	Scenario B (22%, 4.8%, 31%)	10.55	15.06
	Scenario C (44%, 4.8%, 62%)	7.10	10.13
	Scenario D (60%, 4.8%, 85%)	4.54	6.48
	Scenario E (60% 4.8% 100%)	3.00	4.28

In the worse case scenario (A), there is no recycling (all lead is virgin material and all batteries enter the waste stream), a 10.3 kilogram battery (BSEB) and a 17.4 kilogram battery (SSEB) emit 14 and 20 kilograms of lead, respectively. As expected, these values are higher than the lead content of the battery (emissions=battery weight + manufacture loss + production loss). More realistic scenarios B and C assume moderate recycling rates reported by Mao et al. (Mao, Lu et al. 2006). Scenarios D and E assume very high recycling rates as reported by electric bike manufacturers. The actual lead loss is likely between scenario C and D.

A conservative estimate of battery life is up to 300 cycles or 10,000 kilometers. For scenario C, this results in the emission of 710 mg/km of lead for BSEBs and 1013 mg/km of lead for SSEBs. To put this into perspective, a car running on leaded fuel that has a 7.9L/100km (30 mpg) fuel economy emits 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).

4.1.4 Use Phase

Electric bikes are recharged by plugging into standard wall outlets. This is a great advantage because there is no need for dedicated refueling/recharging infrastructure. Most electric bikes have removable batteries and chargers so that they can be transported into an apartment or workplace and recharged during the day or night. With their increased popularity, many apartments or workplaces are retrofitting bicycle parking areas to accommodate electric bikes by providing electrical outlets. Batteries require about 6-8 hours to charge. Charging electric bikes at night can increase the efficiency of the electric power generation network. By recharging batteries overnight, 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 electric bikes have zero tailpipe emissions, they do use electricity, whose generation emits high amounts of conventional pollutants and greenhouse gases, but electric bikes are very cheap and efficient to operate. Most electric bikes have a range of about 50 kilometers on a single charge. Considering an average SSEB with a 350W motor and a 48V 14Ah battery, the electricity requirement is 1.3kWh/100km. This is consistent with manufacturer reporting and requirements. In China, the energy mix is 75% coal, 15% hydro, 8% gas and 2% nuclear (National Bureau of Statistics 2005). The emission factors of typical Chinese power plants are presented in Figure 4.1 (Energy Foundation China 2005). Figure 4.1 shows that wind turbines have zero air emissions during the use phase and it is implied that hydro-electric power plants also have zero emissions during the use phase. This is untrue, since biological processes resulting from flooded and decaying biomass emit greenhouse gases (Pacca and Horvath 2002). Moreover, flooding an ecosystem reduces the net amount of carbon that can be absorbed from the atmosphere, known as the net ecosystem production (NEP). Estimates show that the average greenhouse gas emission rate from flooded biomass in one reservoir is on the order of 20g CO_2/kWh over the lifecycle of the dam. This value depends on a lot of variables, particularly whether the hydro-electric power plant is in an arid environment. For an average electric bike, the resulting emission rate from hydro generated electricity is about 0.3 g/km, a fraction of the emission rate from coal generated electricity, about 13.5 g/km. Because most cities in China are heavily reliant on coal power, the influence of CO_2 emissions from reservoirs is considered negligible.

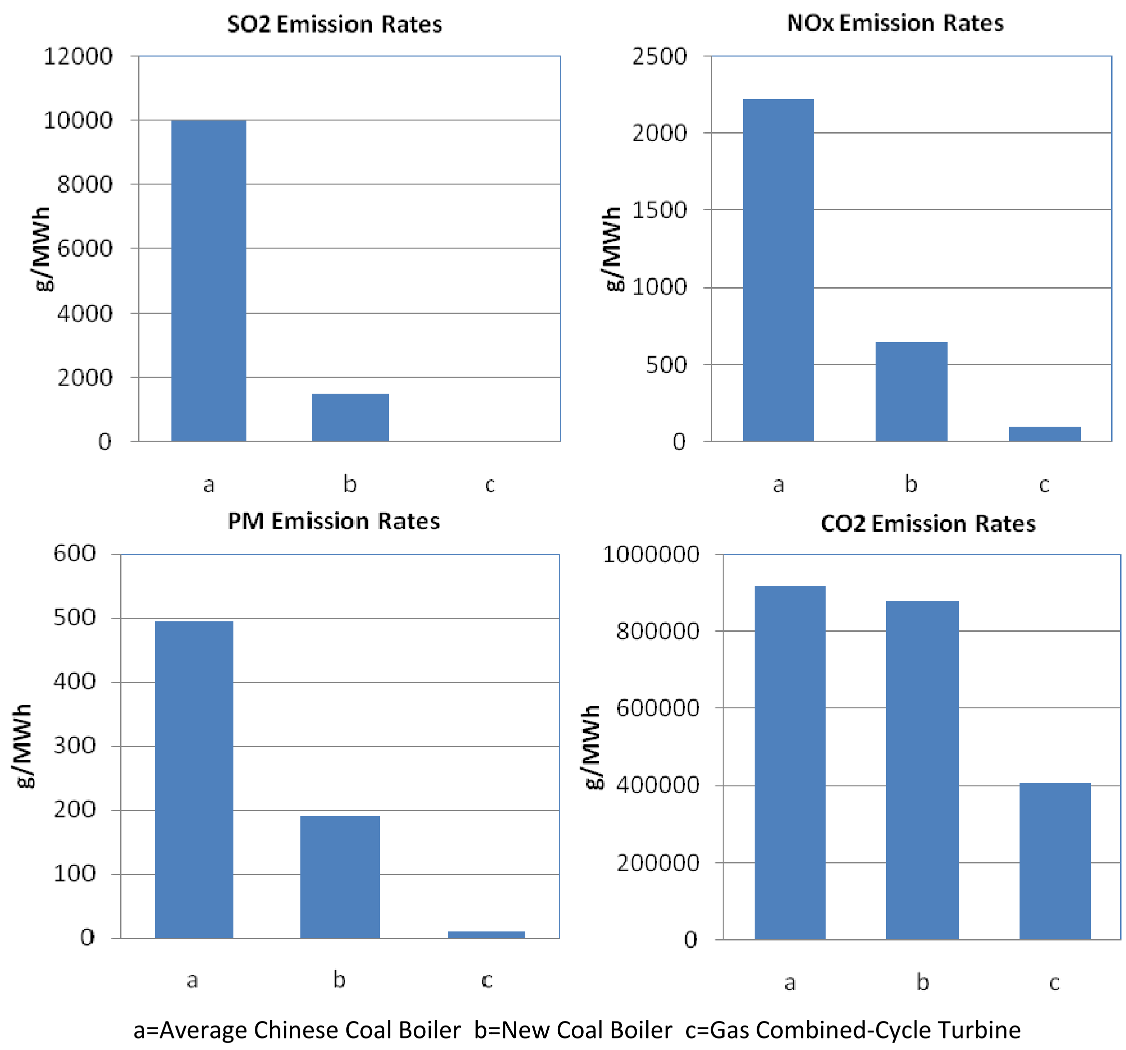

Figure 4.1: Emission Rates from Chinese Power Plants (Energy Foundation China 2005)

Most of China's electricity is generated by coal power plants, but the actual energy mix of a city depends on its region. China consists of 15 power grids that have limited levels of connectivity (Zhu, Zheng et al. 2005). Each of these grids has different energy mixes and each city within a power grid receives most of its electricity from its grid. In order to calculate the pollution due to electricity generation, the energy mix for the grid must be determined. Two examples of cities with high levels of electric bike usage and vastly different energy mix are Kunming and Shanghai. Kunming is located in the Yunnan Provincial Power Grid and Shanghai is located in the East China Power Network, which contains Shanghai Municipality and Zhejiang, Jiangsu and Anhui provinces. The energy mix for the Yunnan Power Grid (Kunming) is 52% hydro power and 48% coal power. The energy mix for the East China Power Network (Shanghai) is 98% coal power and 2% hydro power.

Using the emission factors from Figure 4.1, energy mix, assuming 1.3kWh/100km and including an electricity transmission loss factor of 6.6% and in-plant use rates of 6.1% (National Bureau of Statistics 2005) results in an average energy demand of about 1.5kWh/100km. Some estimates (Lawrence Berkeley National Laboratory 2004) indicate that the actual transmission loss rates might be double those reported by the official statistics, but the official numbers are used here. The emission rate per kilometer traveled is generated and presented in Table 4.3.

Table 4.3: Scooter Style Electric Bike Emissions (g/km)

	Kunming	Shanghai	All China
SO_2	0.066	0.137	0.104
NO_x	0.015	0.031	0.023
PM	0.003	0.007	0.005
CO_2	6.105	12.808	10.063

It is worth noting that these emissions, like all emissions from electric bikes are non-local. 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; Zhou, Levy et al. 2006). This has significant public health benefits compared to modes with same emission rates in urban areas.

4.1.5 Total Environmental Impacts of Electric Bike Lifecycle

Based on available data, previous research and evidence from interviews of members of the electric bike industry, life cycle energy use and emissions estimations are made. These estimations have omitted some factors for which there are no data available and that the authors perceive to contribute little to the total energy use and emissions of the electric bike. Keeping that in mind, the values presented in this and previous sections should be considered a lower bound, but include the most energy intensive processes. The total life cycle energy use and emissions include production processes (mining and manufacturing), vehicle use, and vehicle disposal.

The primary energy use of electric 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, energy density of coal is about 29 GJ/tonne and the energy density of natural gas is about 39 MJ/m^3. The average efficiency of fossil fuel power generation is approximately 33.4% (Lawrence Berkeley National Laboratory 2004). Considering an average SSEB, the primary energy requirements could range from 1.5 kWh/100km for electricity generated exclusively from renewable sources to 4.5 kWh/100km for electricity generated exclusively from fossil fuel sources.

Since electric bikes efficiently convert energy (electricity) into movement, a large portion of electric bike energy use and emissions are expended during the *production* phase, particularly on energy intensive processes such as steel and lead production, the two materials that the electric bike uses the most of during its lifecycle. The *use* phase of the life cycle emits high amounts of SO_2 as a result of electric bikes' reliance on high emitting coal power plants. Figure 4.2 and Figure 4.3 illustrate the proportion of energy and emissions from each process of a typical BSEB and SSEB, respectively. The values on top of the chart display the total energy use or emission of the total life cycle of the electric bike.

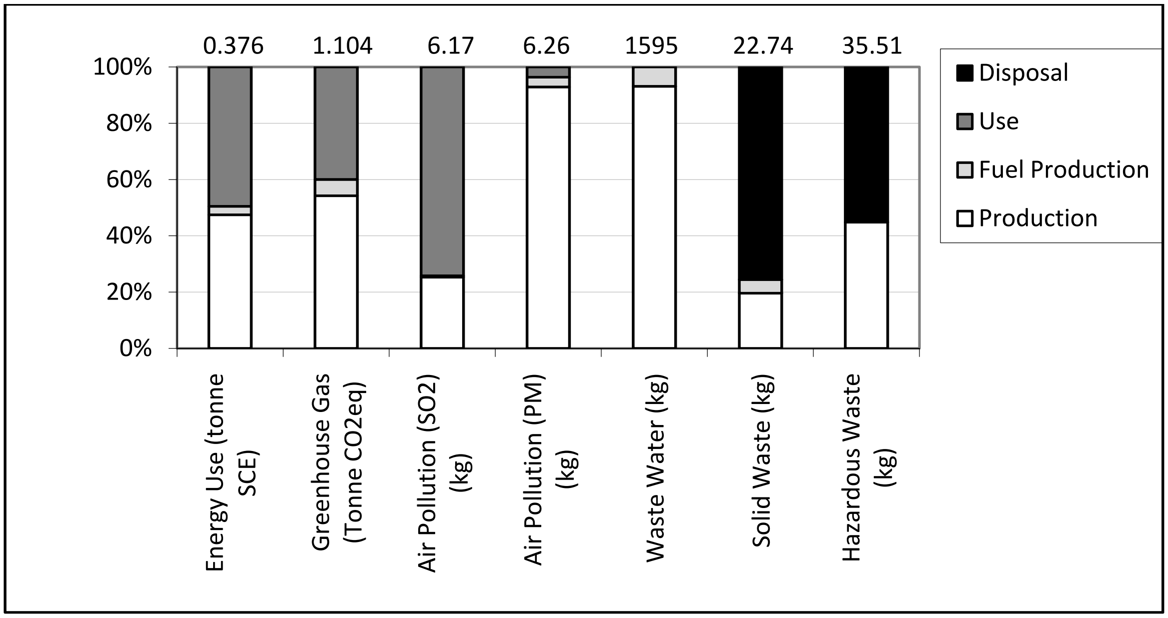

Figure 4.2: Pollution of BSEB Over Lifecycle

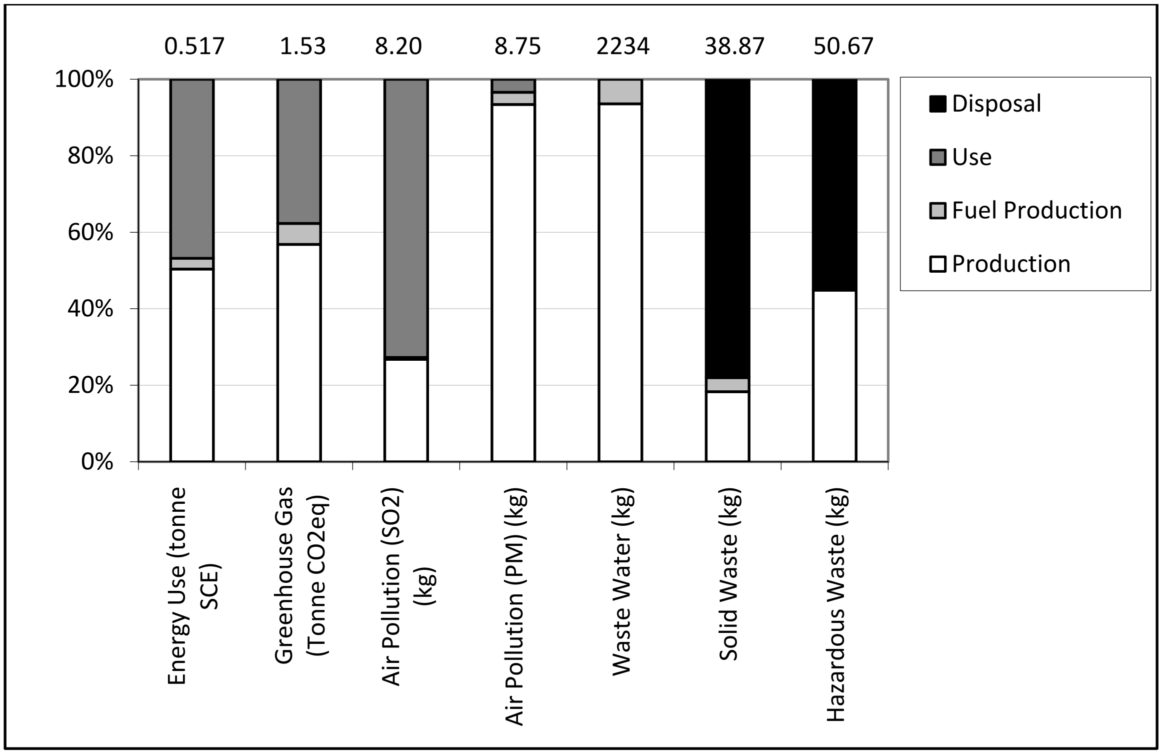

Figure 4.3: Pollution of SSEB over Lifecycle

This is a very different picture than life cycle inventories of personal cars or buses that produce 80-90% of their environmental impacts during the *use* phase (Sullivan, Williams et al. 1998; Danielsson and Gunnarsson 2001).

4.2 Environmental Impacts of Alternative Modes

Life cycle impacts of transportation modes are somewhat meaningless by themselves. For the most part, transportation services are a derived demand. People do not demand transportation services for the utility derived from transportation, but they demand access to locations, goods, services etc. When identifying the environmental impacts of any policy decision, energy use and environmental comparisons must be made between the competing alternatives. Since electric bikes provide a transportation service, the assumption is that the users will make the trip by another mode if the electric bike were not available. User surveys show that predominant alternative modes of electric bike users are public buses and bicycles (Cherry and Cervero 2006; Weinert, Ma et al. 2007). In order to identify the *net* environmental impact of electric bikes, comparisons should be made that show the difference between the same trip made by the competing modes of transportation.

4.2.1 Energy Use and Emissions of a Bicycle

4.2.1.1 Production Phase

The vast majority of bicycle impacts come from the production phase of the life cycle. Most bicycles used in China for commuting are constructed primarily of steel, plastic, rubber and aluminum. Unlike electric bikes, there are no electronic components, batteries, or body components, so the overall weight of a bicycle is significantly lower than a bicycle style electric bike and most of the weight reduction is due to the absence of a battery. Table 4.4 shows the material inventory, emissions and energy use of an "average" city bicycle in China[6].

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

Table 4.4: Material Inventory, Emissions and Energy Use-Bicycle

Weight of Bicycle Materials (kg/bike)		
Total Plastic	2.0	11.1%
Total Rubber	2.0	11.1%
Total Steel	13.0	72.2%
Total Aluminum	1.0	5.6%
Total Weight	18.0	
Associated Energy and Emissions of Manufacturing Processes		
Energy Use (tonne SCE)	0.045	
Energy Use (kWh)	363	
Air Pollution (SO2) (kg)	0.275	
Air Pollution (PM) (kg)	1.176	
Greenhouse Gas (tonne CO_2eq)	0.097	
Waste Water (kg)	393	
Solid Waste (kg)	0.641	

4.2.1.2 Use Phase

The *use* phase of a bicycle's life cycle uses energy in the form of human power. Estimated energy use of moderate bicycle riding (12-14 km/hour) ranges from 15-35 calories per kilometer (reduced by a factor that accounts for calories used while resting). Assuming a 10 year lifespan of the bicycle and 2000 km per year (Cherry and Cervero 2006), this is approximately 600 kWh of energy use over the lifespan of the bicycle. 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 China 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 bicyclists do not intake calories that correspond to the energy needs of riding a bicycle, they just weigh less than non-bicycle riders. If they do require more food consumption, then there could be considerable environmental impacts of producing that food (Ulrich 2006). The proportion of life cycle energy use and emissions is displayed in Figure 4.4.

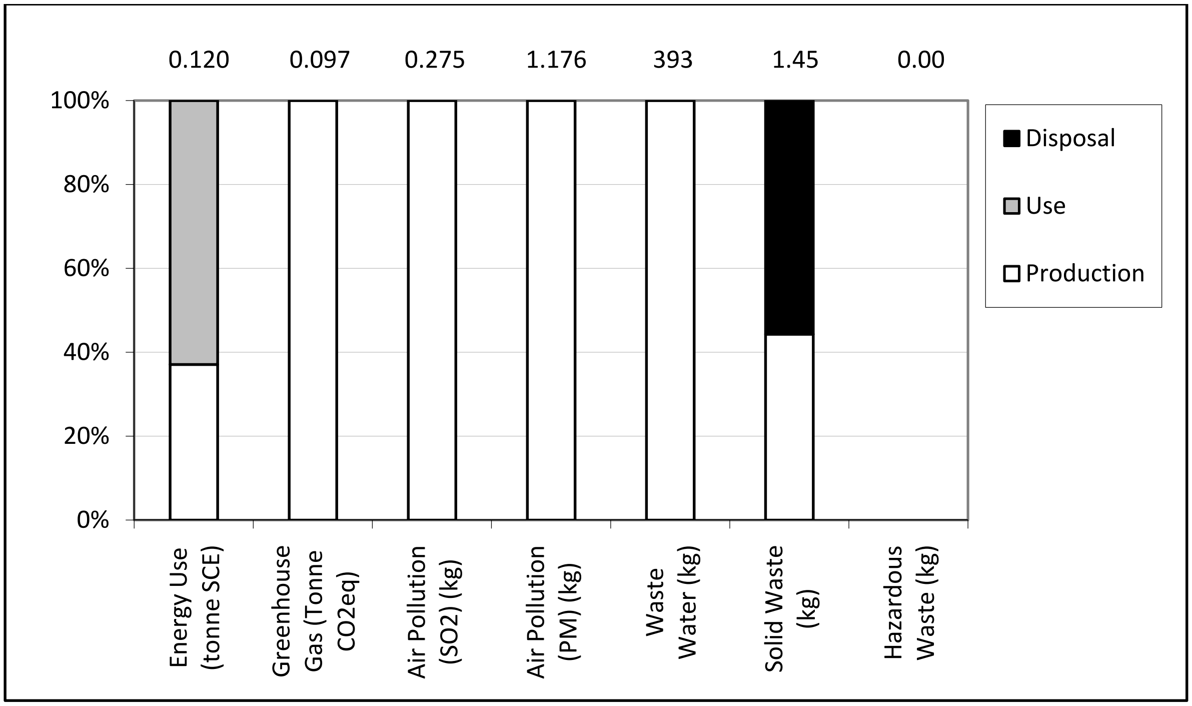

Figure 4.4: Pollution of Traditional Bicycle over Lifecycle

As expected, most of the environmental impacts occur during the production phase, primarily through the steel production processes. Fuel production is omitted on this figure because it is unclear how much more food a bicyclist requires than a non-bicyclist. If bicyclists consume substantially more food than non-bicyclists, the energy use and emissions of food production should be considered in this analysis. This could significantly increase the environmental impact of bicycle use.

4.2.2 Energy Use and Emissions of a Bus

The environmental impacts of bus transport are significantly different than bicycle and electric bike impacts. 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 emissions 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.

4.2.2.1 Production Phase

Bus material inventories were acquired from Volvo Bus Company, who builds Sunwin buses in China (Volvo 2006). This is the second largest bus company in China and could represent an "average" bus.

Table 4.5: Material Inventory, Emissions and Energy Use-Bus

Weight of Bus Materials (kg/bus)		
Total Plastic	553	5.1%
Total Rubber	405	3.7%
Total Wrought Iron	502	4.6%
Total Cast Iron	1029	9.4%
Total Rod Steel	2408	22.1%
Total Hot Rolled Steel	1590	14.6%
Total Colled Rolled Steel	586	5.4%
Total Stainless Steel	690	6.3%
Total Aluminum	1666	15.3%
Total Copper	109	1.0%
Total Glass	490	4.5%
Total Lead	90	0.8%
Total Oil	78	0.7%
Total Wood	396	3.6%
Total Other	308	2.8%
Total Weight	10900	100.0%
Associated Energy and Emissions of Manufacturing Processes		
Energy Use (tonne SCE)	34.345	
Energy Use (kWh)	279605	
Air Pollution (SO2) (kg)	274	
Air Pollution (PM) (kg)	1064	
Greenhouse Gas (tonne CO_2eq)	70.601	
Waste Water (kg)	291182	
Solid Waste (kg)	756	

The values presented in Table 4.5 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 data available. The average energy and emission intensities (impact/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.

4.2.2.2 Lead Pollution from Bus Batteries

The same approach was taken as the electric bike battery analysis regarding the emissions of lead from bus batteries. Even under the best scenarios, electric bikes emit an enormous amount of lead into the environment through the mining, production, recycling and disposal processes. Buses use lead acid batteries also and thus emit lead into the environment. These batteries are much heavier than electric bike batteries, but need to be replaced less often, on the order of every three years or 250,000 km. Table 4.6 identifies the lead lost to the environment through the various production processes.

Table 4.6: Electric Bike Lead Emissions

			Bus	
	Battery Weight (lead content) kg		90	
I	**Lead Production Loss (% Recycled Material)**			
		0%	28.08	
	(Mao, Lu et al. 2006)	22%	25.80	
		44%	23.53	
		60%	21.87	
II	**Manufacture Loss**			
	(Mao, Lu et al. 2006)	4.8%	4.32	
III	**End-Of-Life Loss (Recycling Rate)**			
		0%	90.00	
	(Mao, Lu et al. 2006) official	31%	62.10	
	(Mao, Lu et al. 2006) estimate	62%	34.20	
	(E-bike manufactures)	85%	13.50	
		100%	0.00	
	Scenarios (Production, Manufacture, EOL)			
	Scenario A (0%, 4.8%, 0%)		122.40	
	Scenario B (22%, 4.8%, 31%)		92.22	
	Scenario C (44%, 4.8%, 62%)		62.05	
	Scenario D (60%, 4.8%, 85%)		39.69	
	Scenario E (60% 4.8% 100%)		26.19	

In the worse case scenario, all lead comes from virgin production (no recycled materials) and all batteries are discarded. The emissions of one 90 kg battery would be 122.4 kg of lead. In the best case scenario, where 60% of lead is from recycled materials and 100% of the batteries are recycled, 26.2 kg of lead will be emitted into the environment. Like electric bike batteries, a realistic estimate is probably between scenario C and D. Under Scenario C, assuming a 12 year, 1,000,000 km lifespan, a bus using four batteries in its lifespan will emit 248 mg/km, three to four times lower than SSEBs. Considering an average load factor of 50 passengers on an average Chinese bus, the emission rate per passenger kilometer drops to about 5 mg/passenger-km, or about 140 times lower than SSEBs.

