

**Driving Change: Evaluating Strategies to Control Automotive
Energy Demand Growth in China**

by

Ingrid Gudrun Bonde Åkerlind

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Author
Engineering Systems Division
May 10, 2013

Certified by
Professor John B. Heywood
Professor of Mechanical Engineering
Sun Jae Professor, Emeritus
Thesis Supervisor

Accepted by
Professor Dava Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

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Abstract

As the number of vehicles in China has relentlessly grown in the past decade, the energy demand, fuel demand and greenhouse gas emissions associated with these vehicles have kept pace. This thesis presents a model to project future energy demand, fuel demand and carbon dioxide emissions for the Chinese light duty vehicle fleet. Results indicate that China can offset rapid vehicle energy demand growth with reductions in fuel consumption and new vehicle technologies. These reference scenario results indicate that future light duty vehicle energy demand and carbon dioxide emissions will peak below 400 mtoe and 1700 mmt carbon dioxide, respectively. In addition, a scenario based sensitivity analysis reveals that vehicle stock, vehicle fuel consumption and vehicle fleet electrification are the most significant drivers in determining future light duty vehicle energy demand, fuel demand and carbon dioxide emissions.

The Chinese government is concerned with these trends. In a complementary analysis, I investigate existing government policy strategies that may affect future automotive energy demand. I find that policy strategies are fairly well aligned with the significant drivers to reduce automotive energy demand. However, I also find that national government policies are often not implemented as intended at the local government level. Finally, I analyze current domestic and joint venture brand vehicle technology, where I find that domestic car technology lags joint venture car technology.

Thesis Supervisor: Professor John B. Heywood
Title: Professor of Mechanical Engineering
Sun Jae Professor, Emeritus

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Part I

Fleet modeling in China

Chapter 1

Introduction

1.1 Motivations

1.1.1 China: a growing consumer of transportation energy

By all metrics, China's energy demand and China's transportation energy demand are growing fast. During the multiple periods of political instability in the 20th century, China's economy stagnated or regressed. The past thirty years have sharply reversed that trend. As a result, China's total energy consumption has ballooned, both in relative and absolute terms. Chinese energy consumption as a share of international energy demand grew from 10.5% in 1990 to 17.5% in 2010 (IEA, 2012b). In absolute terms, China's transportation energy demand has grown more than tenfold since 1971 (Figure 1-1). Comparing total transportation energy demand to road transportation energy demand shows that much of that growth is directly attributable to growth in road transport. Diesel oil was not used in road transportation until the 1990s but road fragmentation accounted for the majority of growth in diesel demand since the 1990s. Motor gasoline has always fuel road transportation, but gasoline consumption has more than doubled since 1990. As a result, while China accounted only for 2.45% of international transportation energy demand in 1990, it now in 2010 accounts for 7.45% (IEA, 2012b).

The past decade has seen a rapid increase in consumer energy demand across many sectors. Historically, while China's industrial energy demand increased quickly to support its manufacturing sector, the Chinese people consumed relatively little energy. The rise of a robust middle class during the past two decades has generated new sources of energy demand growth. These consumers purchase new real estate, passenger cars and other luxury goods. Hence, the portion of the vehicle fleet composed of private passenger cars has dramatically increased (Figure 1-2). Almost singlehandedly, growing sales of the "small passenger" vehicle category (light green), corresponding with a conventional passenger car, has led to a doubling of vehicle stock between 2002 and 2010. The more encompassing passenger vehicle category that includes both cars and buses increased fivefold from 1990 to 2002.

Partially as a result, the portion of energy the transportation sector consumes as a share of total energy demand grew from 5.76% in 1990 to 11.57% in 2010. It is still far below the world average of 27.22% (IEA, 2012b). But because the transportation sector is one of the fastest growing energy consuming sectors in China, this fraction is expected to double before 2050 (Zhou et al., 2011).