4.2.2.3 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 China 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. Because of these factors, most buses have very different emission rates. The diesel powered buses examined here use about 45 liters of diesel fuel per 100 kilometers. The tailpipe emissions are highly related to the sulfur content of the fuel. During combustion, sulfur is oxidized to sulfate, which binds to fine particulates to increase the mass of particulate emissions per kilometer (ACEA, Alliance et al. 2002). Likewise, Carbon Monoxide emission rates increase with increased sulfur content. Conversely, increased sulfur content reduces Nitrogen Oxide and Hydrocarbon emission rates. China imports much of its oil from the Middle East and as a result, the diesel fuel has very high sulfur levels. All of China's diesel fuel requires a maximum sulfur concentration of 2000 ppm. Major cities like Shanghai and Guangzhou have adopted more stringent 500 ppm standards and Beijing has adopted 350 ppm standards. In 2002, China officially adopted Euro II heavy duty diesel exhaust standards and these are thought to be an optimistic estimate of current bus emission rates[7]. 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 China, two dynamometer studies report bus emission rates for Euro II-III emission

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[7] Personal correspondence with Michael Walsh from the Institute of Global Communications

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 4.7.

Table 4.7: Emission Factors of Urban Buses (g/km)

	Euro II[i]	Volvo-Sunwin[ii] (Volvo 2006)	MEX[iii]	ARB[iv] (Air Resource Board 2001; Air Resource Board 2002)	VTT[v] (Nylund and Erkkilä 2005)	Average Value	Per-Cap Emissions[vi] (g/Pax-km)
CO	6.66	1.91	19.3	4.43	1.5	7.97	0.159
CO_2		1175	1299		1350	1275	25.490
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	0.270
SO_2		0.073				0.073	0.0015
PM	0.416	0.257	1.57	0.888	0.2	0.769	0.015

[i] 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).

[ii] Values adjusted from EPD 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

[iii] Used values presented for 12m Volvo city bus using diesel fuel with a sulfur content of 350ppm

[iv] Used average values for mid-1990's bus fleet in the EMFAC2000 and speed adjusted EMFAC2001 models

[v] Euro II technology operating on diesel fuel with 50ppm sulfur content. Because of this, CO and PM rates are likely lower than buses in China and NO_x and HC rates are likely higher than buses in China.

[vi] Assumes an average load factor of 50 passengers

Emissions from refineries also contribute greatly to energy use and emissions, especially SO_2 and PM emissions. Figure 4.5 shows the estimated total lifecycle energy use and emissions of a bus manufactured and used in China. The refining and burning fossil fuels constitutes over 90% of energy use and greenhouse gas emissions over a buses lifecycle. These processes also contribute to over 60% of the lifecycle's SO_2 and PM emissions. This is consistent with other lifecycle studies of internal combustion engine vehicles (Sullivan, Williams et al. 1998; Delucchi 2003; Volvo 2006).

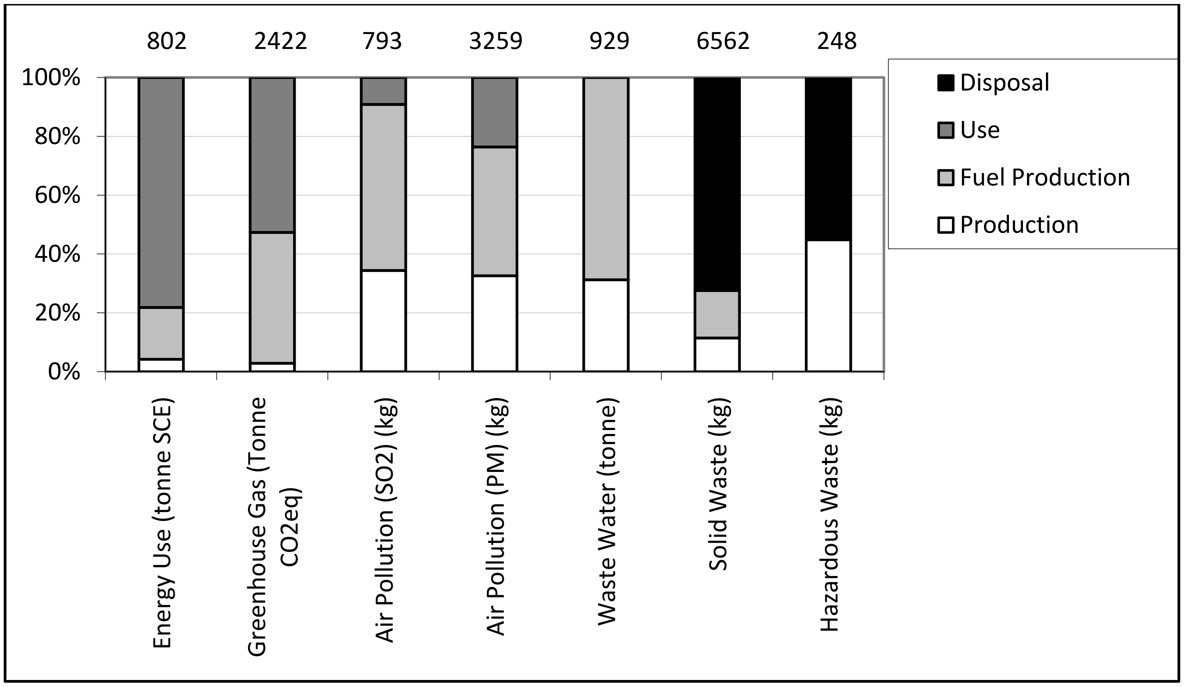

Figure 4.5: Pollution of Bus over Lifecycle

4.3 Modal Comparison of Environmental Impacts

The life cycle emissions of bus, bicycle, and electric bike differ greatly as a result of their different material inventories, fuels, and usable lifespan. Buses use more energy and emit more air pollution--several orders of magnitude higher than bicycles or electric bikes over their life cycle, but they also carry more passengers and travel more kilometers. Table 4.8 compares the lifecycle emissions and energy use per passenger kilometers of the different modes. This table also includes estimates from a LCA study of a typical passenger car that was completed in the United States in the mid 1990's. These numbers can cautiously be compared with the other modes because the emission technology of a vehicle made in the United States is similar to that of a vehicle made in China today. To the extent that most life cycle impacts of a car occur during the use phase suggests that this comparison could be appropriate. 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. Because of this, the emission rates of buses below should be compared to personal modes with caution and personal modes will perform better than the table implies because they make the most efficient route choice. This will be explicitly considered in the case studies in Chapter 7.

Table 4.8: Lifecycle Environmental Impact Per Passenger Kilometer Traveled[a]

	Energy Use (kWh/100 pax-km)	CO2 (g/pax-km)	SO2 (g/pax-km)	PM (g/pax-km)	CO (g/pax-km)	HC (g/pax-km)	NOX (g/pax-km)	Pb[b] (g/pax-km)
Car[c]	140	306	0.689	0.277	10.06	1.67	1.32	0.299
Bus	13.06	48.4	0.022	0.065	0.159	0.015	0.270	0.005
Bicycle	4.88	4.70	0.014	0.059	Unkn	Unkn	Unkn	0.000
BSEB	6.12	22.08	0.123	0.125	Unkn	Unkn	0.027[d]	0.710
SSEB	8.42	30.44	0.164	0.175	Unkn	Unkn	0.020[d]	1.013

[a] Assuming lifespan of 1,000,000 km, 20,000 km, and 50,000 km and average load factors of 50 pax, 1 pax, and 1 pax for bus, bicycle and electric bike, respectively.

[b] Assuming one battery every 10,000 km for electric bikes and one battery every 3 years or 250,000 kilometers for buses.

Note: some fields are Unknown (Unkn) because data are not available for the emission of these pollutants from production processes and/or power plant emissions

[c] Sullivan et al. 1998-LCA of Generic US Car

[d] Only *Use* phase emission rate, no production processes included

Note: some fields are Unknown (Unkn) because data are not available for the emission of these pollutants from production processes and/or power plant emissions

While electric bikes have lower emission rates per passenger kilometer compared to bus during the *use* phases, when including the emission impacts during the *production* phase of both modes, electric bikes have equal or higher emissions on most metrics. Bicycles on the other hand outperform all modes in terms of environmental impacts. Compared to a bus, electric bikes still have lower average energy use and comparable greenhouse gas emissions, but SO_2 emissions are 5-7 times higher and PM emissions are 2-3 times higher per passenger kilometer.

As discussed earlier, lead pollution of electric bike battery production and disposal processes is two orders of magnitude higher than buses, on a per passenger kilometer basis. Unleaded gasoline and diesel does contain some naturally occurring lead, so the tailpipe lead emissions from buses and cars are not zero. In the United States, lead quantities are restricted to a maximum of 13 mg/L (Lankey, Davidson et al. 1998). The naturally occurring lead content in Chinese gasoline is unknown. If gasoline and diesel has this level of lead, then the tailpipe emissions will be on the order of 1 mg/km for cars and 0.1 mg/passenger-km for buses. These rates of lead emission are dominated by the rates of lead emission from battery production and disposal processes and are not included in the analysis.

Carbon Monoxide (CO), Hydrocarbons (HC) and Nitrogen Oxide (NOx) emissions are unknown because of lack of data availability for production processes and/or power plant emission factors. The tailpipe emissions from a bus have been estimated and the above table indicates these emission rates. While electric bikes have some higher emission rates on some criteria pollutants, they perform well to some extent (with the exception of lead) against the two most efficient and sustainable modes we know of, bus and bicycle. Compared to other motorized modes that electric bikes could potentially displace (motorcycles or cars), electric bikes would probably perform very well.

4.4 Exposure of Populations to Air Pollution

While it is interesting to identify and compare emission rates of competing modes, policy makers are more concerned with ecological and public health impacts of various pollutants. Public health can be impacted in a number of ways by various criteria pollutants (US EPA 2006). Public health impacts of airborne toxins are well documented and can often be estimated through concentration response functions if the ambient air concentration or contribution to ambient concentration of the airborne pollutant is known (Xu, Gao et al. 1994; Xu, Li et al. 1995; Wong, Ma et al. 2001; Chen, Hong et al. 2004; Li, Guttikunda et al. 2004; Mead and Brajer 2005). As a proxy of public health effects, intake of pollutants can serve as an indicator of public health impacts. One metric used to calculate intake is the intake fraction (iF). The intake fraction is defined as the proportion of pollutant emitted that is ingested into human systems (Bennett, McKone et al. 2002; Li and Hao 2003; Marshall, Riley et al. 2003; Marshall and Nazaroff 2004; Marshall, Teoh et al. 2005; Zhou, Levy et al. 2006). For example, if a power plant emits one metric ton of SO_2 and one gram of that ton is ingested into a human system, then the intake fraction is $1x10^6$. For air pollution, intake fraction is a function of population density and distribution, ambient concentration of a pollutant, average breathing rate of the population and total emission. Intake fraction, this can be calculated in a number of ways, but is commonly calculated as follows.

$$iF = \frac{\sum_{i=1}^{N}(P_i \times C_i \times BR)}{Q}$$

Where a region is divided into *i* zones and *P* is population of zone *i*, *C* is pollutant concentration of zone *i*, *BR* is the average breathing rate of the population and *Q* is the total mass of pollutant emitted into the environment. The intake fraction is unit-less and can be a powerful tool to identify health impacts due to incremental changes in emissions such as pollution controls on power plants or added emissions due to electric bicycle use.

It is also helpful to compare public health impacts of various alternative technologies without calculating public health end-points. That is, a technology with twice the intake fraction will have twice the public health impacts.

4.4.1 Intake Fraction of Power Plant Emissions

Intake fractions of power plant emissions can be calculated using the above methodology. Several studies, in the Chinese context, have investigated power plant emission intake fraction, using sophisticated atmospheric pollution dispersion models (Li and Hao 2003; Zhou, Levy et al. 2003; Zhou, Levy et al. 2006). The most comprehensive of these efforts (Zhou, Levy et al. 2006) modeled power plant emissions from 29 representative power plants throughout China. Table 4.9 shows the average intake fraction from those power plants of various pollutants.

Table 4.9: Intake fraction average and range in China (Zhou, Levy et al. 2006)

	SO_2	**SO_4**	**NO_3**	**PM_1**	**PM_3**	**PM_7**	**PM_{13}**
Mean	4.80E-06	4.40E-06	3.50E-06	1.00E-05	6.10E-06	3.50E-06	1.80E-06
Min	1.80E-06	7.30E-07	8.00E-07	2.80E-06	1.70E-06	1.10E-06	6.70E-07
Max	8.90E-06	7.30E-06	7.10E-06	1.90E-05	1.20E-05	8.20E-06	5.20E-06

The range of values span about an order of magnitude for most pollutants, suggesting that there are exogenous factors that influence intake. Zhou et al. (2006) found that single largest predictor of intake was population distribution. For most pollutants, the closer the population is to the power plant, the higher the exposure and thus intake. They also found that meteorological factors also significantly affect intake. Multivariate regression analysis performed by Zhou et al. (2006) produces the following predictive relationships that can be extended to predict exposure from any power plant in China (Table 4.10).

Table 4.10: Regression Coefficients of various pollutants (Zhou, Levy et al. 2006)

Independent Variables-coefficients and standard errors (in parenthesis)

Restricted Model Specification (no meteorological characteristics)

	R^2	Population within 100 km	Population between 100 and 500 km	Population between 500 and 1000 km	Population beyond 1000 km	
SO_2	0.95	9.5E-8** (3.9E-8)	1.2E-8** (4.6E-9)	2.5E-9 (2.3E-9)	1.4E-9* (7.0E-10)	
PM_1	0.95	1.3E-7 (8.2E-8)	2.0E-8** (9.8E-9)	9.8E-9** (4.8E-9)	2.9E-9* (1.5E-9)	
PM_3	0.89	1.2E-7 (7.9E-8)	1.3E-8 (9.4E-9)	4.5E-9 (4.6E-9)	1.5E-9 (1.4E-9)	
PM_7	0.88	9.1E-8* (4.7E-8)	7.1E-9 (5.7E-9)	2.1E-9 (2.8E-9)	7.8E-10 (8.5E-10)	
PM_{13}	0.87	6.4E-8** (2.6E-8)	3.6E-9 (3.1E-9)	5.6E-10 (1.5E-9)	4.5E-10 (4.7E-10)	
SO_4	0.93	1.5E-8 (4.2E-8)	6.0E-9 (5.1E-9)	5.9E-9** (2.5E-9)	1.8E-9** (7.6E-10)	
NO_3	0.86	2.9E-8 (5.0E-8)	9.6E-9 (6.0E-9)	2.0E-9 (2.9E-9)	1.3E-9 (9.1E-10)	

Fully Specified Model (meteorology included in "Region" dummy)

	R^2	Population within 100 km	Population between 100 and 500 km	Population between 500 and 1000 km	Population beyond 1000 km	Region
SO_2	0.96	9.9E-8** (3.8E-8)	1.3E-8** (4.6E-9)	3.0E-9 (2.2E-9)	1.8E-9** (7.2E-10)	-1.2E-6** (4.3E-7)
PM_1	0.96	1.5E-7* (7.8E-8)	2.3E-8** (9.3E-9)	1.1E-8** (4.6E-9)	3.9E-9** (1.5E-9)	-3.0E-6** (8.4E-7)
PM_3	0.92	1.4E-7* (6.7E-8)	1.7E-8** (8.1E-9)	6.4E-9 (3.9E-9)	3.0E-9** (1.3E-9)	-3.4E-6** (7.2E-7)
PM_7	0.91	9.9E-8** (4.3E-8)	8.9E-9* (5.2E-9)	3.1E-9 (2.5E-9)	1.5E-9* (8.2E-10)	-1.9E-6** (4.6E-7)
PM_{13}	0.89	6.7E-8** (2.5E-8)	4.3E-9 (3.0E-9)	9.4E-10 (1.5E-9)	7.3E-10 (4.8E-10)	-8.4E-7** (2.8E-7)
SO_4	0.95	2.4E-8 (3.7E-8)	7.9E-9* (4.5E-9)	6.9E-9** (2.2E-9)	2.6E-9** (7.1E-10)	-1.7E-6** (4.1E-7)
NO_3	0.93	4.3E-8 (3.7E-8)	1.3E-8** (4.4E-9)	3.5E-9 (2.2E-9)	2.5E-9** (7.1E-10)	-2.4E-6** (4.0E-7)

Note:
1. ** Parameter estimate significant at 0.05 level.
2. * Parameter estimate significant at 0.10 level.
3. Numbers in parenthesis are the standard error of parameter estimates.
4. PMx= particulate matter with diameter precisely equal to x Am.
5. Population variable in millions of people.
6. No intercept term is used in the above regression models and R-square is not corrected for the mean.
7. Climate region variable is defined to be one for power plants in the subtropical and tropical zone; zero for plants in the temperate zone. Generally, locations south of the 33˚ N latitude are considered to be tropical and subtropical and north of 33˚ N latitude are considered temperate.

4.4.1.1 Intake of Pollutants Emitted Power Plants – Kunming

For the sake of this comparison, we will assume that all of Kunming is served by all power plants in the Yunnan Power Grid, in proportion to their generating capacity. This might overestimate emissions, because during low demand hours, the cleanest plants generate most of the electricity. There are also seasonal differences related to energy mix, with rainy seasons providing increased hydro power and dry seasons providing increased fossil fuel power. To calculate the intake fraction, the regression framework developed by Zhou et al. (2006) and presented above is used. The location and capacity of power plants in Yunnan province are found in the RAINS-Asia model and the Yunnan Power Grid Corporation (International Institute for Applied Systems Analysis, World Bank et al. 1999; Yunnan Power Grid Corporation 2005). Data related to population distribution throughout China are found in the GIS data from the China Census (All China Marketing Research Co. Ltd. 2003) and the USGS (US Geological Survey 2001).

Using GIS tools, population within the four distance ranges required for the regression models were calculated for each coal power plant serving Kunming and are shown in Table 4.11.

Table 4.11: Intake Fraction Calculations of Emissions from Power Plants in Yunnan Provincial Power Grid

Power Plant Characteristics

Plant Name	Capacity (MW)	Population (0-100 km) (million people)	Population (100-500 km) (million people)	Population (500-1000 km) (million people)	Population (>1000 km) (million people)
Kunming	200	10.267	66.441	209.684	992.231
Yangzonghai	400	11.183	70.557	223.468	973.415
Xiaolongtan	600	3.93	63.837	227.381	983.475
Qujing	600	6.27	105.565	234.36	932.428
Xuanwei	600	6.161	135.423	230.93	906.109

Intake fraction of estimates from regression models presented in Table 4.10 (with region dummy)

	SO_2	**PM_1**	**PM_3**	**PM_7**	**PM_{13}**	**SO_4**	**NO_X**
Kunming	3.10E-06	6.24E-06	3.49E-06	1.85E-06	1.06E-06	3.10E-06	2.12E-06
Yangzonghai	3.25E-06	6.55E-06	3.72E-06	1.99E-06	1.13E-06	3.20E-06	2.21E-06
Xaiolongtan	2.47E-06	5.39E-06	2.64E-06	1.24E-06	6.29E-07	3.02E-06	1.85E-06
Qujing	3.17E-06	6.58E-06	3.57E-06	1.79E-06	9.35E-07	3.33E-06	2.39E-06
Xuanwei	3.49E-06	7.11E-06	3.96E-06	1.99E-06	1.03E-06	3.47E-06	2.7E-06
Capacity Weighted Average iF	3.08E-06	6.39E-06	3.45E-06	1.74E-06	9.26E-07	3.25E-06	2.28E-06

The population density surrounding the power plants has the most impact on the exposure of the population to emissions. In the top half of Table 4.11, Kunming and Yangzonghai plants are located closest to population centers and thus emissions from those power plants have higher iF than from other power plants, with some exceptions. Small and light particles, like PM_1 have longer transport ranges and thus more influence on populations located some distance from the source. So the variation of iF between power plants is rather low. Large and heavy particles, like PM_{13}, have higher iF on nearby populations, so plants like Kunming have higher iF for this pollutant than more remote plants. For each pollutant the average iF of all plants, weighted by plant capacity, is calculated. The average intake fractions range from 0.9 to 6.4 units of pollution inhaled per every million units emitted.

This model does not explicitly identify trans-boundary effects. When identifying population within the various distance ranges from the model, populations of other countries are not included. Yunnan province borders several southeast Asian countries and the iF calculation does not consider populations exposed to this trans-boundary pollution. The estimated intake fractions could be seen as under-estimates of the total exposure. The regression model can be extended to include these populations, but the underlying model estimation procedure did not include these populations and could result in biased estimates.

4.4.1.2 Intake of Pollutants Emitted from Power Plants – Shanghai

Similar regression analysis is done in the case of Shanghai. The results of the analysis are shown in Table 4.12. Shanghai is part of a larger electricity generation network, so there are many more power plants represented. This full table is included in Appendix B.

Table 4.12: Intake Fraction Calculations of Emissions from Power Plants in East China Power Network

Mean Power Plant and Population Distribution Characteristics

Number of Power Plants	Mean Capacity (MW)	Mean Population (0-100 km) (million people)	Mean Population (100-500 km) (million people)	Mean Population (500-1000 km) (million people)	Mean Population (>1000 km) (million people)
39	951	14.082	187.179	442.513	634.849

Intake fraction of estimates from regression models presented in Table 4.10 (with region dummy)

	SO_2	**PM_1**	**PM_3**	**PM_7**	**PM_{13}**	**SO_4**	**NO_X**
Capacity Weighted Average iF	5.05E-06	1.07E-05	6.43E-06	3.46E-06	1.78E-06	4.79E-06	3.72E-06

Interestingly, the intake fractions in the Shanghai case are higher than in Kunming. This is because of the higher population densities on China's east coast and thus closer proximity of power plants to population centers.

4.4.2 Intake Fraction of Vehicle Tailpipe Emissions

A few researchers have calculated intake fractions of mobile emission sources, such as bus or car. Notably, two studies in the USA have used and compared different methodologies to calculate intake fractions of vehicle emissions, using different data sources (Marshall, Riley et al. 2003; Marshall, Teoh et al. 2005). One significant difference between estimating exposure from power plants and mobile (local and urban) sources is that exposure differs depending upon microenvironments within the city and activity levels within those micro environments. If many activities involve proximity to busy roadways, such as walking, waiting for the bus, bicycling, or driving, then the exposure to pollutants is higher during those activities (Chan, Lau et al. 2002; Zhao, Wang et al. 2004). City-wide intake fraction of pollutants can be adjusted to reflect the proportion of time the population is participating in activities in various microenvironments.

Intake fraction of vehicle emissions can be calculated if the total tailpipe emission and the proportion of those emissions contributing to ambient pollution concentration are known for a city. Often times these are difficult parameters to estimate and require accurate monitoring and modeling data that are difficult to collect in many cities. A more simplified approach that provides reasonable estimates of exposure to non-reactive pollutants is the one-compartment model (Marshall, Teoh et al. 2005). This model estimates intake exposure to pollutants that have an atmospheric persistence (slow deposition or chemical transformation) that exceeds the amount of time taken for the pollutant to leave the air basin, primarily through advection. The one-compartment model assumes relatively constant concentrations and thus constant exposure. The factors that influence estimation of the one-compartment intake fraction are the volume of the urban air basin, the average wind speed and population parameters. Intake fraction using the one compartment model is calculated using the following formulation from Marshall et al. (2005).

$$iF = \frac{QP}{uH\sqrt{A}}$$

Where Q is the average population breathing rate, P is the population living in the urban air basin, u is the average wind speed, H is the atmospheric mixing height and A is the area of the urban air basin. Importantly, this estimation method does not require information related to pollution emission rates or emission concentrations. The primary assumption is that the airshed is well mixed and in a steady state condition. A breathing rate of 20 m^3/day is used and consistent with other iF studies in China (Li and Hao 2003; Zhou, Levy et al. 2003; Zhou, Levy et al. 2006). Other iF studies in the United States use lower breathing rates of 10-15 m^3/day (Marshall, Riley et al. 2003; Marshall and Nazaroff 2004; Marshall, Teoh et al. 2005). The product of u and H is known as the dilution rate and is the average of the harmonic mean of the wind speed and mixing height measurements taken four times daily.

4.4.2.1 Tailpipe Intake Fraction in Kunming and Shanghai

The intake fraction formulation used above is utilized to estimate the intake fraction of the city of Kunming. The input parameters are estimated from a number of sources. The breathing rate (Q) is assumed to be 20 m^3/day to be consistent with the power plant iF formulation presented by Zhou and Levy et al. (2006). The urban population (P) of 2.09 million people occupies an area (A) of 190 square kilometers (National Bureau of Statistics 2005). The mixing heights (H) every six hours are attained from the National Oceanic and Atmospheric Administration's NCEP-DOE Reanalysis 2 dataset (National Oceanic and Atmospheric Administration 2006). The six hourly mixing height data were interpolated to attain information on hourly mixing heights. It should be noted that the mixing heights during the night are reported at about 1000 meters, which is significantly higher than the boundary layer is in most places, which is on the order of 200-400 meters. This could be a problem with the definition, so the analysis presented will likely underestimate the intake fraction if the boundary layer is in fact lower. Hourly near surface wind speeds are attained from METAR (airport) data provided by Weather Underground (Weather Underground 2006). The wind speed was averaged over the corresponding mixing height using the wind profile power law expressed as:

$$u_x = u_r (z_x / z_r)^{\alpha}$$

Were u_x is the wind speed at height z_x, u_r is the wind speed at a known reference height z_r, and α is the stability, assumed to be 0.143. The reference height is assumed to be 10 meters (consistent with typical airport weather stations).

For Kunming, this analysis yields an intake fraction of slowly reacting pollutants of approximately 1.2e-5, between two and six times higher than power plant emissions presented in Table 4.11. In the case of Shanghai, the same methodology was used, using Shanghai's meteorological and demographic data. The intake fraction in Shanghai's case is slightly higher, 1.3e-5. However, this intake fraction is only two to four times higher than the average intake fraction of power plants serving Shanghai shown in Table 4.12.

These analyses imply that the exposure and thus public health impacts of urban tailpipe emissions from motor vehicles is several times higher than those of power plants.

4.4.3 Normalized Emissions Considering Exposure

Public health effects are linked to exposure to pollutants in the urban area. While the existence of electric bikes results in decreased emissions of some pollutants and increased emissions of others, what we are most concerned about is exposure of populations to those pollutants. Intake fraction is a metric used to identify exposure differences. Electric bikes emit pollution from remote stationary power plants. Buses and cars emit pollution from mobile, urban sources. The previous section showed that population exposure to power plant emissions is several times lower than exposure to tailpipe emissions. To identify normalized emissions that consider exposure for sake of comparison, one would weight urban tailpipe emissions higher than power plant emissions.

The public health effects of emissions from different production processes are likely similar to each other. That is, all modes of transportation are likely manufactured in similar industrial areas, primarily in provinces along China's east coast. The emission rates from the *Use* phase are weighted to reflect their relative intake fraction, compared to electric bikes. For instance, if the intake fraction for particulates from a tailpipe is 2.0e-5 and the intake fraction for particulates from a power plant is 3.1e-6, then one gram of particulate emission from a bus has an equal public health effect as 6.4 grams of particulates from a power plant. The total emissions can be normalized using the following equation:

$$E_{normalized}^{total} = \sum_i \left(\left[\left(\frac{iF_l}{iF_r} \times ER_i^{tailpipe} - ER_{e-bike}^{powerplant} \right) + \left(\frac{iF_p}{iF_p} \times ER_i^{production} - ER_{e-bike}^{production} \right) \right] \times PKT_i \right)$$

Where:

$E_{normalized}^{total}$ = the total iF normalized emission of a pollutant from all modes per year [g/yr]

i = relevant alternative modes

iF_l = intake fraction from local emission sources (tailpipes) [unitless]

iF_r = intake fraction from remote sources (power plants) [unitless]

iF_p = intake fraction of emissions from production processes [unitless]

$ER_i^{tailpipe}$ = tailpipe emission rate from alternative *i* [g/pax/km]

$ER_{e-bike}^{powerplant}$ = power plant emission rate from e-bike use [g/pax/km]

$ER_i^{production}$ = emission rate from production processes of alternative *i* [g/pax/km]

$ER_{e-bike}^{production}$ = emission rate from production processes of e-bike [g/pax/km]

PKT_i = Total yearly passenger kilometers shifted from e-bike to alternative *i* [pax-km/yr]

The total emissions are the sum of all emissions, including urban (tailpipe) emissions of certain pollutants scaled up to reflect the increased exposure they represent. Non-urban (production and power plant emissions) are held constant. In the case of emissions from production, iF_p is unknown, but I assume that exposure to pollution from the production processes of all modes occurs at the same rate, so the ratio is equal to one. The above equation also assumes that production emissions have the same influence on total emissions as power plant emissions. This could be true, but some of the production processes occur in urban or suburban settings, which might result in higher exposure rates.

4.5 Distribution of Environmental Impacts

All modes require different proportions of their lifecycle impacts during different phases in the lifecycle. 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. Electric bikes are efficient energy users, so the use phase constitutes a smaller portion of the lifecycle impacts. Moreover, they have zero tailpipe emissions, so the use phase results in regional and national pollution impacts from power plants. These power plant emissions can have trans-boundary effects and impact populations in other nations as well, particularly in the case of small particles (which have long transport ranges) and in areas close to national borders. A larger portion of electric bike lifecycle impacts are imposed on non-local communities, where production processes occur. Bicycles impose almost all of their lifecycle impacts on different communities because almost all of their impacts are incurred during the production phases. All modes emit greenhouse gases during various stages of their lifecycle which have global consequences. Electric bikes perform very well on global greenhouse gas emissions compared to most alternatives.

4.6 Direction of Public Health Impacts

4.6.1 Public Health Impacts of Air Pollution

Electric bikes have higher emission rates over the lifecycle of some pollutants (SO_2 and PM) and less of others (NO_X) compared to motorized alternative modes such as buses and cars. The public health impact of shifting electric bike users to other motorized transport in order to reduce SO_2 and PM impacts would likely result in more severe public health impacts from NO_X. From Chinese literature, the total mortality rate for increased NO_X and SO_2 concentrations are comparable to each other and four to six times higher than PM mortality impacts. The direction of the public health impact of a shift from electric bikes to each alternative mode or set of alternative modes can be estimated by the sum of the net pollution of the criteria pollutants, with PM reduced by four to six. For example, each electric bike on the roadway in Shanghai might result in net increases of 152 g/yr of PM and 137 g/yr of SO_2 and a net decrease of 773 g/yr of NO_X. The direction of the public health impacts can be identified by the mortality weighted sum of these emission (152/4+137-773 = -598), which is negative, indicating that the decreased mortality from reduced NO_X emissions is greater than the increased mortality from increased PM and SO_2 emissions.

4.6.2 Public Health Impacts of Lead Pollution

The exposure pathways of lead are largely unknown and people are exposed 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, to name a few (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 China related to battery production (Shen 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 4.2. 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 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 electric bike battery producers (about 25% of the market[8]) following hundreds of children's hospitalizations 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 China. Based on the high lifecycle emission rates, 10-20 times higher than tailpipe emissions from leaded fuel, the public health impacts are likely significant and should be remediated.

4.7 Policy Discussion, Conclusion and Future Work

The electric bike market is expanding at an amazing rate in China. Electric bikes serve the enormous low income populations that are currently using bicycles and public

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[8] Based on an interview with a company manager on 4/16/2006 at the Shanghai Bike Expo

transportation; providing an alternative transportation option that has much of the mobility benefits of a personal car, but is cheaper to own and operate. They are touted as a clean form of transportation and they do not emit any local pollution, but they do increase demand on electricity, increase power plant emissions and introduce a large amount of lead into the environment. Electric bikes are efficient low cost modes and as a result, much of their life cycle energy is consumed during the production processes. The operation of electric bikes produces a high proportion of SO_2 air pollution in the life cycle, but few other major impacts. This is primarily due to an electricity supply network that primarily consists of coal power plants.

When developing environmental policy on electric bikes, it is important to perform a comparative analysis with other modes of transportation that are in electric bike riders' choice set. In the two cities investigated, Shanghai and Kunming, the majority of electric bike users are previous bus riders or would use a bus in the absence of an electric bike. The electric bike performs well in terms of environmental impacts compared to the bus. Electric bike sulfur dioxide emissions are considerably higher (because of high sulfur coal), but other pollutants are lower than or on the same order of magnitude of 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 electric bikes.

The lead (Pb) emissions from battery use reported in this chapter are not "tailpipe" emissions for any mode, but rather emissions from production, recycling and disposal processes, spread over the lifecycle of the vehicle. Lead emissions per passenger kilometer are several orders of magnitude higher for electric bikes than for buses primarily because buses use fewer (although heavier) batteries during their lifecycle and get much more mileage from each battery.

Lead acid batteries are not necessary for electric bike operation. Commercially available alternative technologies, such as Nickel Metal Hydride (NiMH) and Lithium Ion (Li-Ion) batteries are much more expensive, but also have much higher energy densities, so battery weight can be reduced by more than half. Of these batteries, NiMH is the lowest cost and could have the best chances for near term adoption in electric bikes in China. NiMH batteries have longer lifetimes compared to lead, between 60% and 300% more recharge cycles are available (from 300 cycles for lead to 500-1000 for NiMH).

A NiMH battery that is equivalent (in power) to lead acid would cost about six times a lead acid battery. However, it is likely to have about twice the lifespan, so the actual price is about three times that of an equivalent lead acid battery (Jamerson and Benjamin 2004). The cost of lead acid batteries range from 250 RMB to 300 RMB, or about 0.03 RMB/km. An equivalent NiMH (accounting for a 100% increase in range) would cost 750-900 RMB/battery, or about 0.09 RMB/km. If the entire electric bike industry shifted to this technology, then any shift to alternative motorized modes would emit more lead into the environment because buses, cars, and motorcycles will continue to use lead acid starting batteries. If lead acid batteries could be replaced, then electric bikes would be perhaps the most environmentally sustainable motorized mode available in China. Policy mechanisms to induce such a shift are discussed in Chapter 8.

CHAPTER 5: SAFETY IMPACTS OF ELECTRIC BIKES IN CHINA

Safety is one of the more commonly cited reasons used by electric bike opponents argue for strict regulation of their use and design. Safety is one of the main reasons that Guangzhou recently imposed a ban on electric bikes (Guangzhou Daily 2006). When Beijing officials attempted to ban electric bikes, they also cited safety concerns, while electric bike proponents posited that electric bikes are safer than other modes (Ribet 2005). Detailed primary crash data are largely unavailable to the public in most Chinese cities, so advocates and opponents often cite aggregate statistics. One of the issues raised is the safety of electric bikes in bicycle lanes. Critics state that they are too fast and heavy to operate in the bicycle lane and too slow for the car lane. They often cite crash statistics or number of fatalities when arguing against electric bike use. Electric bikes affect the safety of the transportation system in three ways:

1) they interact with other non-motorized vehicles in the bicycle lane, possibly endangering bicyclists

2) they increase the amount of vulnerable road users on the road, increasing the severity of injury if a collision occurs with an automobile

3) many electric bikes operate much like a motorcycle, but require no training, licensing or helmet use, resulting in potential injury from misuse, or operator error.

These factors all have different effects on the safety of the transportation system and policy makers have been trying to address some of them. Ultimately, electric bikes should only be regulated for safety if they are inherently unsafe vehicles, not just vulnerable. If they are simply vulnerable, then the impact of shifting electric bikes users from a vulnerable mode (bicycle or electric bike) to a truly unsafe mode (cars for instance) could decrease the safety of the transportation system. This section will identify factors that influence the safety characteristics of electric bikes operating in Chinese bicycle lanes. It will look at safety statistics for several regions in China and project safety impacts of various shifts between modes if electric bikes were banned.

5.1 Designing Electric Bikes for Safety

Bicycle advocates and industry members, like the China Bicycle Association were influential during the development of the first technical design standards for electric bikes (China Central Government 1999), that limited the weight, width, brake distance, wheel size, and speed of electric bikes. These standards were developed to ensure that electric bikes would mix well with current vehicles in the bicycle lane. Because of safety concerns, these design standards precluded development of what are now known as scooter style electric bikes (SSEB). Several of the design standards are mandatory, while others are recommended. Electric bike maximum speed must be below 20 km/hr and the bike must meet minimum brake distance requirements. If these standards are not met, they cannot be licensed as electric bikes in many cities. Other standards are recommended, including the maximum weight of 45 kg. If the recommended standards are exceeded, then the producer must pay a fine that is often levied at the discretion of the local standards bureau. Lenient enforcement of these standards has resulted in the growth in production of SSEBs to meet consumer demand for faster and more comfortable electric bikes. Additionally, many electric bike manufacturers meet the maximum speed threshold by equipping their electric bikes with speed regulators, which can be easily removed. Most SSEBs weigh more than 60 kg and can operate at speeds exceeding 30 km/hr.

Although electric bikes are able to operate at much higher speeds than an average bicycle, the relevant question is how much faster they actually operate. A floating vehicle study (discussed in detail in Chapter 7) was conducted in both Shanghai and Kunming in Spring 2006 to determine how much faster electric bikes operate compared to bicycles. The results between both cities were very consistent, implying transferability to different cities. Average free-flow operating speed (not including stops) in Shanghai was 18.2 km/hr and 13.0 km/hr for electric bikes and bicycles, respectively. Kunming's operating speeds were similar, 17.9 km/hr and 12.8 km/hr for electric bikes and bicycles, respectively. For both cities, electric bikes operate about 5 km/hr, or 40% faster than bicycles. While this "average" speed does not reflect outlying electric bikers that travel very fast, it represents a significant speed differential. However, it shows that the average operating speed is lower than the 20 km/hr threshold, although a large portion of the distribution lies above 20 km/hr (Figure 5.1 and 5.2). If the speed maximum is regulated (mechanically) at 20 km/hr for electric bikes, and all speed observations above this value are set at 20 km/hr, then the speed differential falls to 3.9 km/hr, or 30% in Shanghai and Kunming (Figure 5.3 and 5.4).

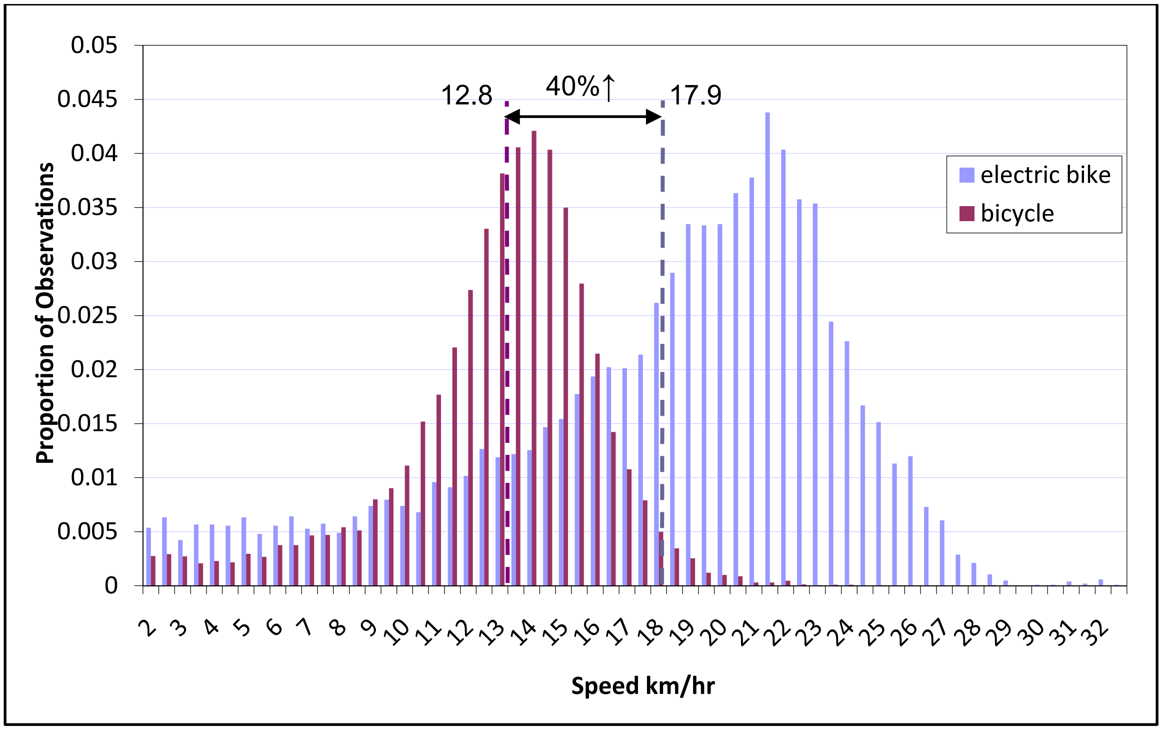

Figure 5.1: Histogram of Moving Speeds (No Stops) - Kunming

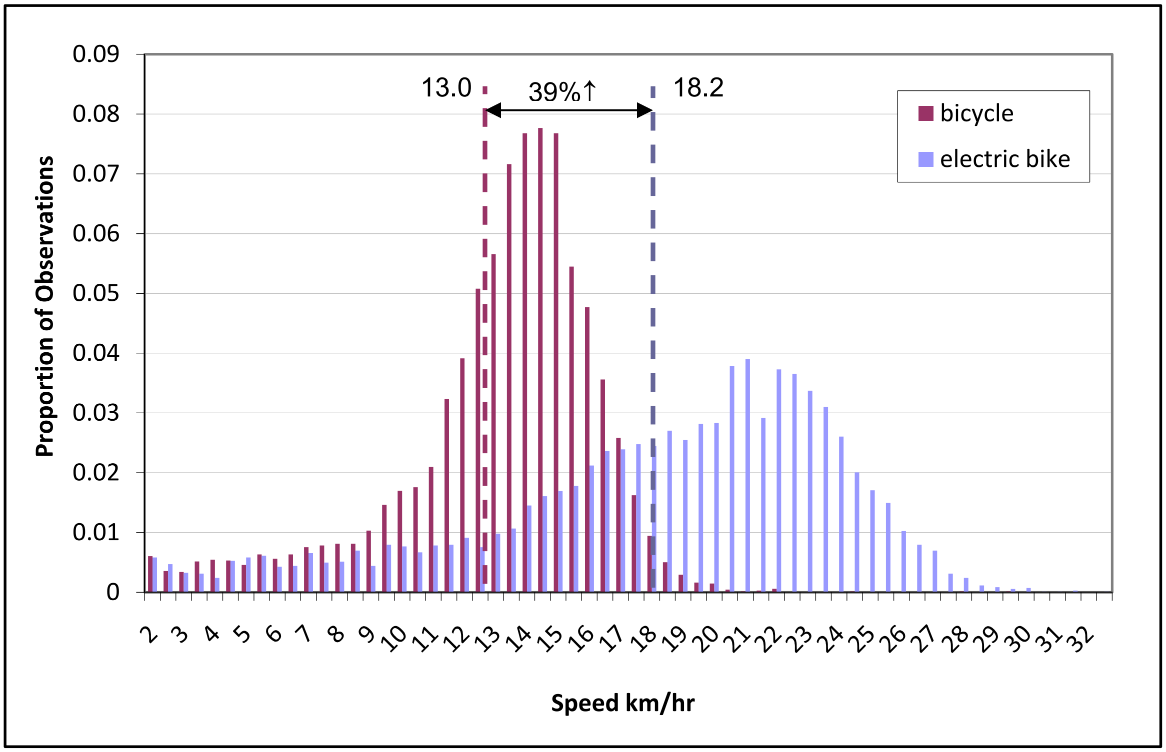

Figure 5.2: Histogram of Moving Speeds (No Stops) - Shanghai

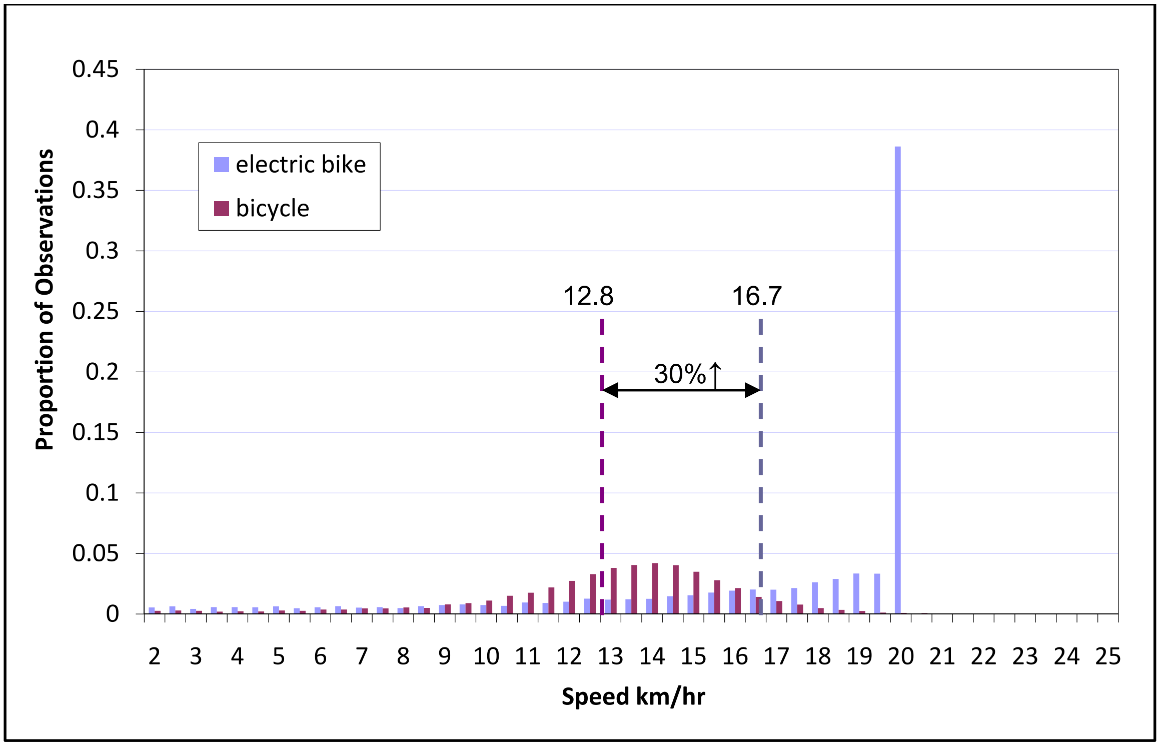

Figure 5.3: Histogram of Moving Speeds (No Stops) - Kunming 20 km/hr Limit on Electric Bikes

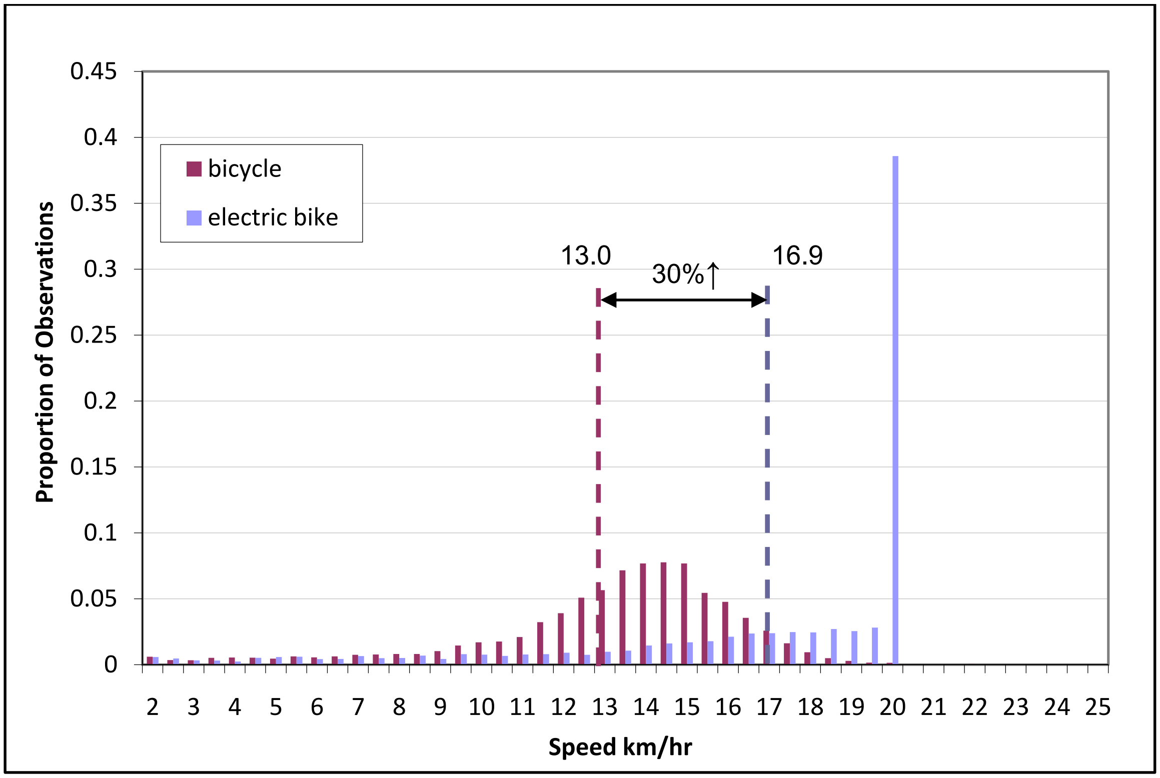

Figure 5.4: Histogram of Moving Speeds (No Stops) - Shanghai 20 km/hr Limit on Electric Bikes

While electric bikes operate faster than bicycles in the bicycle lane, there are certain features that improve their safety. Most SSEBs have horns, headlights, taillights, turn signals and brake lights. Additionally, many of them have advanced, motorcycle-style braking systems. Most electric bikes have a heavy battery pack under the foot board or on the frame of the bike, lowering the center of gravity and making the electric bike more stable. These features make electric bikes more maneuverable than standard bicycles. Although electric bikes are significantly faster than bicycles, the increased speed reduces the speed differential between electric bikes and cars, reducing the chances of a high impact collision with large vehicles.

5.2 Unsafe versus Vulnerable

Electric bike opponents often cite the number of recent electric bike rider fatalities in a given city as evidence of electric bike's poor safety performance. Those opponents rarely cite what type of vehicle is at fault in an accident or the safety performance of alternative modes. While a collision with a motor vehicle will almost certainly result in injury or death of an electric bike user, it is important to emphasize that increased fatalities by a certain mode do not necessarily imply that that mode is increasingly dangerous. It could imply that electric bikes are simply vulnerable road users, like bicycles and pedestrians. As the proportion of heavy vehicles on the roadway increases, the vulnerable modes may seem increasingly dangerous, when in reality the heavy vehicles are the cause of the increased fatalities. Some 60% of fatalities in China are vulnerable road users (pedestrians and two-wheeled vehicle users) (Wang, Chi et al. 2003; People's Daily Online 2005) .

If a portion of electric bike users shifted to automobiles, perhaps the overall transportation fatality rate would be worse. Because there would still be a high number of "exposed" vulnerable road users, such as bicyclists and pedestrians (either accessing transit or walking to their destination), the increase in automobile traffic would likely reduce the safety of these vulnerable road users. There would also be more collisions between automobiles. From the survey data presented in section 2, 30-60% of users would shift to public transit if electric bikes were banned (depending on the city). While public transit riders are generally safe, they would have to walk to transit stops and be exposed to traffic during that walk. From the survey data, a large portion of the electric bike population would shift to bicycle. The risk involved in riding a bicycle could be similar to that of an electric bike. Now that electric bikes are becoming more prevalent, some data are showing that electric bikes are not as dangerous as one might expect. The China Bicycle Association cited that the 2002 crash rate (crashes/vehicle population) for electric bikes in Shanghai is 0.17%, while the crash rate for cars is 1.6% (Ribet 2005). Of course a crash on an electric bike might be much more damaging than a crash in a car, and minor electric bike crashes could go unreported. Policy makers need to consider not only crash rates, but fatality rates, expressed in terms of fatalities per vehicle kilometer traveled. Table 5.1 shows 2004 safety data in Zhejiang Province (bordering Shanghai to the south) and Jiangsu Province (bordering Shanghai to the west).

These figures are supported by 2005 data provided by the Kunming Public Safety Bureau citing a crash rate of 0.05% for electric bike users, with five fatalities. Using a conservative estimate of 171,000 electric bikes and 2400 vkt/year results in a fatality rate of 0.012 fatalities/million-vkt.

Assuming that electric bike users are equally vulnerable as bicyclists, these data show that, at the margin, electric bikes are slightly more dangerous than bicycles but much safer than cars. The safety impacts compared to riding a bus are unclear, since the bus trip includes walk access. While bus riders might be safe while on the bus, the most hazardous part of the journey is likely the walk to and from the bus stop.

Motor vehicles are the cause of most accidents and also the most unsafe mode of transport because of the high fatality rate per million vehicle kilometers traveled. A shift from bicycle or electric bike to motor vehicle will likely cause a significant increase in transportation related fatalities. Occupants of passenger vehicles will be victims of road fatalities and vulnerable road users will also be victims of more heavy vehicles on the roadway. While only a small portion of electric bike users would shift to car or taxi, this small shift could lead to a big increase in crashes and fatalities. Passenger vehicle fatality rates are one to two orders of magnitude higher than bicycle or electric bike fatality rates, so if electric bikes are banned in a city and 5-10% of electric bike users shifted to cars (see figures 3.2 and 3.3), then the fatality rate in the transportation system could be higher than if electric bikes were allowed on the roadway.

To the extent there is not a major structural shift in the mix of vehicles on the road, the crash rate will be determined by the crash rates of each individual mode. This is unrealistic however, because more cars on the road might increase the fatality rate of bicycles or pedestrians. Over 92% of crashes in China involved a four-wheel vehicle (Wang, Chi et al. 2003). A study in Shanghai reported 90% of crashes are cause by four wheel vehicles, 54% caused by cars (Zacharias 2002). Only 10% of the crashes are caused by vulnerable road users. Since about 54% of crashes, and presumably vulnerable road user fatalities, are the fault of car drivers, the added VKT of cars would result in secondary fatalities of vulnerable road users. A secondary fatality rate is calculated as 54% of vulnerable road user fatalities (those caused by small vehicles) divided by the number of automobile kilometers traveled.

Table 5.1: Safety Data from Zhejiang and Jiangsu Provinces (2004)

	Fatalities[a]	Injuries[a]	Econ. Loss (million RMB)	Veh pop[b] (million)	Vkt/yr[c] (million)	Fatality Rate (fatalities/m-vkt)	Secondary Fatality Rate[d] (fatalities/m-car vkt)
Zhejiang Province							
Passenger vehicle	3731	29884	unk	1.81	18100	0.206	
Bicycle	1194	7148	unk	24.9	53012	0.023	0.036
Electric bike	129	1660	unk	1.5	3255	0.039	0.004
Pedestrians	2100	8586	unk				0.063
Jiangsu Province							
Passenger vehicle	2153	8180	96.176	1.13	11300	0.191	
Bicycle	210	507	0.384	41.9	89205	0.002	0.010
Electric bike	65	538	0.297	4.2	10307	0.007	0.003
Pedestrians	255	143	0.480				0.012

[a] Secondary source Zhejiang Public Security Bureau, Zhejiang Bicycle Association, Jiangsu Public Security Bureau (PSB)
[b] Zhejiang, Jiangsu and China Statistical Yearbooks 2005
[c] 10,000 vkt/year/veh assumed for motor vehicles and average of Kunming and Shanghai survey data for bicycle (2129 km/bike/yr) and e-bike (2454 km/ebike/yr).
[d] Calculated as: $\text{Fatalities}_{\text{VRU}}*0.54/\text{VKT}_{\text{CAR}}$. This represents the additional VRU fatalities as a result of increased car use.

The economic loss from crashes in Jiangsu province was reported by the Public Security Bureau (PSB) and is worth mentioning. It is unclear how this number was calculated and how or if human life, injuries and property damage are valued, but it is worth noting that the economic costs of debilitating injuries could exceed the economic cost of fatalities. Using the data in table 5.1, the economic loss per million VKT is on the order of 8500 RMB (US $1060) for passenger vehicles, 4.3 RMB (US $0.50) for bicycles, and 29 RMB

(US $3.60) for electric bikes. These numbers seem to imply only property damage. Considering only fatalities and the estimated Value of a Statistical Life (VOSL) in China of around US$500,000 from the literature (Liu 1997; Feng 1999; Brajer and Mead 2003), the economic impact from 210 bicycle fatalities alone (not including injuries and property damage) would exceed 840 million RMB, compared the 384 thousand RMB reported by the PSB.

5.3 User Perceptions

While one would expect electric bikes to be a menace and hazard to bicycle users, bicyclist survey responses suggest otherwise. In Kunming and Shanghai, 70% and 77% of bicycle users say that they would like to see the government encourage the development of the electric bike industry. A survey conducted in Shijiazhuang addressed some specific questions related to user perceptions of safety and conflict (Weinert, Ma et al. 2007). Bicyclists who responded to the survey said that other bicyclists and pedestrians ranked were more bothersome than electric bikes. However, most electric bike and bicycle respondents think that electric bikes are too fast in the bicycle lane.

5.4 Policy Implications

There is a conflict between electric bike industry members and bicycle advocacy groups. Bicycle advocacy groups generally support electric bikes, so long as they remain bicycle style electric bikes. Electric bike industry members (including those influential in drafting the first technical standards) are beginning to make scooter style electric bikes to meet the market demand for heavier, more comfortable and faster vehicles. Most SSEBs are capable of speeds exceeding 30 km/hr and can carry multiple passengers or cargo. These larger electric bikes operate more like motorcycles than bicycles and should be treated as such. A subset of the electric bike manufacturing industry is attempting to define SSEBs as light electric vehicles (LEVs), which will hopefully pave the way for battery electric cars. While this innovation and technology evolution could be beneficial to China's transportation system, LEVs don't fit well within the current transportation system. They are too fast for the bicycle lane and too slow for the auto lane. If LEVs are allowed in the transportation system, they should be allowed to expand their performance characteristics to operate in mixed flow traffic, which would call for helmet and license requirements. China's bicycle fatality rate due to head injuries is several times higher than developed countries (Li and Baker 1997), raising an important issue of implementation and enforcement of mandatory helmet laws on electric bikes. Licensing procedures should be put in place to train riders of large electric bikes to safely operate electric bikes in mixed traffic conditions. BSEBs and SSEBs should be allowed in bicycle lanes so long as there is strict adherence to specified speed restrictions. These policies should be implemented in such a way as to not discourage electric bike use. The data above show that even a small shift to personal automobiles will result in a large impact on safety. Electric bikes are still new road users and as electric bike riders become more accustomed to their performance, they will likely become safer drivers. Also, as electric bikes become more ubiquitous in Chinese cities, car drivers will become more used to sharing the road with this higher speed mode.

CHAPTER 6: MOBILITY AND ACCESSIBILITY IMPROVEMENTS OF ELECTRIC BIKE USERS

6.1 Mobility versus Accessibility

All modes of transportation have certain environmental and social costs. A society can tolerate those costs if the benefits are tangible and outweigh the costs. The primary benefit of any transportation service is the mobility and accessibility increases it provides to the user. If a mode has the same mobility and accessibility characteristics, but higher environmental externalities of an alternative, then it might be seen as an inferior mode. In the case of the electric bike, it certainly emits more pollution and has a slightly worse safety record than a bicycle or a bus, but it provides much higher levels of mobility and thus accessibility in Chinese cities.

Mobility is dependent upon the performance of the transportation system and the ease of movement through the urban area. Mobility improvements are often realized by increases in roadway capacity, improvements in operations to decrease congestion delay as well as development of high speed, grade separated transportation systems. While ease of movement is important to any urban area, the indicator that is most relevant to the needs of travelers is accessibility. Accessibility is defined as ease of reaching opportunities throughout the urban area, such as jobs, shopping, medical and social activities. Accessibility levels are dependent upon the urban form, distribution of land uses, impedance (travel time) and transportation infrastructure. Accessibility can be improved in two ways, by proximity or mobility (Cervero 2005). Proximity is a function of urban form (i.e. jobs-housing balance) and mobility is determined by transportation system operations and vehicle performance characteristics. Cities with low auto-mobility could have high levels of accessibility due to proximity, such as an urban center. Cities with high auto-mobility might have low levels of accessibility due to lack of proximity, such as sprawling suburban communities. Cities with low auto-mobility might have high levels of accessibility via alternative modes because of compact development. Accessibility to jobs has been identified as a major contributor to poverty in developing countries and is an essential impact to consider in the development any transportation policy (World Bank 2002).

Accessibility is often quantified as an accessibility index (AI) - that is, the number of opportunities reached in a certain time. There are two methods commonly employed when developing an accessibility index (Cervero 2005). The first of these is a gravity based model, expressed mathematically as follows:

$$AI_i = \sum_j \left[Jobs_j \times Time_{ij}^{-v} \right]$$

The urban region is divided into small zones and the AI of residential zone *i* is the sum of all jobs across all zones *j* multiplied by an impedance factor, or the travel time from zone *i* to zone *j*. The exponent, *-v* is an empirically estimated factor to account for different travel time values of different trips. For instance, people value time differently for job and shopping trips, and are thus more inclined different amounts of time accessing those opportunities.

The second and perhaps more intuitive method to quantify accessibility is to use an isochronic methodology. This simply calculates the total number of opportunities accessible within a certain travel time. It can be expressed as follows:

$$AI_i = \sum_j \left[Jobs_j (Time_{ij} < m) \right]$$

This is similar notation as the previous equation. This expression summarizes the total number of jobs in zones *j* that are within *m* minutes travel time of residential zone *i*. While AI is different using both of these methodologies, when consistent models are used, accessibility comparisons can be made on several different factors, including the comparison of accessibility between modes, regions in a city, and socioeconomic classes. The AI ratio between two units of comparison is the relative accessibility advantage. For instance, a mode of transportation that can reach 500 jobs within 20 minutes has a relative accessibility advantage of 2, when compared to a mode that can reach 250 jobs within the same time period.

Much of these analyses are dependent upon the quality and level of aggregation of data available to the analyst. Speed studies were conducted in Kunming and Shanghai to identify mobility advantages of electric bike users. To identify accessibility changes, census-type data was acquired that includes the spatial distribution of jobs and residential locations. These analyses are presented in the following sections.

6.2 Measuring Mobility Increases

In order to identify the differences in mobility between modes, the average operating speed of electric bikes, bicycles and buses are identified. The average operating speeds of buses in Kunming and Shanghai is just over 10 km/hr (including stops) (Fudan News 2004; Xinhua Net 2005). In Kunming, this is down from 16 km/hr in 2003 (Hook 2005; Kunming University of Science and Technology 2005). This operating speed does not truly represent the travel time of riding a bus because it does not include the time lost due to access and egress from bus stations, nor does it include wait time or transfer times. In Kunming, the average walk distance to or from a bus stop is about 300-400 meters and the average bus headways are around 6 minutes. Additionally, recent smart card fare payments have shown that the average rider transfers 0.5 times (Kunming University of Science and Technology 2005). These out-of-vehicle time losses, inherent in public transportation systems, result in about a 9 minute "penalty". Studies in the context of developed countries have shown that out-of-vehicle travel time (walking, waiting, and transfering) is two to three times more onerous than in-vehicle travel time (Truong and Hensher 1985; Small 1992). Depending on the length of the trip, this out-of-vehicle time can actually be more than the total in-vehicle time and in many cases represents much higher disutility than the in-vehicle time.

Most electric bikes have maximum operating speeds of around 30 km/hr and bicycles can also approach this maximum speed. In order to identify the true travel time increases, average operating speeds (including signal delay) need to be measured for both modes. This was done using a floating vehicle methodology. Speed measurements captured with a handheld Global Positioning System (GPS) interfaced with a Geographic

Information System (GIS). The software and hardware configuration is shown in Table 6.1.

Table 6.1: Hardware and Software Configuration Used For Speed Collection

Hardware/Software	*Specifications*
Dell Axim X5 Handheld PDA	Windows Mobile 2003, 300MHz Intel
US Global Sat Compact Flash GPS Receiver	SiRF Star III Chipset
ESRI ArcPad 7.0 PDA GIS Application	
ESRI ArcGIS 9.0 Desktop GIS Application	

A speed measurement is collected every second. Under the floating vehicle methodology, the measurement vehicle "floats" in a traffic stream or platoon of vehicles, adopting the average speed and balancing the number of vehicles that are overtaken by the number of vehicles that overtake the measurement vehicle. This results in an approximate median speed distribution. Since the sum of overtaken vehicles is zero, the speed observations from floating vehicle studies represent the space mean speed (McShane, Roess et al. 1998). The difference in average speed observations represents the mobility advantage of various modes.

From March to May 2006 speed studies were conducted for bicycles and electric bikes during weekday morning (7am to 10am) and evening peak (4:30pm to 7pm) travel periods on all major roads in Kunming and a subset of major commute routes in Shanghai. Each road was traversed twice in each direction, once representing an average bicycle and once representing an average electric bike. A visual example of the data collected and displayed on a GIS application is shown in Figure 6.1.

Figure 6.1: Example Speed Data Collected in Southeast Kunming

Each point in Figure 6.1 represents a GPS data point and a speed observation. Some observations are missing, because of the urban canyon effect obscuring a large portion of the sky, and thus reducing the GPS signal strength. This could possibly introduce bias into the recorded speeds; but the direction of the bias is unknown. In the urban centers, where observations are missing, the street network is denser than areas with low building heights, causing more intersection and signal delay. Undersampling these points would result in measured average speeds that are *higher* than actual average speeds, that is, one would oversample areas outside of the densest urban areas where operating speeds are higher. However, the urban canyon effect is most pronounced in mid-block sections, where vehicle speeds are higher, thus undersampling high speed sections and oversampling low speed areas at intersections (where the view of the sky is larger). This would result in measured speeds that are *lower* than the actual average speed. These effects should be small since there are few areas where this bias might occur.

In Kunming, over 10,000 speed observations were collected for electric bikes and over 13,000 speed observations for bicycles. In Shanghai, over 7,000 electric bike and over 6,000 bicycle speed observations were collected. The speed distributions for both cities are shown in Figure 6.2 and 6.3, with the dashed lines indicating average speed, not including stops, and the solid lines indicating average speed including stops (as presented in Figure 5.1 and 5.2). There is little difference between the speeds in both cities, implying that these results may be transferable to other cities with similar bicycle infrastructure.

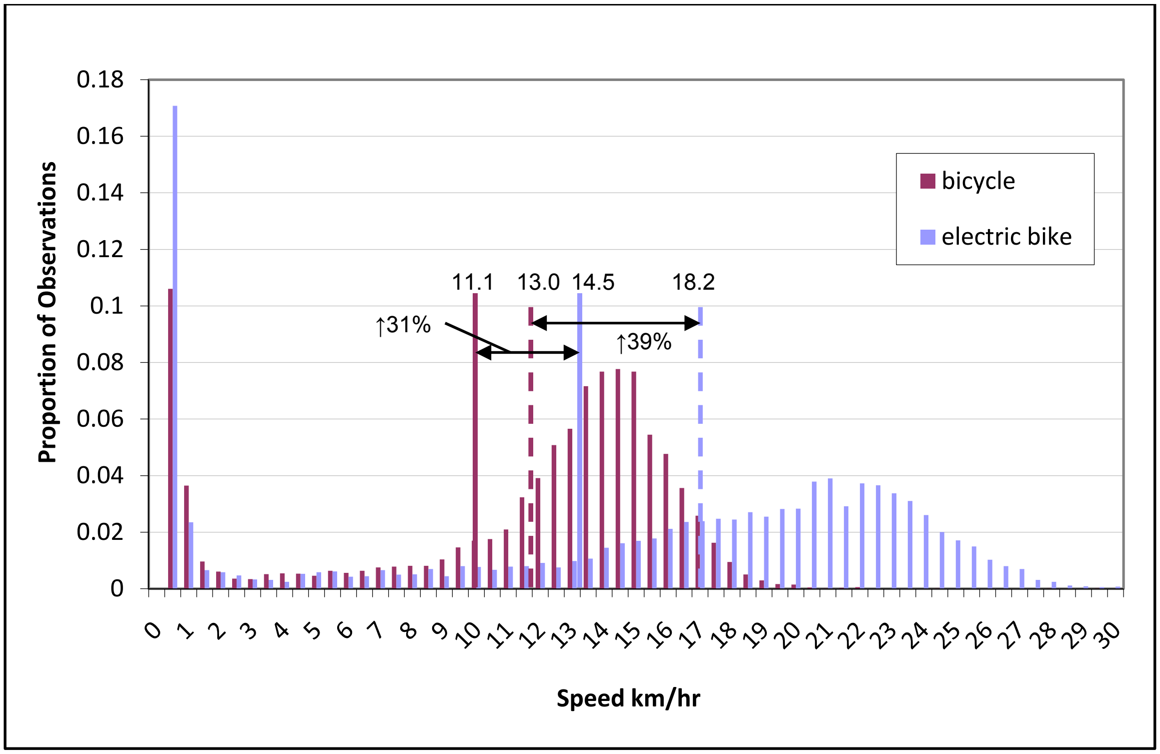

Figure 6.2: Histogram of Measured Speed Data in Shanghai

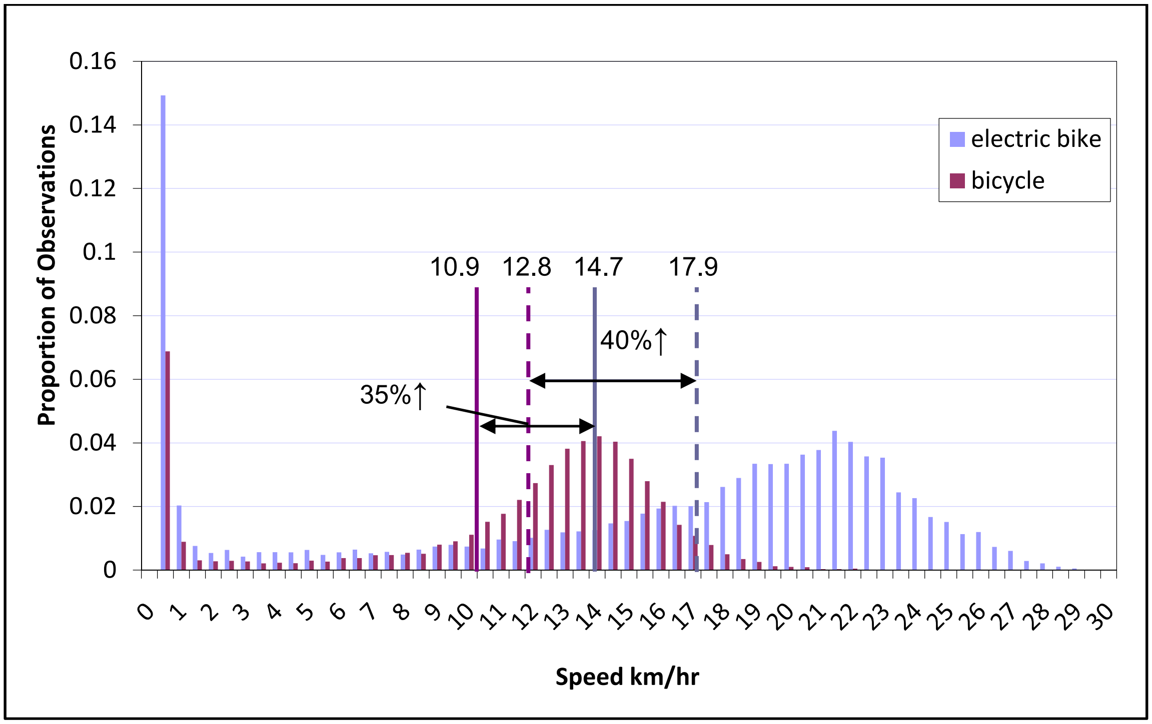

Figure 6.3: Histogram of Measured Speed Data in Kunming

The figures show that electric bike users do in fact travel significantly faster than bicyclists. The average speed (not including stops) is about 18 km/hr, or 40% higher than the average speed of bicycles (13 km/hr). Since electric bikes are faster than bicycles, they spend a higher proportion of their travel time stopped at signals. Electric bikes spend 17% and 15% of the time stopped in Shanghai and Kunming, respectively; compared to 10% and 7% for bicycles in both cities. The overall average speed drops to about 14.6 km/hr and 11 km/hr for electric bikes and bicycles, respectively. Assuming that bicycles and electric bikes travel on the same network, this results in about a 33% mobility advantage for electric bikes. Figure 6.4 shows the average distance and travel time differences of the three competing modes in Kunming.

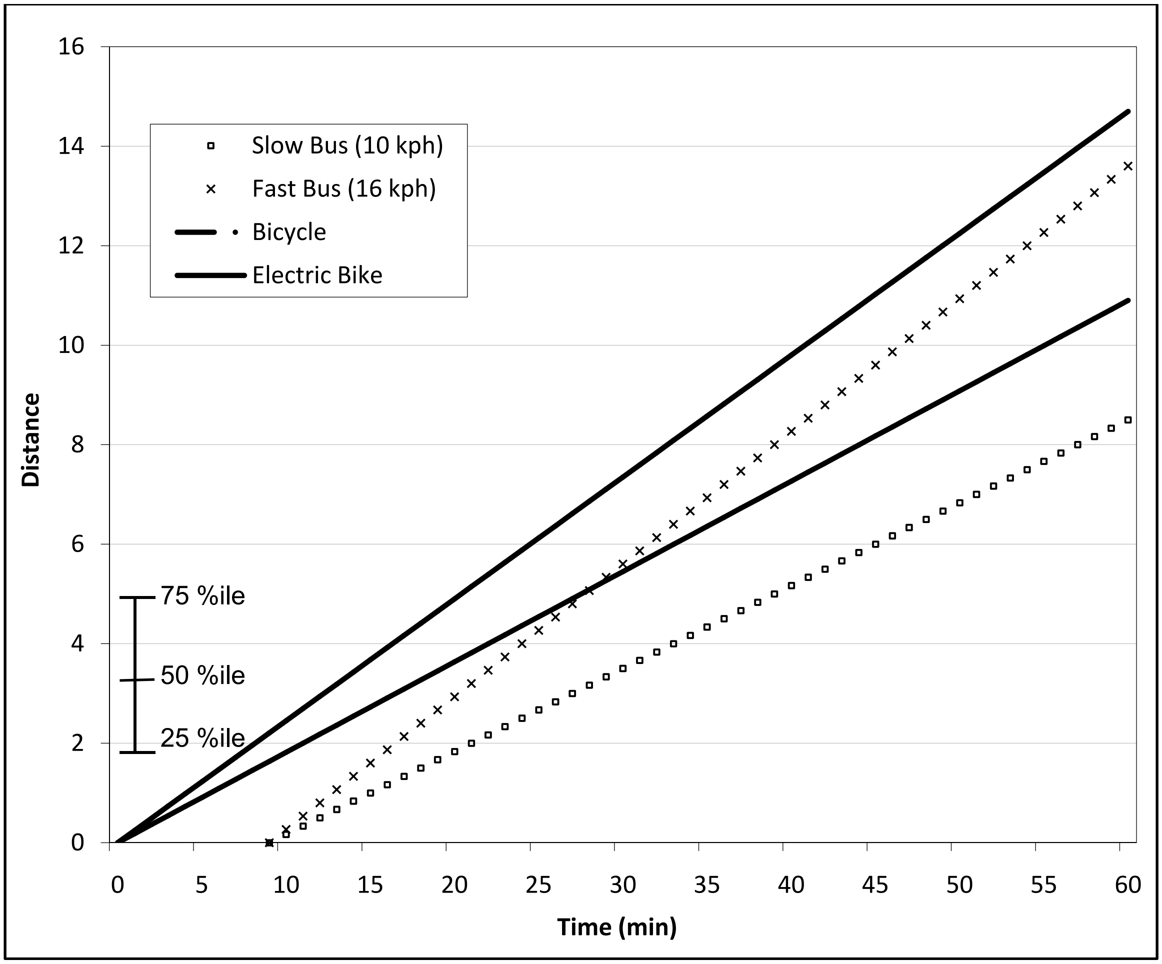

Figure 6.4: Speed Advantage of Various Alternative Modes

The four modes represented are the slow bus (10 km/hr), the fast bus (16 km/hr), the bicycle (10.9 km/hr) and the electric bike (14.7 km/hr). The interquartile trip lengths for two-wheelers, obtained from the travel surveys, are shown on the left side of Figure 6.4. This figure represents straight line travel routes for all modes implying that buses and two-wheelers share the same network distance, which is slightly unrealistic. This graph underestimates the advantage of two-wheelers, since it implies that buses and two-wheelers take the same route. This is not true and buses generally have to travel less direct routes, increasing their average origin to destination trip length and thus travel time, relative to two-wheelers. For buses, because of the lost time throughout the trip, the fast bus is only competitive with bicycles on trips longer than about 5 km, which comprise only 25% of the two-wheeled vehicle trip lengths. It is considerably higher than the median trip length of two-wheeled vehicles (about 3.25 km). It is never competitive with electric bikes. The slow bus, which represents Kunming's current bus operation is never competitive (in terms of travel time) with either two-wheel mode.

6.3 Job Accessibility Gains: The Case of Kunming

The higher speeds of electric bikes will increase the accessibility for shopping, services and job opportunities in Kunming's urban area. In the case of Kunming, spatial representations of origins (points representing the centroid of 3000 residents) and destinations (points representing the centroid of 3000 jobs) were entered in a GIS system overlaid with a bus network. Kunming is a monocentric city with over 45% of the employment opportunities located within the first ring road, where gasoline motorcycles and other forms of low cost, informal transportation are prohibited. An additional 35% of the employment opportunities are located between the 1st and 2nd ring road. Similar to most cities in China, residential development is occurring rapidly in suburban areas. In 1995, only 32% of Kunming's population lived outside of the 2nd ring road. In 2002, that number grew to 65% of the population residing in residential districts outside the 2nd ring road, mostly on transit oriented corridors to the north, southwest and southeast (Kunming University of Science and Technology 2003). Figure 6.5 shows the distribution of jobs and residents in Kunming's urban area (not including the distant suburbs to the south).

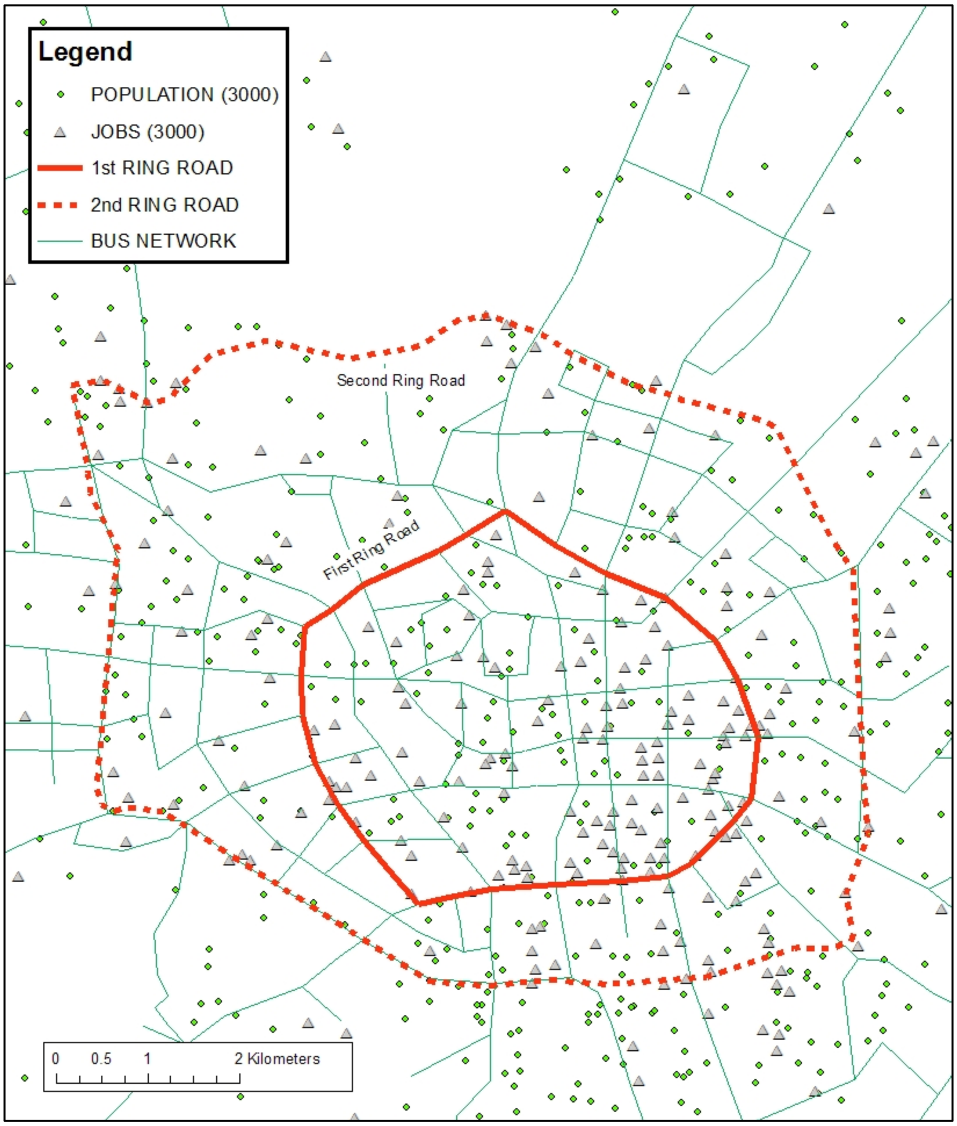

Figure 6.5: Residential and Job Distribution in Kunming

An isochronic accessibility index is used to identify the accessibility advantage of various modes in Kunming. To calculate the mode-specific job accessibility index, the total number of jobs that can be accessed from a destination, within a certain travel time are counted. In order to identify the travel time from the origin to the destination, the city-wide average speed is used for each mode, 10.0 km/hr, 10.9 km/hr and 14.7 km/hr for bus, bicycle, and electric bike, respectively. The distance from the origin is calculated using these speeds and the predetermined time thresholds. In the case of the bus, the shortest path across the bus network is calculated, and the travel time is increased by nine minutes to reflect the average lost time spent walking to and from the bus stop, waiting for the bus and transferring. Since bicycles and electric bikes have much more flexible route choice characteristics, Euclidean distance is used and reduced by 1.17 to reflect the network reduction factor (Euclidean distance/network distance) estimated from the origin and destination pairs in the surveys.

The map presented in Figure 6.6 shows an example of isochronic job access by the three modes within 20 minute travel time from an origin in the city center. Each point represents 3,000 jobs and it is clear that bus access is by far the mode with the poorest accessibility. Within 20 minutes, electric bikes can reach most of the job opportunities in the urban area, bikes reach a smaller proportion and buses reach a very small proportion. This is clearly because bus riders rely on a non-demand responsive mode that does not provide door-to-door access. Bus riders spend nearly half of the travel time accessing the bus network and waiting for the bus.

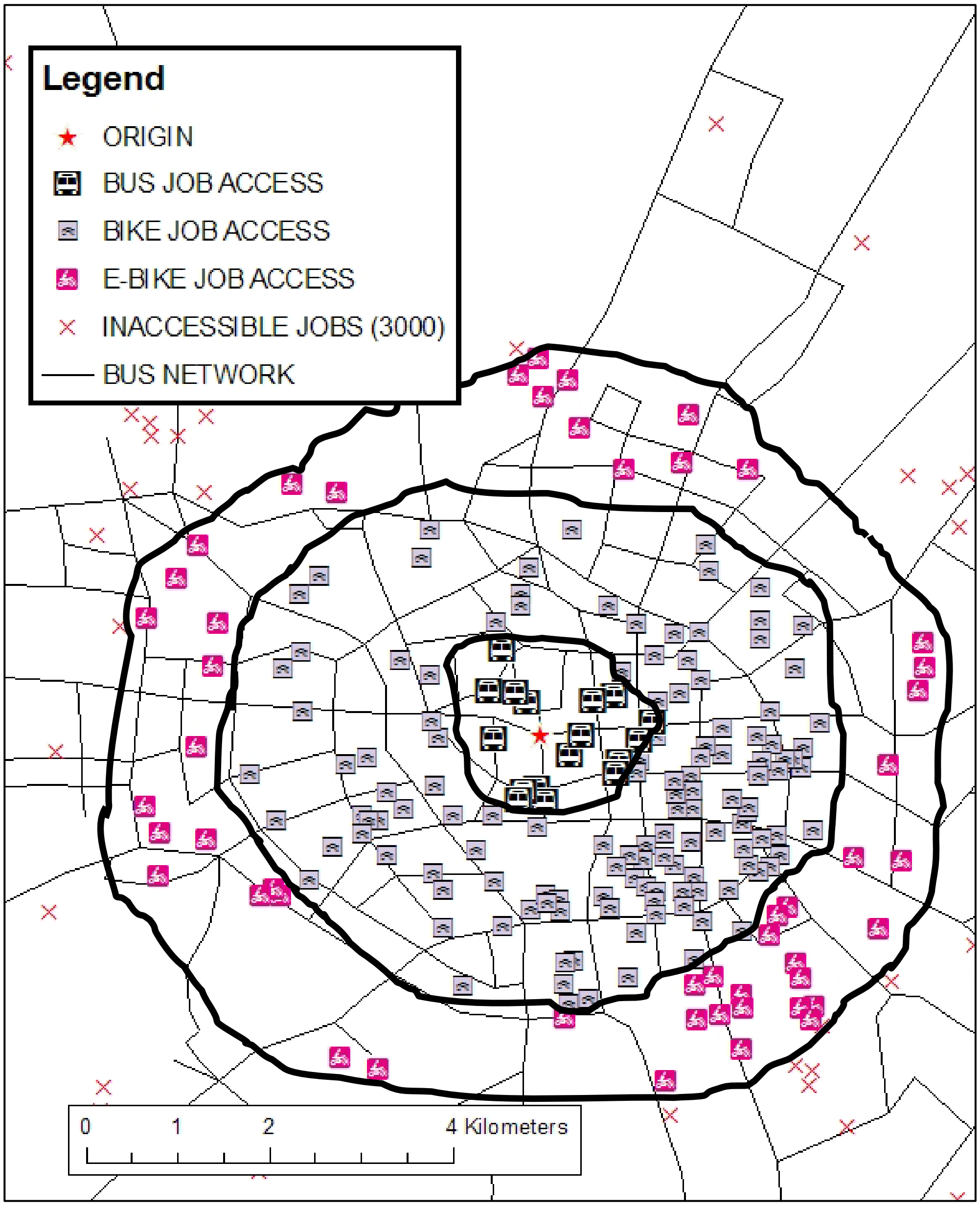

Figure 6.6: Mode Specific Jobs Access Within 20 minutes of Kunming City Center

Buses operate on a limited network, but could have higher operating speeds on certain corridors. Figure 6.6 illustrates a bus operating at 10 km/hr and about half of the 20 minute trip time is lost during access, wait, and egress times. As trip distances extend, a higher proportion of the time is spent moving and the bus' disadvantage is reduced.

While this map is an interesting illustration, to calculate the true accessibility advantages of electric bikes in Kunming, one has to calculate the number of jobs accessed at different time increments from all residential locations. From a given origin, if a traveler can reach 20 jobs by bicycle and 30 jobs by electric bike within a certain time frame, then the accessibility index ratio would be 1.5, or electric bikes provide 50% more accessibility than bicycles. Using GIS tools, accessibility indices are calculated in ten minute increments for all 695 residential locations, each representing 3000 residents. Table 6.2 shows the average accessibility indices for electric bikes compared to buses and bicycles. Bus is included twice, the current 10 km/hr operating speed and the 16 km/hr operating speed of a couple of years ago. This illustrates the drop in accessibility as a result of reduced operating speeds.

Table 6.2: Job Accessibility Between Electric Bike and Alternatives

	Cumulative jobs accessed from all residential origins (x3000)					
	10 min	*20 min*	*30 min*	*40 min*	*50 min*	*60 min*
Bicycle	12508	43984	80814	115223	146332	171103
Bus (10kph)	0	3002	17938	42587	68878	99021
Bus (16kph)	0	8672	44753	90246	132313	165930
E-bike	21985	69673	116736	157266	183590	195956
	Accessibility Index Ratio					
	10 min	*20 min*	*30 min*	*40 min*	*50 min*	*60 min*
E-bike/Bicycle	1.76	1.58	1.44	1.36	1.25	1.15
E-bike/Bus (10kph)	Inf	23.21	6.51	3.69	2.67	1.98
E-bike/Bus (16kph)	Inf	8.03	2.61	1.74	1.39	1.18

Because of electric bikes' higher operating speeds and door-to-door performance, they provide, by far, the highest level of accessibility. Electric bikes have the highest accessibility advantage over alternative modes for short trips. Notably, electric bikes provide access to 23 times more jobs than buses within a 20 minute travel time. Electric bikes also provide 58% more accessibility to jobs than a bicycle within 20 minutes. This is significant, because 70% of all trips made by bicycle and electric bike fall within this time category. As trips become longer, vehicles begin to reach most of the jobs in the region and the higher speed of electric bikes does not result in increased job access. The jobs reached within 60 minutes are similar across modes (except the slow bus), because all modes can reach most jobs in the region within one hour.

The reduced speed of buses over the past several years has had a major effect on job accessibility. In 2003, the job access by bus within 30 minutes was 2.5 times higher than what it is now. This is a significant decline and reduces the competitiveness of public transportation compared to personal transportation modes. There are some nuances that were not considered in this analysis, particularly route or segment specific bus operations. The average operating speed for the entire bus network was used, but there are some very poorly operating routes, with average speeds on the order of 4 km/hr (Kunming University of Science and Technology 2005). There are also some very efficient segments, particularly the BRT lines that traverse the center of the city, with speeds approaching 15-18 km/hr (Hook 2005). Kunming's goal is to operate these segments at around 20-25 km/hr. In the future, as trip distances increase because of urbanization and spatial expansion, there are many opportunities to improve bus job access. If jobs and housing orient themselves around these BRT stations such that walk distances and wait times are minimized and high operating speeds are maintained, then buses can provide high levels of access to the city. As long as development patterns are not oriented around transit infrastructure and buses do not have dedicated infrastructure, then they will almost certainly provide relatively poor mobility and access to opportunities in the city.

Electric bikes provide high levels of accessibility in a number of ways.

1) They are flexible and meet the needs of individuals accessing spatially separated opportunities as a result of disorganized development patterns that characterize many Chinese cities.
2) They operate on somewhat dedicated infrastructure, in most cases bicycle lanes. The maneuverability of bicycles allows bicycle lanes to provide high levels of capacity and two-wheeler congestion in bicycle lanes is rarely a significant cause of delay.
3) They provide door-to-door service, requiring less time lost to walking
4) Often times, they are able to take more direct routes from the origin and destination.
5) They are faster than most other modes, including personal cars during peak periods on congested corridors.
6) They have more range and are more comfortable than bicycles, allowing users to increase trip lengths.
7) They are easy to park.
8) They are maneuverable and small and thus can navigate congested transportation infrastructure that larger vehicles cannot.

All of these factors contribute to the accessibility advantage of electric bikes, compared to almost any other mode, including personal automobiles. The goal of a policy maker is to maximize accessibility benefits of a transportation mode and minimize user and social costs. Electric bikes provide high levels of mobility and accessibility and somewhat low operating and ownership costs.

CHAPTER 7: IMPACTS OF ELECTRIC BIKE PROHIBITION

The previous chapters investigated some of the environmental and safety costs associated with electric bike use and some of the mobility and accessibility benefits to the users of electric bikes. This chapter will synthesize these findings and identify the effects of electric bike regulation, such as a city-wide ban, on the transportation system. The city-wide impacts of such a ban are estimated for both of the case cities, Kunming and Shanghai[9]. The environmental impact of a full ban will be quantified, along with safety impacts and mobility losses.

7.1 Kunming

7.1.1 Vehicle Population and Travel Behavior

By March 2006, Kunming had approximately 137,000 electric bikes registered with the local Public Security Bureau (PSB). The PSB estimates 60-70% of electric bikes in Kunming are registered. Field observations found this value to be close 60%, resulting in about 230,000 electric bikes in Kunming. Figure 7.1 shows the rapid growth of electric bikes in Kunming. The exponential growth indicates that, left unchecked, electric bike ownership will continue to rise in the coming years.

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[9] It is important to note that both of these cities have generally adopted electric bikes and are thought of as pro-electric bike cities. Neither city has expressed an explicit desire to ban them so these analyses are hypothetical and could be thought of as “representative” cities with different characteristics. More importantly, these case studies present a framework to analyze the impacts in any city.

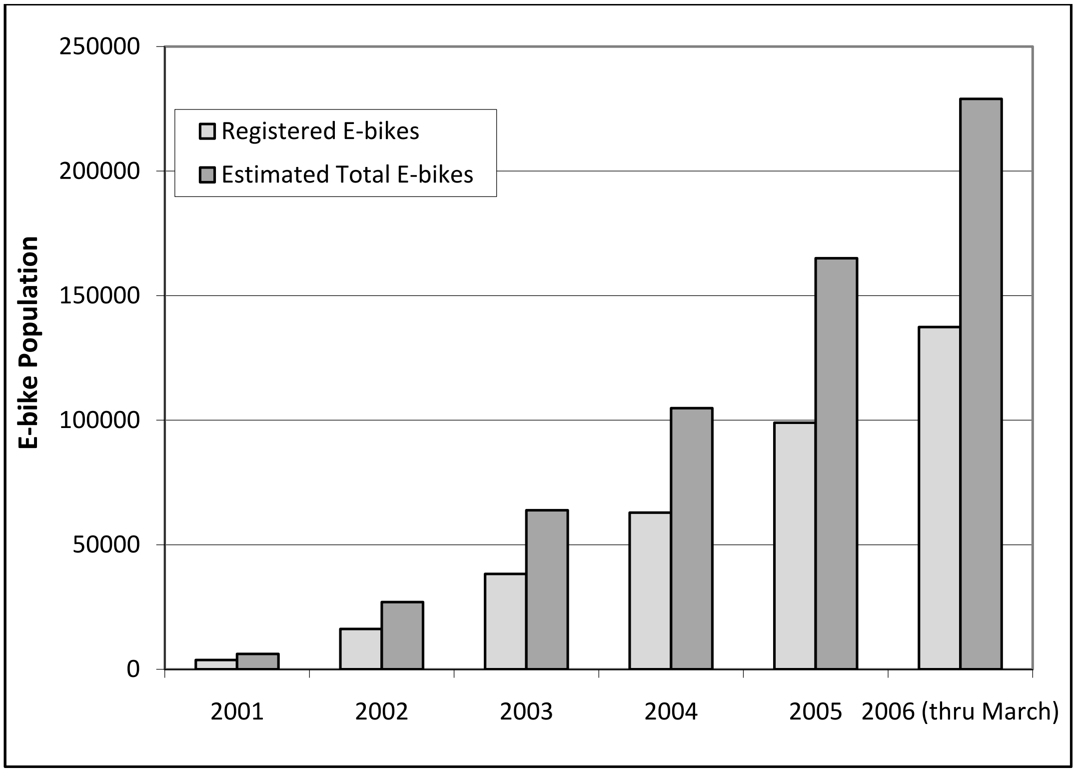

Figure 7.1: Electric Bike Ownership in Kunming

In order to make any inference regarding the impact of regulation on electric bikes in China, the use patterns of electric bike riders must be considered. Data from the survey discussed in Chapter 3 indicate that, on average, electric bike riders travel 9.2 km/day, on a weekday. The data also indicate that over 60% of the trips on an average weekday are work or school related commute trips. Since little is known about weekend travel, this analysis consider the average electric bike use only during the week, which results in about 2400 km/e-bike/yr. Using these estimates, the total electric bike kilometers traveled in 2006 is 552 million (230,000 e-bikes X 2400 km/e-bike/yr).

If electric bikes are prohibited, electric bike users will still make most of the trips that they previously made. Very few electric bike respondents said they would not take the trip if an electric bike were unavailable. This analysis assumes that all trips will be made between the same origin and destination by the best stated alternative. Figure 7.2 (derived from figure 3.2) shows the distribution of mode choice that electric bike users in Kunming stated they would shift to if electric bikes were banned. So, all 230,000 electric bike users would make all of the same trips by various alternative modes if electric bikes were banned. This would shift about 535 million yearly passenger kilometers to alternative modes. Figure 7.2 also shows the total passenger kilometers traveled (PKT) that shift to those modes in parenthesis based on average trip lengths made by each stated alternative mode. For instance, while 8% of electric bike *trips* would switch to walk trips, because of the shorter average distance of walk trips, less than 4% or 20 million *PKT* will shift to walk trips if electric bikes were unavailable. An important adjustment was made to the displaced bus PKT. Since buses are constrained to a bus network that takes less direct routes, the displaced PKT from a trip that originated on a personal mode of transportation (electric bikes) will be about 10% more distance by bus. This value was calculated by comparing the network reduction factors (network distance divided by euclidean distance) for buses and personal modes, which are 1.29 and 1.17, respectively. This is an important distinction as it will increase the effective travel of a person who shifts to bus and thus increase emissions. It is important to measure displaced PKT because the above analyses presented in previous chapters identify impact rates per kilometer (i.e. fatalities/1,000,000 VKT or grams of pollution/kilometer). This difference is important when considering the *net* environmental and safety impacts of a mode shift.

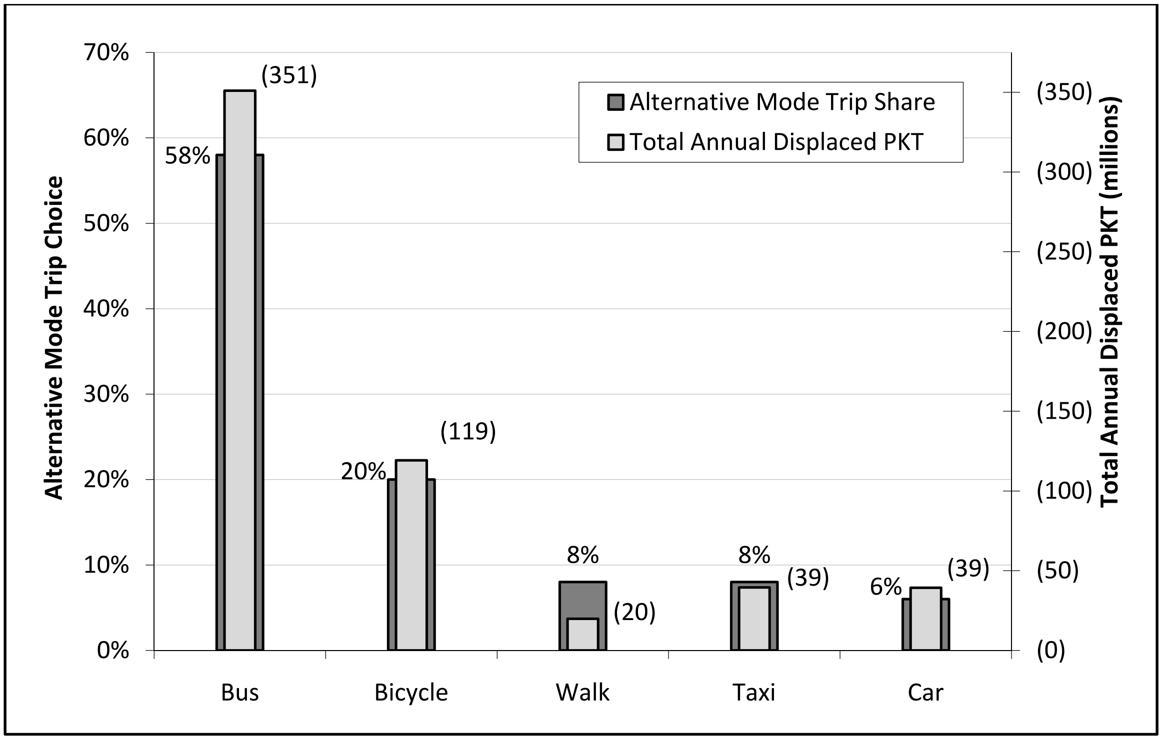

Figure 7.2: Best Stated Alternative Mode and Displaced PKT in Kunming

As discussed in previous chapters, the electric bikes' net impact on the transportation system is related to the relative advantage or disadvantage it has on many metrics compared to alternative modes. As expected, most trips (86%) would be made on other low cost and environmentally friendly modes, namely buses, bicycles, and walking. Still, a small but significant share of the trips is made by automobiles and, because autos have impacts that are orders of magnitude higher than buses or bicycles, this small shift could have major economic and environmental implications.

7.1.2 Environmental Impacts of Mode Shift in Kunming

Notably, 58% of electric bike trips switching to bus trips would add 351 million passenger kilometers of bus travel to the bus system. Because buses are inherently indivisible, it is unclear how much additional pollution and energy use would result from these trips. If this extra demand can be met by excess capacity during the off-peak hours, then the marginal environmental impact would be negligible. In Kunming, the average load factors are 105% (75 passengers/bus) in the peak hours and 48% (34 passengers/bus) over the entire day (Kunming University of Science and Technology 2005). Since most electric bike travel is for commute purposes, a considerable amount of capacity would likely have to be added and thus result in higher emissions. For the sake of this analysis, I will assume that all increased demand as a result of electric bike shifts to public transit will result in a concomitant increase in capacity.

Bicycles are the most environmentally friendly mode of transportation. An estimated 20% of the electric bike trips would shift to bicycle if electric bikes were banned, resulting in an additional 119 million vehicle kilometers traveled by bicycle. Although bicycles use human energy and don't emit any pollution during use, they do have some environmental impacts during the production phases, resulting in some lifecycle emissions. It is unclear how much additional caloric energy requirements are met by increased food consumption and the environmental effects of food production. This issue is outside the scope of this work.

In Kunming, approximately 70% of the electric bikes are SSEBs, which require more energy and emit more pollution than BSEBs. Table 7.1 (adapted from Chapter 4) shows the weighted average emission rates from electric bikes, accounting for SSEB and BSEB ratios. Additionally, the environmental impacts are shown for buses and bicycles. While it was outside the scope of this work to conduct a full environmental life cycle analysis of an average car in China, a study was conducted in the USA (Sullivan, Williams et al. 1998), whose results could be cautiously[10] compared with other more sustainable modes. These impacts are adjusted to be consistent with this dataset and included in Table 7.1.

Table 7.1: Environmental Impacts in Kunming (g/pax/km unless otherwise noted)[i]

Life Cycle Phase	Mode	CO[ii]	CO_2	HC[ii]	NO_X[iii]	SO_2	PM	Lead (Pb)	Energy (kWh/pax/km)
Prod.	Bus[iv]	Unk	22.9	Unk	Unk	0.014	0.050	0.005	0.029
	E-bike[iv]	Unk	16.7	Unk	Unk	0.041	0.152	0.922	0.040
	Bicycle[v]	Unk	4.7	Unk	Unk	0.014	0.059	0.000	0.018
	Car[vi]	0.623	91.8	0.562	0.307	0.689	0.277	0.299	0.224
Use	Bus	0.159	25.5	0.015	0.270	0.002	0.015	0.000	0.102
	E-bike	Unk	6.5	Unk	0.016	0.070	0.003	0.000	0.027
	Bicycle	0.000	0.0	0.000	0.000	0.000	0.000	0.000	0.031
	Car[vi]	9.434	214.2	1.108	1.010	0.000	0.000	0.000	1.176
Total	**Bus**	**0.159**	**48.4**	**0.015**	**0.270**	**0.016**	**0.065**	**0.005**	**0.131**
	E-bike	**Unk**	**23.2**	**Unk**	**0.016**	**0.111**	**0.156**	**0.922**	**0.067**
	Bicycle	**0.000**	**4.7**	**Unk**	**0.000**	**0.014**	**0.059**	**0.000**	**0.049**
	Car	**10.057**	**306.0**	**1.670**	**1.316**	**0.689**	**0.277**	**0.299**	**1.400**

Notes:
Unk=Unknown
i-Assumed lifespan affects these numbers. The assumed lifespans are based on interviews or product specifications and can vary depending on the manufacturer. The generally accepted values are as follows: Bus-1,000,000 km, Bicycle-20,000 km, Electric Bike-50,000 km. Average bus loading assumed is 50 passengers, which results in 50,000,000 passenger kilometers over the lifespan of the bus.
ii-CO and HC emission rates are unavailable for production processes and for power plant in China, so several values are unknown. The values reported in the "**Total**" rows are considered minimums because the omit some of the life cycle processes.
iii-NO_X emission rates are unknown for production processes, but are known for power plants. The values reported in the "**Total**" rows are emission rates during the use phase, but do not include the production process emissions.
iv-Production processes include manufacturing processes and fuel production (diesel refining or coal mining and processing)
v-Production processes include manufacturing and does not include any fuel processing
vi-From (Sullivan, Williams et al. 1998)

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[10] An LCA was conducted of an "average" car in the USA in 1995. The "average" American car is likely larger than the "average" Chinese car and might get lower fuel economy. However, emission standards in the USA (Tier I) in 1995 are similar to Euro III emission standards that China plans to adopt nationwide in 2007. Also, manufacturing processes could be "dirtier" in China than they were in the USA in the mid 1990s.

As discussed in Chapter 4, electric bikes perform better on some metrics and worse on others. As expected, bicycles have the best environmental performance, by several orders of magnitude on most metrics. These emission rates can be extended identify the total emissions from a massive mode shift. Given that 351 million passengers kilometers of travel will shift to bus and 119 million will shift to bicycle, the net impacts of such a shift will result in increased total emissions of some pollutants and decreases in others. Additionally, all shifts must be considered. Omitting certain modes will underestimate the total environmental impact, especially if the omitted mode has a large environmental impact like an automobile.

Although only 14% of the trips, or 78 million of the total passenger kilometers traveled, will be displaced to personal motorized transport (car or taxi), this small shift most likely has the greatest environmental impact. These impacts are shown in Table 7.2.

Table 7.2: Total Emission Changes Resulting From Mode Shift-Kunming [i]
(metric ton/yr unless otherwise noted)

Shift to mode:	CO_2	NO_X[ii]	SO_2	PM	Lead (Pb)	Energy (MWh/yr)
Bus (58%)	9624.5	89.8	-29.8	-26.9	-292.0	24618.0
Bicycle (20%)	-2201.4	-1.9	-11.6	-11.6	-109.9	-2139.4
Walk (8%)	-459.8	-0.3	-2.2	-3.1	-18.3	-1.3
Car/Taxi (14%)[iii]	22266.1	102.4	45.5	9.5	-49.1	104992.3
Total Yearly Net Impact	**29229.4**	**190.0**	**1.9**	**-32.1**	**-469.3**	**127469.6**
Impact Per Electric Bike Taken Off Roadway (g/yr unless otherwise noted)						
	CO_2 (g/yr)	NO_X[ii] (g/yr)	SO_2 (g/yr)	PM (g/yr)	Lead (Pb) (g/yr)	Energy (kWh/yr)
Net Impacts Per E-bike	**127639.1**	**829.8**	**8.4**	**-140.0**	**-2049.3**	**556.6**

Notes:
i-calculated as: (Emission rate$^{\text{alternative mode}}$ -Emission rate$^{\text{e-bike}}$) x displaced passenger kilometers
ii-This does not include NO_X emissions from production processes of bicycle, bus, car, or electric bike
iii-From (Sullivan, Williams et al. 1998), assuming average American made car with lifespan of 120,000 miles

Considering only the shift from electric bike to bus or bicycle results in a net increase in CO_2 and NO_X emissions and a net decrease in other emissions and energy use. However when car trips are included, the shift from electric bike to all alternative modes results a net increase in vehicle life cycle emissions of CO_2, NO_X, and SO_2 as well as increased energy use. Notably, the 14% of electric bike users who shift to cars equates to over 50% of the negative impacts estimated from a ban on electric bikes. Car shifters totally negate the SO_2 benefits of electric bike users shifting to bus or bicycle. They also nearly double the amount of extra NO_X that is emitted from bicycles and buses and cars quintuple the amount of CO_2 emitted resulting from a shift to bus and bicycle. Electric bikes still result increased PM and Lead (Pb) emissions overall. Electric bike use in Kunming results in the emission of some 469 tonnes of lead per year into the environment, through various production processes.

The last row of the table shows the environmental impact per electric bike. This is the marginal effect of removing one electric bike from the roadway and distributing that rider into the transportation network using the alternative mode distributions. Every electric bike results in a net increase of 2 kilograms of lead into the environment, yearly. Other impacts are smaller. For every electric bike on the roadway, 128 fewer kilograms of CO_2 per year are emitted into the environment than if electric bike users shifted to alternative modes. Removing an electric bike from the roadway would result in over 500 kWh increase in energy demanded per year. To put this into perspective, the per capita primary energy consumption in China was about 9800 kWh/yr in 2002 (Lawrence Berkeley National Laboratory 2004). The energy saved by electric bike use results in about an 18% reduction in yearly energy demanded, per electric bike user.

7.1.3 Exposure Effects of Change in Pollution Levels in Kunming

Net pollution can be normalized by weighting urban tailpipe air emissions more heavily than generally non-urban production and power plant air emissions using the methodology described in Section 4.4.3. Normalizing, using these weights, results in lower overall public health impacts from air pollution when electric bikes are used because exposure of tailpipe emissions from buses and cars are higher and thus considered more heavily. Even so, overall PM emissions are still higher when electric bikes are used (particularly because cars emit very little PM from the tailpipe). Table 7.3 shows the results of this adjustment, considering the three criteria pollutants that have a large effect on public health and for which the most complete data are available.

Table 7.3: Total iF Normalized Net Emission Changes Resulting From Mode Shift-Kunming [metric ton/yr (remote source equivalent)]

	NO_X[a]	SO_2	PM
Bus	504.2	-28.2	1.7
Bicycle	-1.9	-11.6	-11.6
Walk	-0.3	-2.2	-3.1
Car	543.3	44.5	9.3
Net Normalized Impact	**1045.3**	**2.5**	**-3.6**

Notes:
[a]-only the total NO_X emissions from the use phase are included.

As expected, the impact of bicycles does not change (they have no tailpipe emissions, so the normalized emissions are only the production emissions). All pollutants increase for buses because of weights applied to tailpipe emissions of all three pollutants. Cars have minimal levels of SO_2 and PM pollution from the tailpipe, resulting in little change from Table 7.2, but significant change in NO_X as a result of weights applied to the tailpipe emissions. Considering exposure, the total net impact significantly changes in NO_X and PM with minor changes in SO_2, compared to Table 7.2. This illustrates the importance of considering exposure, rather than net pollutants emitted.

7.1.4 Transportation Network Safety in Kunming

Safety information is scarcely available to researchers in many Chinese cities. In Kunming's case, I was able to attain the total number of electric bike fatalities in 2005, which is hardly a representative sample. However, using these data and information about vehicle population and use, the average fatality rate for electric bike riders is 0.012 fatalities/million VKT. This is between Jiangsu and Zhejiang province's fatality rates of 0.007 and 0.039, respectively, so Kunming's seems reasonable. Zhejiang and Jiangsu provinces also include rural crashes, which could be more severe. Again, the safety impact is highly determined by the mode shift of electric bike users, should they be banned. Given that a portion (54% from (Zacharias 2002)) of crashes and thus fatalities are caused by cars, secondary fatalities rates are also estimated for bicyclists and pedestrians by multiplying the total yearly vulnerable road user fatalities by 54% (those caused by cars) and dividing by the total car kilometers traveled.

Considering the shift to various modes outlined in Figure 7.1 and the average crash rates for cars, bicycles, and electric bikes, the expected numbers of fatalities are shown in Table 7.4. The values in Table 7.4 could be considered a lower bound because they do not include primary safety impacts of bus users (who walk and wait along roadways while accessing the bus) and pedestrians who make the entire trip on foot. It is difficult to develop "fatality rates" based on exposure to traffic hazards for pedestrians.

Banning electric bikes could increase the pedestrian fatality rate by adding more pedestrians on the street, but that is not accounted for in this table. It also assumes that there is no induced travel from mode shift. That is, all shifts will only result in the same VKT as electric bike users. Bicyclists will likely travel less and cars will likely travel more, meaning that the total number of fatalities would increase because of the expected increased travel by cars.

Table 7.4 presents three scenarios based on the available data sets presented in Chapter 5. The *Low* scenario represents the lowest crash rates in the dataset, the *High* scenario represents the highest crash rates in the dataset and the *Avg* scenario represents the average crash rates in the dataset. The first three rows of the table represent the current situation in Kunming, with 536 million electric bike VKT and expected fatalities using the three scenario fatality rates. The bottom part of the table represents the expected fatality increases in the three scenarios, assuming mode shifts consistent with Figure 7.2.

Table 7.4: Net Safety Impacts of Electric Bike Ban in Kunming

		Average PKT (million)	Fatality Rate (fatality/ million VKT)	First Order Expected Fatalities	Second Order Fatality Rate (fatality/ million Car VKT)	Second Order Expected Fatalities	Total Expected Fatalities	Net Safety Impact (fatalities/ year)
Current Safety Situation								
Low	e-bike	536.15	0.007	3.75			3.75	
Avg	e-bike	536.15	0.019	10.37			10.37	
High	e-bike	536.15	0.039	20.91			20.91	
Shift to alternative mode								
Low	car/taxi	78.73	0.191	15.04			15.04	+13.10
	bus	351.00	?	?	?	?	0.00	
	bicycle	119.17	0.002	0.24	0.010	0.76	1.00	
	walk	19.84	?	?	0.011	0.82	0.82	
Avg	car/taxi	78.73	0.199	15.63			15.63	+11.27
	bus	351.00	?	?	?	?	0.00	
	bicycle	119.17	0.013	1.49	0.023	1.73	3.22	
	walk	19.84	?	?	0.037	2.78	2.78	
High	car/taxi	78.73	0.206	16.22			16.22	+5.50
	bus	351.00	?	?	?	?	0.00	
	bicycle	119.17	0.023	2.74	0.036	2.70	5.44	
	walk	19.84	?	?	0.063	4.75	4.75	

Although most opponents of electric bike use cite safety as a primary reason for regulating electric bike use, the safety situation of the entire transportation system would worsen if electric bikes were banned in Kunming. If the lowest fatality rates are used (primarily those reported in Jiangsu Province), there would be about 13 more fatalities per year in Kunming. If the highest fatality rates were used (primarily those reported in Zhejiang Province), there would be about 5 more fatalities per year. If the average crash rates of all data are used, then there would be about 11 more fatalities per year. Regardless of which scenario is chosen, increases in pedestrian fatalities (by walking to the destination or walking to the bus) are not considered and would result in at least a marginal increase of the yearly fatalities shown above. Almost all of these fatalities are car occupants, followed by vulnerable road users killed as a result of the increased auto traffics.

7.1.5 Mobility and Accessibility Advantages of Electric Bikes in Kunming

The above two sections show that electric bikes provide significant benefits to the transportation system. Although they are more polluting than buses and bicycles on many metrics and most electric bike users would otherwise use buses or bicycles in the absence of electric bikes, the negative impacts from the minority that switches to cars overwhelms the benefits of shifting from an electric bike to a bus or bicycle. Electric bikes provide clear benefits compared to almost all other modes in terms of increased mobility and accessibility to users. From Table 7.2, electric bikes increase commuter accessibility to jobs compared to bicycles and buses. Jobs access is 58% higher by electric bike than bicycle for over 70% of the trips. Jobs access is over six times higher by electric bike than by Kunming's current bus system for all trips less than 30 minutes.

Travel time savings are another metric to quantify the effects of mode shifts. Again, accessibility and mobility impacts are influenced by the proposed shift from electric bikes to alternative modes. Using a similar methodology as the ones in the previous section, Table 7.5 is generated. Mode shifts are proposed and travel time savings are generated based on average trip lengths and vehicle operating speeds. The operating speeds of electric bikes and bicycles are those measured in the field and the operating speeds of buses and cars are those reported in (Kunming University of Science and

Technology 2005; Xinhua Net 2005). Bus speeds are reduced to reflect nine minutes of access time and the average operating speed of buses over the average trip distance of those who would choose bus as an alternative. The trip lengths of bus riders are 10% longer than the same trip made by electric electric bikes, which exacerbates the already slow operating speeds of buses.

Table 7.5: Time Savings From Using Electric Bike in Kunming

		Average PKT (million)	Average Door-to-Door Operating Speed (km/hr)	Net Yearly Travel Time Saved (hr)	Total Yearly Time Savings (hr) (slow bus)	Total Yearly Time Savings (hr) (fast bus)
Current Electric Bike Operation Characteristics						
Current	e-bike	536	14.7			
Shift to Alternative Mode						
Future	car/taxi	78.73	15	107,117	**-33,563,557**	**-20,573,325**
	slow bus	351.00	7.1	-27,784,964		
	fast bus	351.00	9.6	-14,794,732		
	bicycle	119.17	10.9	-2,826,237		
	walk	19.84	4.5	-3,059,474		

Travel time savings can be calculated if it is assumed that all travel patterns are constant during this mode shift, that is, people will continue to make the same trips from the same origins and destinations but by alternative modes. Using the slow bus scenario, which Kunming is currently experiencing, maintaining electric bike use results in over 33 million hours of travel time saved per year. Almost all of these benefits are experienced by the 230,000 electric bike users. This results in an average time savings of 145 hours per electric bike user per year. The people who have most to gain are those who would otherwise switch to bus, who would save on average 208 hours per year. Supposing that the bus operating speed increases to what it was a couple of years ago, the travel time savings is still over 20 million hours per year. Economists often try to value travel time savings and often use a value of time methodology to estimate travel time savings. Often the value of time for work trips is the hourly wage of the worker, while the value of time on discretionary trips is somewhat lower. Considering electric bike users' average wage of 1905 RMB/month in Kunming and using conservative assumptions of 50 hour work weeks for 52 weeks results in an hourly wage of about 8.9 RMB/hr or about $1.15/hr. This results in between 23.7 and 38.6 million dollars of benefits per year to electric bike users.

7.1.6 To Ban or Not to Ban-Kunming?

In the case of Kunming, there are some very clear benefits to electric bike use. From an environmental perspective, allowing electric bikes reduces most emissions of pollutants when considering the full lifecycle impacts. Banning electric bikes would result in the yearly emission of 30 additional kilotonnes of CO_2 emissions, 190 tonnes of additional NO_X, 1.9 additional tonnes of SO_2, and 127 additional GWh of energy requirements. Banning electric bikes would result in some notable decreases in net emissions, particularly PM and Lead. However, most of these emissions occur during the production processes and are therefore not local, so the externalities of these emissions are not borne by Kunming residents. Still, a net release of some 469 tonnes of Lead will be emitted into the environment every year from electric bikes if they are allowed to continue to operate in Kunming. Considering exposure to urban versus non-urban emission sources, negative public health impacts of banning electric bikes are even greater than the net emission changes suggest.

Some of these externalities can be partially or fully offset by the improvements in transportation safety and travel time savings. The ban of electric bikes would result in a small shift to auto modes, which could result in 5-13 more fatalities per year than would have otherwise occurred. These fatalities would be the result of increased fatalities of auto occupants as well as increased secondary fatalities of vulnerable road users as a result of increased automobiles on the roadway.

Accessibility and mobility gains are a major benefit to Kunming's electric bike users. Job access increased by at least 58% for over 70% of the trips that would shift to bicycle. Job access also increased by six times for trips less than 30 minutes compared to buses. If these users are forced to find alternative modes to make the same trips, some 17-29 million hours of travel will be lost, resulting in decreased productivity and economic gains for the city. A value of time methodology results in between 20 and 33 million dollars worth of benefits experienced by electric bike users. If these benefits outweigh the costs of remediation of Lead pollution, then electric bikes should be promoted as a more sustainable mode in Kunming, to the extent that they reduce auto use.

7.2 Shanghai

Shanghai is a much larger city with much higher electric bike populations. Some of the data sources in this analysis do not have the same level of detail, but inferences can still be made. Shanghai generates most of its electricity from coal power plants and has different modal alternatives, resulting in different results than those presented above. A parallel analysis is presented below using the same methodologies used in the Kunming case.

7.2.1 Vehicle Population and Travel Behavior

Electric bike growth has occurred in Shanghai as it has in most cities over the past five years. Recent assessments estimate that the electric bike population to be around one million. As shown above, knowing the proposed mode shift if a ban is implemented is essential to understanding the net impacts. Electric bike users in Shanghai travel about 9.7 km/day on an average weekday. Similar to Kunming, over 50% of the trips are work related, indicating much of the travel occurs during the work week. Assuming the electric bike users only use their electric bike during the five day week, an average electric bike user might travel about 2500 km/e-bike/yr, a little higher than Kunming's average. Combining these estimates with vehicle population results in about 2.5 billion electric bike VKT per year.

Using the same assumptions as those above, I will assume that trips will be made by the best stated alternative. Figure 7.3 (derived from figure 3.2) shows the best stated alternative mode for electric bike users in Shanghai as well as the yearly total passenger kilometers traveled (PKT) that would shift to those modes in parenthesis. Based on Kunming's network reduction factors, it is assumed that bus trips are 10% longer than a personal mode between the same origin and destination, resulting in higher displaced passenger kilometers traveled by bus.

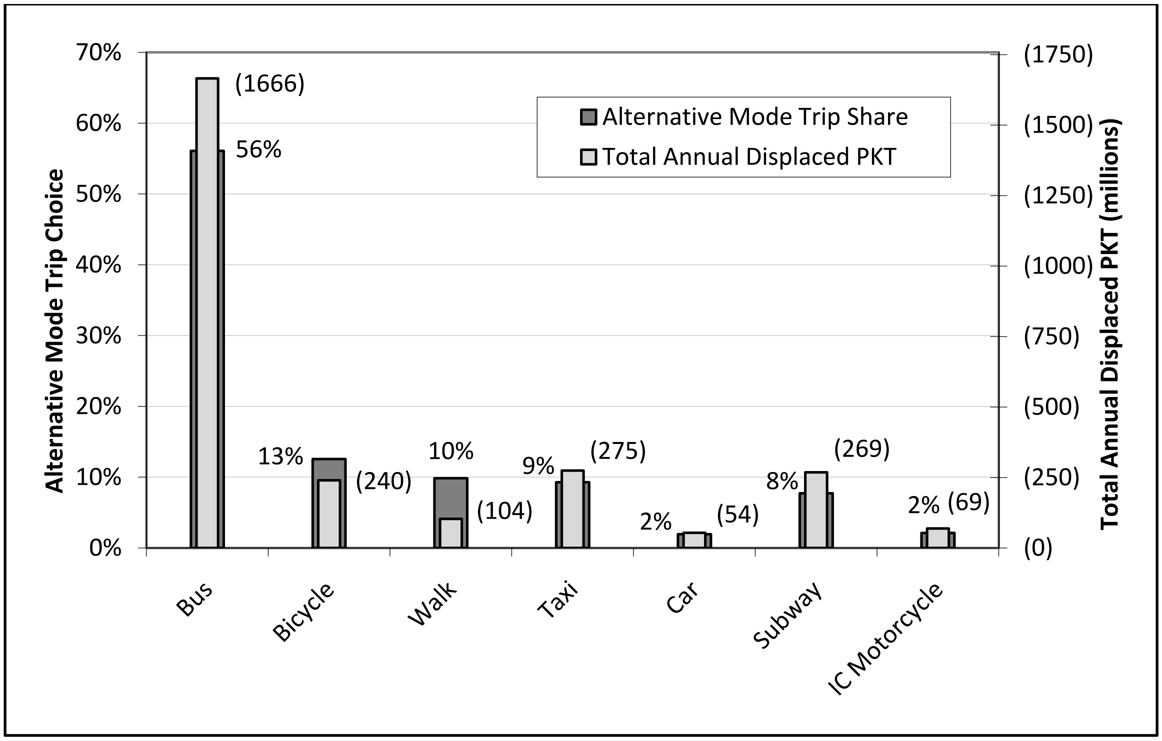

Figure 7.3: Best Stated Alternative Mode and Displaced PKT in Shanghai

This is similar to Kunming's distribution of responses with a couple of notable differences, particularly bicycles only capture 13% of the mode share and auto related modes (taxi and car) only capture 11% of the mode share. Subway and internal combustion engine (LPG and Gasoline) motorcycles are categories that were not available to Kunming. Because of shorter than average trip lengths, bicycle and walk modes only constitute about 14% (244 million kilometers) of the displaced PKT, although they displace 23% of the trips.

7.2.2 Environmental Impacts of Mode Shift in Shanghai

Electric bikes operated in Shanghai are powered by electricity that is almost exclusively coal generated. This results in increased emission and energy rates per kilometer compared to cities like Kunming that are more reliant on "clean" power generation. More primary energy is used because of the lack of renewable sources and more energy is required to produce coal. Bicycle style electric bikes are more popular than in Kunming. Based on observations, it is assumed that there is a 50% split between BSEBs and SSEBs. Using the same methodology as section 7.1.2, Table 7.6 is generated.

Table 7.6: Total Emission Changes Resulting From Mode Shift-Shanghai [i]
(metric ton/yr unless otherwise noted)

Shift to mode:	CO_2	NO_X[ii]	SO_2	PM	Lead (Pb)	Energy (MWh/yr)
Bus (56%)	36493.7	403.2	-240.2	-123.3	-1385.4	100886.2
Bicycle (13%)	-5889.7	-7.4	-39.1	-22.7	-221.3	-6837.7
Walk (10%)	-3030.5	-3.2	-18.3	-15.9	-95.6	-8005.0
Car/Taxi (11%)[iii]	91023.8	422.8	168.5	40.8	-205.1	435161.0
Total Yearly Net Impact (Omit IC Motorcycle and Subway	**118597.3**	**815.4**	**-129.1**	**-121.0**	**-1907.5**	**521204.5**
Impact Per Electric Bike Taken Off Roadway (g/yr unless otherwise noted)						
	CO_2 (g/yr)	NO_X[ii] (g/yr)	SO_2 (g/yr)	PM (g/yr)	Lead (Pb) (g/yr)	Energy (kWh/yr)
Net Impacts Per E-bike	**118597.3**	**815.4**	**-129.1**	**-121.0**	**-1907.5**	**521.2**

Notes:
i-calculated as: $(\text{Emission rate}^{\text{alternative mode}} - \text{Emission rate}^{\text{e-bike}})$ x displaced passenger kilometers
ii-This does not include NO_X emissions from production processes of bicycle, bus, car, or electric bike
iii-From (Sullivan, Williams et al. 1998), assuming average American made car with lifespan of 120,000 miles

There are some notable differences between these figures and those presented in Table 7.2 that reflects Kunming's environmental impacts. Firstly, because of Shanghai's near 100% reliance on fossil fuel generated electricity, the emissions impacts of the electric bike use phase are about 50% higher than Kunming. The energy use is even higher because of the inefficiencies in converting primary energy in coal to electricity.

All displaced trips are not included in Table 7.6. Motorcycles are not included in the above tables because of lack of LCA data and their relatively small contribution to the displaced PKT. They would likely improve the position of electric bikes because they are generally understood to be “dirtier” modes. Subway trips are not included either and could potentially change the results because they constitute a significant share of the displaced trips. They probably have a neutral effect on *Use* phase emissions. Consider an average modern metro train (car) that has a capacity of 200 passengers with an energy requirement of 2.6 kWh/km (Environment Canada 2005). This is about 1.3 kWh/100 passenger kilometers, the same as an average electric bike. This energy is required of the electrical power grid, the same source of electricity that electric bikes utilize, conveniently resulting in nearly identical emission rates per passenger kilometer from power plants. However, little is known about the full lifecycle emissions of subway trains, particularly from production processes.

7.2.3 Exposure Effects of Change in Pollution Levels in Shanghai

The intake fraction ratios of local (tailpipe) to remote (power plant and industrial) emission sources for Shanghai are used to normalize the emissions from autos and buses in the urban area to remote emissions, particularly from power plants. Table 7.7 is developed using the weighting technique discussed in section 4.4.3.

Table 7.7: Total iF Normalized Emission Changes Resulting From Mode Shift-Shanghai [metric ton/yr (remote source equivalent)]

	NO_X[i]	**SO_2**	**PM**
Bus	1578.3	-236.0	-55.9
Bicycle	-7.4	-39.1	-22.7
Walk	1553.8	168.5	40.8
Car	-3.2	-18.3	-15.9
Net Normalized Impact	**3121.5**	**-124.9**	**-53.6**

Notes:
i-only the total NO_X emissions from the use phase are included.

7.2.4 Transportation Network Safety in Shanghai

Using the same methodology presented in section 7.1.4, the traffic safety impacts of electric bikes are compared to those that electric bike riders would shift to in the event of an electric bike ban. Table 7.8 shows the results of this analysis.

Table 7.8: Net Safety Impacts of Electric Bike Ban in Shanghai

		Average PKT (million)	Fatality Rate (fatality/ million VKT)	First Order Expected Fatalities	Second Order Fatality Rate (fatality/ million Car VKT)	Second Order Expected Fatalities	Total Expected Fatalities	Net Safety Impact (fatalities/ year)
Current Safety Situation								
Low	e-bike	2521	0.007	17.65			17.65	
Avg	e-bike	2521	0.019	48.74			48.74	
High	e-bike	2521	0.039	98.33			98.33	
Shift to alternative mode								
Low	car/taxi	329	0.191	62.82			62.82	+52.49
	bus	1666	?	?	?	?	0.00	
	bicycle	240	0.002	0.48	0.010	3.30	3.78	
	walk	104	?	?	0.011	3.54	3.54	
Avg	car/taxi	329	0.199	65.29			65.29	+39.13
	bus	1666	?	?	?	?	0.00	
	bicycle	240	0.013	3.00	0.023	7.51	10.51	
	walk	104	?		0.037	12.07	12.07	
High	car/taxi	329	0.206	67.76			67.76	+7.27
	bus	1666	?	?	?	?	0.00	
	bicycle	240	0.023	5.52	0.036	11.72	17.24	
	walk	104	?	?	0.063	20.61	20.61	

The net fatality impacts range from 7 to 52 additional fatalities per year as a result of an electric bike ban. The direction of impact is consistent with Kunming’s and the values vary by an order of magnitude because the high and low fatality rates vary by an order of magnitude. The 11% shift to automobiles will result in over 60 fatalities of auto occupants, not including second-order fatalities due to conflicts with vulnerable road users. Depending on fatality rates of electric bike users, 17-98 electric bike fatalities can be expected per year (under static conditions). If those riders shift to alternate modes, 70-105 fatalities can be expected as a result of the shift. The net increase in fatalities would be somewhere between 7 and 52 fatalities/year. The true number of recent electric bike fatalities in Shanghai is unknown, but would be useful to validate the top half of the above table.

7.2.5 Mobility and Accessibility Advantages of Electric Bikes in Shanghai

Detailed job distributions are unavailable in Shanghai so detailed accessibility analysis is difficult or impossible to perform. Shanghai has a much larger urban area than Kunming, making it impossible to access every area of the city on modes with low range. Additionally, Shanghai is developing into a polycentric metropolis, with two main job centers (Huangpu and Pudong) and 4-5 sub-centers. The operating speeds of different modes are similar to those of Kunming, with electric bikes operating at 14.5 km/hr, bicycles operating at 11.1 km/hr, and buses operate at 10 km/hr now, down from 19 km/hr (Fudan News 2004). It is assumed that access, wait and egress lost time is 9 minutes, as it is in Kunming. It is assumed that cars operate at about 15 km/hr, but his varies greatly depending on the route and time traveled (Shanghai has a network of urban expressways). Subways operate at about 32 km/hr, and maintain average headways of about 5 minutes (similar to bus lines). Access time is assumed to allow for 400 meter (4 minutes X 2) walk access and waiting time of 3 minutes, resulting in 11 minutes of “lost” time. This could be a major underestimate because the limited coverage of the subway network could demand higher walk distances, reducing the total average trip speed. The average trip length of electric bike users who would shift to bus and subway are 5.2 km and 6.7 km, respectively. This results in average operating speeds, including access time and stops of 7.8 km/hr, 12.3 km/hr, and 17 km/hr for the slow bus, fast bus and subway, respectively. Using the travel time methodology in 7.2.5, Table 7.9 is developed.

Table 7.9: Time Savings From Using Electric Bike in Shanghai

		Average PKT (million)	Average Door-to-Door Operating Speed (km/hr)	Net Yearly Travel Time Saved (hr)	Total Yearly Time Savings (hr) (slow bus)	Total Yearly Time Savings (hr) (fast bus)
Current Electric Bike Operation Characteristics						
Current	e-bike	2512	14.5			
Shift to Alternative Mode						
Future	car/taxi	329	15	756,132	**-126,840,373**	**-48,703,287**
	slow bus	1666	7.8	-109,373,539		
	fast bus	1666	12.3	-31,236,454		
	bicycle	240	11.1	-5,068,508		
	walk	104	4.5	-15,880,122		
	Subway	269	17	2,725,664		

Largely because of the operation characteristics of Shanghai's current dominant alternative, the slow bus, electric bike users stand to lose over 126 million hours of productivity through lost travel time. If the bus operation could be improved from 10 km/hr to 19 km/hr, the lost time of such a mode shift could be reduced by nearly two thirds, to 48 million hours. All of these time benefits are borne by the one million current electric bike users. On average, every electric bike user stands to lose 126 hours per year under the worse case and 48 hours per year under the best case.

The average wage of electric bike users in Shanghai is 2563 RMB/month, or 12.3 RMB/hour. This is about $1.60 per hour. Assuming the value of time is the work wage, the monetary value of the above city-wide travel time savings falls between 77.9 and 203.0 million dollars per year.

7.2.6 To Ban or Not to Ban?

Similar to Kunming, electric bikes provide some large and tangible benefits to Shanghai's transportation system, particularly through increased mobility and improved safety to electric bike users. In addition, the overall environmental benefits are strongly positive on some metrics and strongly negative on others. Electric bikes emit more lead than the alternatives as well as more PM, which is similar to Kunming's case. A notable and significant difference is the increased SO_2 emissions. In Kunming's case, electric bikes benefit the transportation system by reducing SO_2 emissions. In Shanghai's case, because of the higher reliance on coal based electricity generation, the SO_2 emissions show a net decrease if electric bikes are prohibited. This is particularly relevant for Shanghai, since it has some of the highest ambient SO_2 concentrations in China and SO_2 reductions in this area are a high priority. Electric bikes reduce overall energy consumption, CO_2 and NO_X emissions. Considering personal exposure to air pollution, electric bikes perform more strongly than total net increases or decreases in pollution presented in Table 7.6 imply. However, adjusting for exposure does not reduce SO_2 acidification potential, which is a serious concern in Shanghai.

There are clear benefits to the transportation system. Each electric bike user saves 126 hours a year in commute time compared to dominant alternatives and under the current transportation conditions. If bus service could be improved, this travel time margin would decrease. Electric bikes improve the overall safety of the transportation and, largely because of the few who would choose auto-mobility, there would be 7-52 addition fatalities if electric bikes were banned or heavily restricted.

Because Shanghai and surrounding provinces are the industrial hub of China, many cars, bicycles, electric bikes and buses are produced in and around the city. Because of this, many of the externalities of all vehicle production processes are likely borne by residents of Shanghai or the surrounding communities. Because of this, policy makers in Shanghai should be more concerned with industrial pollution from the production processes and should focus on modes that have the lowest overall life cycle impacts.

7.3 Conclusion

Two case studies investigated cities with some similar characteristics, namely good public transportation services and high electric bike use. Shanghai and Kunming also have some distinct differences, notably size, electricity generation fuel mix, and modal options. The impacts of electric bike regulation, particularly a ban, is dependent upon dominant alternative modes and the proportion of travelers that would shift to those modes in the event of a ban.

Shanghai and Kunming had similar mode shift responses, with most electric bike users shifting to bus transportation, followed by bicycle. Because of these similarities, the impacts are in the same direction on most metrics. Electric bike use, instead of the alternative, will reduce greenhouse gas emissions, energy use and NO_X emissions. Electric bike use does increase overall PM emissions in both cities, and the large amounts of lead (Pb) pollution from production and disposal processes are especially alarming. Because of Shanghai's reliance on coal-fired power plants, net SO_2 emissions increase in

Shanghai and decrease slightly in Kunming. This is particularly important in Shanghai because of their already high ambient SO_2 concentration levels.

Although detailed safety data are unavailable for both cities, there seems to be a clear improvement in the safety of the transportation system as a result of electric bike use. Using aggregate fatality rates, both cities stand to increase the total number of fatalities per year if electric bikes are banned. Most of the environmental and safety benefits are a result of automobile (either taxi or personal car) trips that are displaced by electric bikes. While most electric bike users would otherwise use bicycles and buses and these modes outperform electric bikes on many metrics, the impacts from the small percentage of those shifting to cars dominate the impacts and negate most of the benefits of the positive shift to cleaner or safer modes. Different cities have different characteristics and depending on the mode shift and energy mix, appropriate policy might be recommended. For example, a recent electric bike user survey in Shijiazhuang found that only about 35% stated that buses are their next best alternative, about 65% would choose bicycles, and about 10% would choose taxi or other modes. Interestingly, when asked about future purchase plans, about 15% of electric bike riders plan on purchasing a car within the next year (Weinert, Ma et al. 2007). Despite the difference in bus and bicycle proportions, displaced taxi trips likely dominate the impacts of electric bike shifts in the event of a ban.

One of the most profound benefits is the increase in mobility and thus accessibility of electric bike users. Most of these mobility benefits are gained by the displaced bus trips, since most buses operate in mixed flow congested conditions. Even if they were able to operate free of congestion, the nature of utilizing buses for short trips in non-transit-oriented cities results in much of the travel time spent outside of the vehicle (walking or waiting). This is a difficult problem to overcome. Bicycles provide a good balance of moderate mobility and low environmental and safety externalities. If a policy maker could force a shift to bicycles and divert all increases in car travel, then the system would likely be better off without electric bikes. However, current trends in China suggest that this might be an impossible goal.

Chinese residents are demanding more flexible, comfortable, and mobile modes of transportation and, based on the above case studies, electric bikes seem to be a mode that can meet these needs while minimizing some of the externalities associated with transportation systems. If the benefits and costs meet the priorities of planners and policy makers, then electric bikes are assets to a city's multimodal transportation system. The next chapter will offer policy recommendations that could provide overall improvements to the transportation system, within the context of electric bike use.

CHAPTER 8: CONCLUSION AND POLICY RECOMMENDATIONS

Electric bikes can provide high levels of mobility and thus accessibility in many Chinese cities, where trip lengths are increasing and residents are engaging in more complex trip-making activities. The research question raised by this dissertation is:

Compared to the predominant alternative modes--bus and traditional bicycle, under what conditions do electric bikes provide a greater relative benefit in terms of mobility and accessibility improvements than relative costs in terms of energy use, environmental impacts and safety?

For each city, the answer to this question depends on predominant alternative mode shift, the energy mix of electricity generation, and the city's environmental, safety and mobility goals. Bicycles have the high environmental performance, a good safety record, and provide high levels of mobility but with limited range. If policy can induce a shift toward bicycles, then that would be a good solution. Buses are environmentally better than electric bikes on some metrics and worse on others. What environmental advantages buses have, they lack in mobility. In general, Table 8.1 shows the relative advantage or disadvantage of electric bikes compared to alternative modes in the choice set, compared to the metrics analyzed in this dissertation.

Table 8.1: Direction and Magnitude of Electric Bike Advantage or Disadvantage

	Electric Bike (dis)advantage compared to:						**Overall Mode Shift Impacts (Kunming and Shanghai in general)**
	Bicycle		Bus		Car		
	Local	Non-Local	Local	Non-Local	Local	Non-Local	
Energy	~	-	++	-	++	++	**+**
CO2	-	-	++	+	+++	++	**+**
NOX	-		++		+++		**+**
SO2	-	-	-	--	--	++	**~**
PM	-	+	+	-	-	+	**-**
Lead (Pb)	---	---	--	--	-	--	**--**
Safety	-		-		++		**+**
Mobility	++		+++		~		**++**
Access	++		+++		~		**++**
User Cost	--		++		+++		**++**

\- electric bikes perform poorly on this metric compared to alternative
\+ electric bikes perform well on this metric compared to alternative
Multiple + or – indicates stronger advantage or disadvantage

The biggest advantage of electric bikes is in the extent to which they delay or replace car use or ownership. Even small shifts from electric bikes to cars result in major impacts. This chapter summarizes some of these aspects and suggests policy recommendations.

8.1 Economics

Electric bikes provide one of the lowest-cost forms of mobility, with operating costs averaging about 0.06 RMB/km. Over half of the operating costs are in battery purchases, about 0.03 RMB/km. The total average user cost (including purchase price) ranges from 0.10-0.12 RMB/km (Jamerson and Benjamin 2004). To put this in perspective, Kunming's bus fare is 1.5 RMB (including an average of 0.5 transfers) with an average trip length of 3.6 km. This is about 0.42 RMB/km. Shanghai's bus trips are more expensive, about 3 RMB (including transfers), with an average trip length of 5.2 km or about 0.57 RMB/km. These user costs are 4-5 times the user costs of electric bikes. This does not include subsidies to either system (operating costs, capital costs, and road allocation), which have a tendency to be very high for public transit systems. Taxi trips are even more expensive, well over 2 RMB per kilometer in most cities. Bicycles, because of very low purchase and operating costs, are the most cost effective form of mobility, to the extent that they are adopted by travelers. The low user costs of electric bikes could result in personal budget reallocation increasing consumption in other areas, such as food, health care, or housing, presumably improving their overall quality of life.

8.2 Environment

The electric bike industry is subject to larger industries in which it has little influence, such as raw material production and electricity generation. As such, many of the environmental impacts of the electric bike are unchangeable by the electric bike industry itself. Electric bike emission rates are subject to power plant emission rates. Most of the production impacts are a result of larger production processes, like steel and lead production. Most of the lead pollution occurs during mining, production or recycling processes, in which electric bike manufacturers have little influence. If governments exert pressure on the electric bike industry to clean up, there is little the electric bike industry can do to improve some of the most difficult challenges they are facing, particularly SO_2 emissions from power plants; lead (Pb) pollution from mining, smelting and disposal processes; and SO_2 and PM emissions from steel and lead production processes. The use of electric bikes is somewhat unique because the spatial distribution of environmental externalities is different than most motorized modes.

8.2.1 Local Impacts

Electric bikes emit no local air pollution, to the extent that power plants are sufficiently removed from the urban area. Any shift from electric bikes to alternative motorized modes will certainly result in increased local pollution in the urban area. However, most power plant emissions do enter urban areas, increasing the effects of electric bike use. During the use phase electric bikes emit 10-20 times more SO_2 from power plants than buses emit from combustion of diesel fuel, on a per-passenger-kilometer basis. The public health effect of this increase is reduced (by a factor of 3 in Kunming) by the fact that power plant emissions are somewhat remote. Nonetheless, public health impacts as a result of increased SO_2 will likely increase. Buses emit significantly more NO_X and PM than electric bikes and the public health impacts of increases in these pollutants could negate any SO_2 savings as a result of a shift from electric bike to bus. Electric bikes emit far fewer air emissions than cars so even a small displacement of car trips results in large reductions of local air pollution.

8.2.2 Non-Local Impacts

Unlike traditional motorized modes, most of the life cycle environmental impacts of electric bikes are incurred during the production processes. Most electric bikes and their components are manufactured in eastern provinces and municipalities, primarily Zhejiang and Jiangsu Provinces, and Shanghai and Tianjin Municipalities and thus, most environmental externalities of the production processes are borne by populations in those provinces. Increases in electric bike use in a non-industrial city impose more environmental externalities on the populations of the industrial provinces than they impose on populations living in cities where electric bikes are used.

Lead (Pb) is perhaps the greatest negative environmental externality related to electric bike use. However, most of the negative health effects related to lead exposure are from mining, smelting, recycling and battery manufacturing processes, impacts largely outside of the control of electric bike manufacturers. High recycling rates are important to reduce solid waste but recycling will not solve the lead pollution problem from production processes.

A positive non-local impact is electric bikes' influence on national energy demand. As China industrializes, energy supplies and security are essential to robust and sustainable economic growth. Every year, the transportation sector consumes a higher portion of China's energy demand, mostly because of rises in motorized transportation modes. Aside from bicycles, electric bikes have the lowest life cycle energy impacts of any mode, consuming very little energy per kilometer. Reducing energy consumption in the transportation sector can benefit all Chinese residents by reallocating energy to the non-transportation sectors.

8.2.3 Global Impacts

Comparable to the energy impacts, CO_2 emission rates of electric bikes are lower than any other motorized mode, primarily because of the energy efficiency of battery electric vehicle systems. As the effects of climate change become more tangible, the option of using renewable or low carbon based energy sources to power the transportation sector is very appealing. The international community has a stake in the transportation choices made by China and it is difficult to find a motorized mode that compares to electric bikes in terms of low greenhouse gas emissions.

8.2.4 Policy Response

Most of these environmental problems are symptoms of larger problems related to China's reliance on coal powered electricity, poor production practices of major industries, and China's rising demand for motorized transportation. There is some potential that electric bike motor efficiency and battery performance can produce some marginal gains in efficiency within the electric bike industry, but changes in the electric bike industry will have little impact on these larger problems. As China industrializes, electricity generation and production processes will become cleaner and, as a result, electric bikes will also become cleaner.

Very few of the environmental impacts of electric bikes are local in nature and most cities would like to have all of the benefits of electric bikes while bearing few of the environmental impacts. Because of this, it seems most appropriate to enact environmental policy at a national or regional level. Specifically, the level of lead emission is unacceptable and can easily (but expensively) be mitigated. Alternative battery technologies that are more environmentally benign do exist and are available on more expensive electric bikes, but the Chinese market has not yet adopted these because of the price.

There are a couple of ways to induce a shift to more environmentally friendly technologies. One way is to simply mandate a ban on lead acid batteries used in electric bikes. All electric bike manufacturers are presumably regulated by standards bureaus and this could be another requirement. Judging by current lack of compliance to existing rules, this type of mandate might be difficult to enforce.

Another way to induce this technology shift would be to exact a tax on lead acid batteries in the electric bike industry. This tax would act as an incentive to pull manufactures toward cleaner technologies. This tax could be high enough to promote a transition such that a portion of lead acid batteries would shift to NiMH so that net lead discharge compared to the dominant alternative is zero. This would be a “lead neutral” policy. High end SSEB’s could have advanced batteries, while low-end BSEB’s could maintain lead batteries. A “zero lead” policy would tax lead acid batteries so they are competitive in price with the cleaner alternative, NiMH. This would hopefully induce a 100% shift to NiMH, having the same effect as a ban. A tax would generate public revenue that could be invested in environmental mitigation, providing further benefits. Of course, as more electric bikes switch to alternative batteries, tax revenue will decline. Any forced or tax induced shift to alternative battery technologies would raise the purchase price of an electric bike by 20-25% and increase the operating cost by 100%, borne by the users. This cost increase would presumably result in a marginal shift away from electric bikes. None-the-less, electric bikes would remain one of the cheapest forms of transportation, with user operating costs around 0.12 RMB/km.

Since electric bikes have some clear benefits in terms of safety and mobility with low user and public costs, it might be worth subsidizing the transition to alternative batteries. If electric bike batteries are replaced every two years, the added cost per year to shift to NiMH battery is on the order of 275 RMB/yr ($35.50/yr). Chapter 8 showed that the value of travel time savings per user exceeds this value by a factor of three. Additionally, if you consider the public subsidy that could be required to meet the added travel demand on public transit, it would be cost effective to simply subsidize the industry to support electric bike use that, in the absence of lead pollution, would have clear environmental benefits.

8.3 Safety

While it is perceived that electric bikes are unsafe road users, this research proposes that they are safer but more vulnerable than opponents suggest. There have been clear directives meant to improve the safety of electric bikes in bicycle lanes. Some of these directives have been successful, while others have failed. Because of these failures, most cities have an abundance of electric bikes on the road that do not meet safety requirements, particularly speed and weight limitations. Public officials should identify the effect of electric bike speed on safety of the transportation system and develop enforceable standards that limit speed to safe levels such that conflict between electric bike users and others in bicycle lanes is minimized.

Some industry members are fighting the development of such a standard, stating that it would limit innovation and potential technology evolution to heavier "light electric vehicles" such as electric mini-cars. If the industry is allowed to move in this direction, there must be clear re-classification of electric bikes so that heavier electric motorcycles require registration, driver training and licensing, and helmet use. Policy makers must seriously consider whether a faster, heavier electric motorcycle belongs in the car lane, bicycle lane, or on the roadway at all.

While electric bikes have higher fatality rates than bicycles and presumably buses (although pedestrian fatality rates are difficult to measure), the overall transportation system will have worse safety performance without electric bikes. This is because even a small shift to automobiles would result in a large negative safety impact. By most of the externality metrics, policy should delay or displace a shift to cars at all costs! On average, in Kunming and Shanghai, fatalities will increase by about 4.4 fatalities/100,000 electric bikes removed from the roadway, if a ban were to occur.

8.4 Accessibility

Electric bikes provide the greatest benefits in terms of the accessibility and mobility advantages they provide to users. Bicycles have good mid-range mobility benefits and very good environmental benefits, but to the extent that social forces are precluding bicycle use, then electric bikes are a good alternative. Electric bikes have the greatest accessibility and mobility advantage over buses. Because of the large shift away from buses in Kunming and Shanghai, an average electric bike user saves well over 100 hours of travel time per year if all of the same trips are made on alternative modes.

Electric bike users overwhelmingly choose electric bikes because of their mobility improvements. Travel time was a significant predictor of mode choice in all of the mode choice models presented in Chapter 3 and users stated that the primary reason for choosing an electric bike was because it is fast. The only mode that has the same mobility and accessibility advantages are cars, although cars have other features that make them more attractive, such as comfort and status.

One way to induce a positive shift away from electric bikes to buses (without heavy regulation that would also induce a negative shift toward cars) is to improve public transportation services in the city. Electric bikes can compliment public transit use by increasing accessibility to regional transit systems, like metros. Improved quality and security of bike parking facilities can encourage this behavior. Increasing speeds of buses to compete with electric bikes would be a difficult task. Because of lost time accessing bus stops and relatively short trip lengths, the operating speeds of buses must be very fast to match the door to door travel time of electric bikes. Consider taking a 5 km trip on a bus or an electric bike. An electric bike can make the trip in 21 minutes. To provide comparable door-to-door service, a bus would have to operate at 25 km/hr including stops, which is difficult to accomplish in an urban area, even with exclusive right-of-way. More dedicated lanes would improve bus performance and make them more competitive with personal modes. Complimenting improved operating speed, improvements in urban form such that origins and destinations are matched along bus corridors would reduce transfers and walk time, which would reduce the inherent disadvantage of public transportation. Ultimately, clean buses that overcome the mobility problem are the best option, but this service is difficult and expensive to provide.

8.5 Cost Effectiveness of Travel

Making some assumptions and drawing on economic analysis in the literature, all of these costs and benefits can be monetized to some extent to develop a measure of cost effectiveness of travel by each mode. Matthews and Lave (2000) summarize studies that monetize the cost of social damage caused by different air pollutants. As expected, the range of remediation costs is high among pollutants and it is difficult to transfer findings from this study to the case of China. In this case, *some* of the direct and indirect costs are monetized to reflect the cost of traveling 100 kilometers by each mode. Table 8.2 breaks down these costs by mode and shows that electric bikes are the most cost effective mode of transportation in China, considering a subset of total costs.

Table 8.2: Cost Effectiveness of Travel by Competing Modes in China

				Cost per 100 pax-km			
		Unit Cost	Rate of Impact	E-bike	Bicycle	Bus	Car
Direct Costs	Battery Cost	$34/battery	10,000km/battery	$0.34			
	Electricity (Use)	$0.08/kWh[a]	1.3kWh/100km	$0.10			
	Gasoline (Use)	$0.56/L[a]	7.9L/100km				$4.42
	Fare[b]	$0.19-0.38 per Trip	4.4km/trip			$6.50	
	Purchase Price[c]			$0.50	$0.25	$0.17	$5.21
	Travel Time[d]			$9.70	$12.70	$20.62	$9.30
Indirect Costs	Safety (car)	$500,000 per Statistical Life[e]	0.20 fatalities per million-v(p)kt				$10.00
	Safety (bicycle)	$500,000 per Statistical Life[e]	0.013 fatalities per million-v(p)kt		$0.65		
	Safety (e-bike)	$500,000 per Statistical Life[e]	0.019 fatalities per million-v(p)kt	$0.95			
	SO_2 Remediation	$1.24/kg[f]	lifecycle g/100km	$0.02	$0.00	$0.00	$0.09
	CO_2 Remediation	$45/tonne[g]	lifecycle g/100km	$0.12	$0.02	$0.24	$1.38
	Lead Acid Battery Alternative[h]	+$69/battery	10,000km/battery	$0.69			
	Partial Cost of 100 kilometers of travel			**$12.42**	**$13.62**	**$27.53**	**$30.40**

Notes:

[a] From (Weinert, Ma et al. 2007) and (Metschies 2007)

[b] It is assumed that Fare covers all operating costs in China, including fuel, maintenance and labor, but not including vehicle capital costs.

[c] Assumes E-bike, Bicycle, Bus and Car cost $275, $50, $85,000, and $10,000, respectively and have useable lives of 50,000, 20,000, 50,000,000, and 197,000, passenger kilometers respectively (Sullivan, Williams et al. 1998; People's Daily Online 2002; Volvo 2006).

[d] Using speeds and trip lengths derived in Chapter 6

[e] Midpoint Value of Statistical Life (VOSL) estimates from (Liu 1997; Feng 1999; Brajer and Mead 2003)

[f] Cost effectiveness study of reducing SO_2 (Li, Guttikunda et al. 2004). These improvements also have more minor co-benefits of reducing NO_X and PM, not accounted for here.

[g] Approximate value of a metric tonne of CO_2 from Clean Development Mechanism (CDM) framework

[h] Cost of remediating all lead pollution from lead acid battery use in electric bikes by shifting to alternative battery technology (NiMH). Not relevant for cars or buses because of different battery technology requirements.

Most of these costs are based on assumptions already discussed in previous sections. The user costs are those borne by the user of the system. These primarily include operating and purchase costs of vehicles and fuels to travel 100 kilometers. Also included is travel time, which is represented by lost productivity that is monetized by the average wage of electric bike users in the two case study cities investigated in this dissertation. All monetized energy, material, and labor costs during the production process are assumed to be embedded into the purchase price of the vehicle, while all monetized costs of fuel production are assumed to be represented within the price of the fuel. This assumption is slightly flawed because the Central government heavily regulates fuel (gasoline, diesel and electricity) prices. The indirect costs primarily represent those externalities that are not explicitly included in the price of the product and therefore, not paid by the user or government. These include the cost to mitigate environmental impacts as well as the public health cost of traffic safety impacts.

Admittedly, this table does not represent all costs, but it does show that, making some contentious assumptions about the value of time and human life, electric bikes provide the most cost effective mobility of any mode in China, even traditional bicycles and loaded buses. This accounting does not include public subsidy of road infrastructure, the effects of each mode on congestion, nor does in explicitly include the public health impacts of pollution.

8.6 Shortcomings of Study and areas of future work

8.6.1 Data Availability and Reliability

One of the biggest challenges related to conducting research in China is acquiring reliable data. Because of this challenge, attempts were made to collect as much primary data as possible, through user surveys and speed studies. Other data, particularly those related to environmental impacts and safety are gathered from secondary sources, such as local and national Statistical and Public Security Bureaus. Because these datasets were developed with unknown data collection methods or controls, the reliability of the data is dependent on the reliability of the source. Some of these data sets were validated against independent alternative data sets and the results are similar, indicating that the data are somewhat reliable.

Most of the safety and LCA data are secondary, so some of it was not in a convenient form or unit. This necessitated data transformations that required some assumptions about yearly and life cycle vehicle use. Some of these assumptions were informed by primary or secondary data while others were not. The boundaries of the LCA were driven much by other studies that show the low relative impact of various LCA processes. Some boundaries were driven by lack of detailed data in certain industries, so aggregate, average environmental impact intensities were used. The same data and methodology was used when calculating the lifecycle impacts of buses, bicycles and electric bikes. Some data were completely unavailable for China, particularly operation emissions of buses. Synthesized reports from various international studies of buses using similar technology as Chinese buses serve as proxies to estimate these impacts. There are a lot of factors that influence bus tailpipe emissions and these tailpipe emission factors are likely an underestimate.

A full LCA of cars made in China is an area of future work that would heavily inform this research, especially since most of the net environmental costs are from cars. This research drew inferences from a study of a car that has similar technology as a

Chinese car, but the boundaries of this study are different than the boundaries of this dissertation, making a comparison between the studies uncertain.

8.6.2 Other Externalities

This study attempted to identify the largest costs and benefits and quantify them in ways that could be compared by some metrics. This would hopefully inform policy on whether electric bikes should or should not be banned in Chinese cities (the most popular form of regulation). It did not consider other externalities, some significant and important for Chinese policy makers.

The largest omission of this dissertation is the effect of electric bikes on congestion, road allocation and capacity, and parking. Buses are the most efficient users of road space but have problems with mobility. Bicycles and electric bikes are less efficient users of road space than buses, but more efficient users of road space than cars. Again, the overall impact on road capacity depends on the distribution of dominant alternative modes. High volumes of two wheelers in bicycle lanes do not mix well with mixed flow lanes of larger vehicles. There are particular conflicts with right turning cars crossing through bike lanes, reducing right turning capacity, which in turn reduces auto and bus throughput. Geometric changes along with signal phase changes could reduce this conflict considerably and some novel strategies have been implemented in Kunming and Shanghai to address this problem. Developing optimum operational strategies to mitigate the conflict between bicycles and cars at intersections is an exciting area of future research.

Electric bikes also require more parking facilities than other efficient modes but they require much lower space for parking than a typical car parking space. Including access ways and the parking space itself, cars generally require about 28 m^2/vehicle. Electric bikes require about 2 m^2/vehicle of parking space. Bicycles require about 0.75 m^2/bicycle. Bus users require no parking. This added parking demand could be a significant cost of electric bike use. However, all modes generally pay for their parking.

This study also did not include analysis of the sprawl inducing effects of electric bike use. As transportation costs (monetary and time) reduce, people are able to afford and willing to live in communities that do not have sufficient mix of uses and are often not organized toward mass transit. To some extent electric bikes are low cost, high mobility modes of personal transportation that could result in a demand for housing that is not oriented around mass transportation infrastructure, making it difficult to efficiently serve Chinese cities with public transit. Electric bikes don’t have huge parking requirements, like cars, so they will not necessarily demand land uses that are separated by parking lots, but electric bikes might exacerbate job and housing mismatch problems that lead to unsustainable suburbanization and sprawl.

One other important omission of this study is that it did not take into account the effect of electric bikes in promoting or inducing more long term auto ownership. This study looks at a snapshot in China’s motorization process and does not include the long term effects of building a culture of personal mobility in China. It is unclear which motorization direction China will move toward. Electric bikes could be a stepping stone to full automobile ownership, hastening the arrival of cars into more households. Alternatively, electric bikes could fill the personal mobility needs of Chinese citizens and thus slow or reduce the transition to automobiles. The surveys conducted in Kunming and Shanghai indicate that there is a proportion electric bike users that would use a car if electric bikes were not available. A similar survey conducted in Shijiazhuang asked about future vehicle purchase behavior of bicycle and electric bike users and found that electric bike users were much more likely to buy a car in the next year than bicyclists (Weinert, Ma et al. 2007). These results indicate that electric bikes might hasten car ownership for some and deter it for others. Electric bikes have much lower costs than personal cars, but provide about the same levels of access and mobility in a city. There are some factors that influence automobile purchase that are difficult to quantify but important to consider, namely status and improved comfort. An important area of future research will be to quantify some of the factors that influence car purchase decisions so that more sustainable modes can improve to provide the comfort, range, and personal mobility needs of Chinese residents.

This study does not explicitly calculate net public health benefits or costs, in terms of increased mortality or morbidity. These are difficult metrics to calculate given limited studies in the Chinese context and difficulty identifying mortality rates for various pollutants and processes, particularly production processes and lead pollution. Also, the benefits of exercise are not included as Chinese residents who shift from bicycle to motorized modes have shown significant weight gain (Bell, Ge et al. 2002). Any shift from bus, walk, or bicycle modes to electric bikes will result in less exercise and increased obesity, causing public health effects that are not accounted for in this study.

8.7 Closing Remarks

This dissertation took a critical look at electric bikes, addressing problems that opponents have noted, such as increased pollution and poor safety. Opponents often cite these impacts, but do not estimate the net impact (as a result of mode shift) of regulating electric bike use in a city. While they cite these problems with electric bikes, they rarely cite the same problems with the automobile, especially in auto-oriented cities like Beijing and Guangzhou who have attempted full bans of electric bikes in the last year. It is true that the massive amounts of lead pollution from lead acid batteries are a significant problem, but this is not a problem with electric bikes per se, but part of a larger problem with the lead production industry. It is also a problem that can be remedied, but will cost electric bike users or the government a significant sum of money to upgrade to better performing and more environmentally benign batteries. The benefits of electric bike use, primarily through saved travel time, reduced roadway fatalities, reduced energy use, and reduced CO_2 and NO_X emissions, are large enough in magnitude to justify such an investment by users or subsidy by the government to push the evolution to better batteries. As power plant emission rates reduce over time and production processes clean up, electric bikes (and all modes) will become cleaner to produce and operate. Since most electric bike impacts are non-local, national or regional policy must be developed that supports the sustainable development of electric bikes in China. Currently most regulatory policy is being made on a local level and outright bans are not the appropriate policy approach. Fixing the few problems with electric bikes will make them one of the most sustainable and cost effective transportation options available to Chinese residents.

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APPENDIX A.1: SURVEY INSTRUMENT (ENGLISH)

Think back to yesterday. Tell me about all of the trips that you made by electric bike.							
	Purpose of this Trip *1=work* *2=school* *3=shopping* *4=entertain* *5=visit* *6=medical* *7=return home* *8=access subway* *9=personal business* *10=other*	**Alternative Mode** *1=bus* *2=subway* *3=car* *4=bike* *5=walk* *6=ebike* *7=taxi* *8=company bus* *9=motor-bike* *10=no alt.* *11=other*	**What mode would you use otherwise?** *1=bus* *2=subway* *3=car* *4=bike* *5=walk* *6=ebike* *7=taxi* *8=company bus* *9=motor-bike* *10=other* *11=no trip*	**Origin**	**Destination**	**Start time**	**What was the Travel Time**
Trip 1							
Trip 2							
Trip 3							
Trip 4							
Trip 5							
Trip 6							
Trip 7							
Trip 8							
Trip 9							
Trip 10							

1. Are you ☐$_1$ Female ☐$_2$ Male

2. When were you born? 19 _____

3. How much school have you completed?

☐$_1$ Less than high school degree
☐$_2$ High school graduate
☐$_3$ Some college
☐$_4$ College degree
☐$_5$ College & graduate work

4. How many persons (including yourself) are in your household?

______Adults ______Working Adults
_______Children

5. How many of each type of vehicle are in running condition and available to you and other members of your household?

Cars ______
Trucks ______
Vans ______
Motorcycles ______
Bicycles ______
Electric Bikes ______

6. What was your Current address?

____

7. Please provide the address of your current school or workplace:

____

8. Why did you choose to purchase an electric motorcycle

☐$_1$ It is fast
☐$_2$ I received a new job that made my commute longer
☐$_3$ I moved so my commute is longer
☐$_4$ I can ride in the bicycle
☐$_5$ Safer than a motorcycle
☐$_6$ Cheaper than an automobile
☐$_7$ Can ride in areas restricted to motorcycles
☐$_8$ Transit is too crowded
☐$_9$ Transit is too expensive
☐$_{10}$ It requires low effort

9. What was your *household* (combined income for all adults) income for LAST YEAR, before taxes?

☐$_1$ Less than 10000 RMB
☐$_2$ 10000 to 20000 RMB
☐$_3$ 20001 to 30000 RMB
☐$_4$ 30001 to 40000 RMB
☐$_5$ 40001 to 50000 RMB
☐$_6$ 50001 to 60000 RMB
☐$_7$ 60001 to 70000 RMB
☐$_8$ 70001 RMB or more

10. What is your monthly salary?

☐$_1$ Less than 500 RMB
☐$_2$ 500 to 1500 RMB
☐$_3$ 1500 to 2500 RMB
☐$_4$ 2500 to 3500 RMB
☐$_5$ 3500 to 4500 RMB
☐$_6$ 4500 to RMB or more

11. What days do you typically NOT work?

☐$_1$ Monday
☐$_2$ Tuesday
☐$_3$ Wednesday
☐$_4$ Thursday
☐$_5$ Friday
☐$_6$ Saturday
☐$_7$ Sunday

12. How long have you owned an ebike?

☐$_1$0-6 month
☐$_2$6-12 month
☐$_3$ 1-2 years
☐$_4$ 2-3 years
☐$_5$ more than 3 years

13. Do you think ebikes should be promoted?

☐$_1$ No
☐$_2$ Yes, but more regulation
☐$_3$ Yes

APPENDIX A.2: SURVEY INSTRUMENT (CHINESE)

请告诉我们您昨天骑电单车的出行情况							
	出行目的： *1*、上班 2、上学 3、购物 4、娱乐 5、拜访亲戚或朋友 6、就医 7、回家 8．转乘地铁 9. 个人家庭业务 10、其他	如果不骑电单车您会选择其他何种交通方式（一项）？ 1、 公车 2、 轿车 3、 自行车 4、 步行 5、 出租车 6、 公司班车 7、 摩托车 8、 地铁 9、 燃气助动车 10、 其他 11、 不出行	在没有电动自行车以前，此行您通常会选择： 1、 公车 2、 轿车 3、 自行车 4、 步行 5、 出租车 6、 公司班车 7、 摩托车 8、 地铁 9、 燃气助动车 10、 其他 *11*、 不出行	起点位置（分区及小区或某两条路的交叉口等具体一点的位置）	目的地（分区及小区或某两条路的交叉口等具体一点的位置）	出发时间	出行耗时
出行 1							
出行 2							
出行 3							
出行 4							
出行 5							
出行 6							
出行 7							
出行 8							
出行 9							
出行 10							

1. 抵别↨ □$_1$局！！□$_2$础

2. 出生年份： 19 _____

3. 学历：
□$_1$高中以下
□$_2$高中毕业
□$_3$大学专科
□$_4$大学本科
□$_5$研究生及以上

4.家庭成员数（包括您自己）
成人______人
其中已就业成年人______人
未成年 ______人

5. 您和您的家人使用或可用的交通工具有：
轿车______辆
卡车______辆
货车______辆
摩托车______辆
助动车 _______辆
自行车______辆
电动自行车 ______辆

6. 住址： _________________小区/分区

7. 上学/工作地址:_______________廪喈

8. 您购买电动自行车的原因：
□$_1$ 快捷
□$_2$找了份新工作，上班地点离家更远了
□$_3$搬了家，家离上班地点更远了
□$_4$性能与自行车相类似,但比自行车省力.
□$_5$比摩托车安全
□$_6$比汽车便宜
□$_7$可以在摩托车受限的地区行驶
□$_8$交通太过拥挤
□$_9$交通费用太高

9. 去年您全家（所有家庭成员收入总和）前总收入（人民币）：
□$_1$10,000 元以
□$_2$ 10,000 元-20,000 元
□$_3$ 20,000 元-30,000 元
□$_4$ 30,000 元-40,000 元
□$_5$ 40,000 元-50,000 元
□$_6$ 50,000 元- 60,000 元
□$_7$ 60,000 元-70,000 元
□$_8$ 70,000 元-80,000 元
□$_9$ 80,000 元- 90,000 元
□$_{10}$ 90,000 元-100,000 元
□$_{11}$ 100000 及以上

10. 您的月收入是（人民币）：
□$_1$ 500 元以下
□$_2$500 元-1500 元
□$_3$ 1500 元-2500 元
□$_4$ 2500 元-3500 元
□$_5$ 3500 元-4500 元
□$_6$ 4500 元-5,500 元
□$_7$ 5,500 元-6,500 元
□$_8$ 6,500 元-7,500 元
□$_9$ 7,500 元-8,500 元
□$_{10}$ 8,500 及以上

11. 您每星期休息日一般是哪几天?
□$_1$ 星期一
□$_2$ 星期二
□$_3$ 星期三
□$_4$ 星期四
□$_5$ 星期五
□$_6$ 星期六
□$_7$ 星期天

12. 你的电动自行车买了多久了?
□$_1$0-6 月
□$_2$6-12 月
□$_3$1-2 年
□$_4$2-3 年
□$_5$超过 3 年

13. 您认为是否应该大力发展电动自行车：
□$_1$是
□$_2$是, 但是需要更多的法律法规 .
□$_3$否

APPENDIX B.1: EAST CHINA POWER NETWORK INTAKE FRACTION ESTIMATION PARAMETERS

Power Plant Capacity and Human Population Distribution					
Plant Name	Capacity (MW)	Population within 100 km	Population Between 100 and 500 km	Population Between 500 and 1000 km	Population Beyond 1000 km
Hefei	1025	9.608	256.244	504.99	507.781
Huaibei	1560	15.792	273.095	355.132	634.604
Pinwei	1200	11.512	279.125	379.22	608.766
Luohe	1200	11.512	279.125	379.22	608.766
Maanshan	850	12.97	238.242	476.437	550.974
Tianjia'an	790	11.512	279.125	379.22	608.766
Wuhu	500	10.493	245.639	480.861	541.63
Tongling	550	10.744	245.893	483.748	538.238
Ligang	1400	18.555	154.098	459.47	646.5
Changshu	1200	18.555	154.098	459.47	646.5
Huaneng Huaiyin	400	13.555	224.811	367.362	672.895
Xinhai	450	14.977	227.032	355.064	681.55
Huaneng Nantong	1400	20.497	159.162	456.256	642.708
Huaneng Nanjing	600	13.608	239.443	468.226	557.346
Tianshenggang	550	15.742	155.453	450.116	657.312
Qishuyan	450	15.79	181.16	470.446	611.227
Xuzhou	1300	15.872	261.328	353.457	647.966
Xuzhou Pengcheng	600	17.045	260.317	353.606	647.655
Yangzhou	400	16.102	215.579	468.934	578.008
Jianbi	1600	14.606	216.401	469.474	578.142
Yangzhou 2nd Plant	1200	16.102	215.579	468.934	578.008
Suzhou	600	18.553	150.05	486.299	623.721
Sheyanggang	250	8.077	195.698	365.056	709.792
Baoshan	700	13.299	128.389	459.327	677.608
Minhang	720	10.077	135.729	468.095	664.722
Shidongkou	1200	8.625	128.31	458.295	683.393
Zhabei	650	8.625	128.31	458.295	683.393
Waigaoqiao	1200	13.916	132.111	457.475	675.121
2nd Shidongkou	1200	8.625	128.31	458.295	683.393
Wangting	1200	18.553	150.05	486.299	623.721
Wujing Cogeneration	2150	12.986	128.367	474.018	663.252
Jinshan Cogeneration	503	17.489	155.864	486.067	619.203
Huaneng Changxing	250	13.93	182.404	492.182	590.107
Taizhou	1410	13.387	128.329	422.318	714.589
Jiaxing	600	16.895	147.617	494.307	619.804
Zhenhai	800	17.69	119.837	446.447	694.649
Beilungang	3000	15.671	112.049	435.474	715.429
Wenzhou GT	900	9.945	167.78	423.676	677.222
Zhenhai GT	550	17.69	119.837	446.447	694.649

APPENDIX B.2: INTAKE FRACTION OF POLLUTANTS FROM EAST CHINA POWER NETWORK

Plant Name	SO2	PM1	PM3	PM7	PM13	SO4	NO3
Hefei	5.51E-06	1.19E-05	7.06E-06	3.66E-06	1.75E-06	5.36E-06	4.38E-06
Huaibei	6.12E-06	1.20E-05	7.63E-06	4.15E-06	2.19E-06	4.94E-06	4.66E-06
Pinwei	5.80E-06	1.17E-05	7.21E-06	3.81E-06	1.93E-06	4.98E-06	4.57E-06
Luohe	5.80E-06	1.17E-05	7.21E-06	3.81E-06	1.93E-06	4.98E-06	4.57E-06
Maanshan	5.60E-06	1.18E-05	7.17E-06	3.81E-06	1.90E-06	5.21E-06	4.30E-06
Tianjia'an	5.80E-06	1.17E-05	7.21E-06	3.81E-06	1.93E-06	4.98E-06	4.57E-06
Wuhu	5.45E-06	1.16E-05	6.95E-06	3.63E-06	1.77E-06	5.22E-06	4.28E-06
Tongling	5.48E-06	1.17E-05	7.00E-06	3.66E-06	1.78E-06	5.24E-06	4.30E-06
Ligang	5.18E-06	1.09E-05	6.70E-06	3.70E-06	1.97E-06	4.81E-06	3.63E-06
Changshu	5.18E-06	1.09E-05	6.70E-06	3.70E-06	1.97E-06	4.81E-06	3.63E-06
Huaneng Huaiyin	5.38E-06	1.09E-05	6.69E-06	3.59E-06	1.87E-06	4.69E-06	4.07E-06
Xinhai	5.53E-06	1.10E-05	6.87E-06	3.73E-06	1.97E-06	4.67E-06	4.14E-06
Huaneng Nantong	5.42E-06	1.13E-05	7.02E-06	3.92E-06	2.12E-06	4.87E-06	3.75E-06
Huaneng Nanjing	5.67E-06	1.19E-05	7.24E-06	3.87E-06	1.95E-06	5.20E-06	4.33E-06
Tianshenggang	4.91E-06	1.05E-05	6.30E-06	3.42E-06	1.79E-06	4.72E-06	3.52E-06
Qishuyan	5.23E-06	1.11E-05	6.73E-06	3.65E-06	1.89E-06	4.95E-06	3.81E-06
Xuzhou	6.00E-06	1.18E-05	7.47E-06	4.06E-06	2.15E-06	4.87E-06	4.54E-06
Xuzhou Pengcheng	6.10E-06	1.20E-05	7.62E-06	4.17E-06	2.23E-06	4.89E-06	4.57E-06
Yangzhou	5.64E-06	1.18E-05	7.25E-06	3.93E-06	2.03E-06	5.13E-06	4.18E-06
Jianbi	5.51E-06	1.16E-05	7.06E-06	3.79E-06	1.93E-06	5.10E-06	4.13E-06
Yangzhou 2nd Plant	5.64E-06	1.18E-05	7.25E-06	3.93E-06	2.03E-06	5.13E-06	4.18E-06
Suzhou	5.17E-06	1.10E-05	6.73E-06	3.72E-06	1.96E-06	4.91E-06	3.61E-06
Sheyanggang	4.52E-06	9.50E-06	5.52E-06	2.84E-06	1.40E-06	4.40E-06	3.54E-06
Baoshan	4.38E-06	9.64E-06	5.62E-06	3.00E-06	1.53E-06	4.56E-06	3.14E-06
Minhang	4.16E-06	9.37E-06	5.31E-06	2.75E-06	1.34E-06	4.57E-06	3.10E-06
Shidongkou	3.93E-06	8.95E-06	4.97E-06	2.54E-06	1.22E-06	4.46E-06	2.95E-06
Zhabei	3.93E-06	8.95E-06	4.97E-06	2.54E-06	1.22E-06	4.46E-06	2.95E-06
Waigaoqiao	4.48E-06	9.79E-06	5.75E-06	3.08E-06	1.58E-06	4.59E-06	3.20E-06
2nd Shidongkou	3.93E-06	8.95E-06	4.97E-06	2.54E-06	1.22E-06	4.46E-06	2.95E-06
Wangting	5.17E-06	1.10E-05	6.73E-06	3.72E-06	1.96E-06	4.91E-06	3.61E-06
Wujing Cogeneration	4.37E-06	9.70E-06	5.62E-06	2.99E-06	1.51E-06	4.62E-06	3.14E-06
Jinshan Cogeneration	5.13E-06	1.10E-05	6.67E-06	3.65E-06	1.91E-06	4.91E-06	3.63E-06
Huaneng Changxing	5.09E-06	1.10E-05	6.57E-06	3.51E-06	1.77E-06	5.01E-06	3.77E-06
Taizhou	4.35E-06	9.39E-06	5.50E-06	2.95E-06	1.53E-06	4.41E-06	3.11E-06

Jiaxing	4.99E-06	1.08E-05	6.50E-06	3.55E-06	1.84E-06	4.89E-06	3.53E-06
Zhenhai	4.70E-06	1.00E-05	6.06E-06	3.34E-06	1.79E-06	4.56E-06	3.22E-06
Beilungang	4.40E-06	9.51E-06	5.63E-06	3.07E-06	1.62E-06	4.43E-06	3.04E-06
Wenzhou GT	4.46E-06	9.65E-06	5.59E-06	2.91E-06	1.44E-06	4.55E-06	3.38E-06
Zhenhai GT	4.70E-06	1.00E-05	6.06E-06	3.34E-06	1.79E-06	4.56E-06	3.22E-06
Weight Avg.	5.05E-06	1.07E-05	6.43E-06	3.46E-06	1.78E-06	4.79E-06	3.72E-06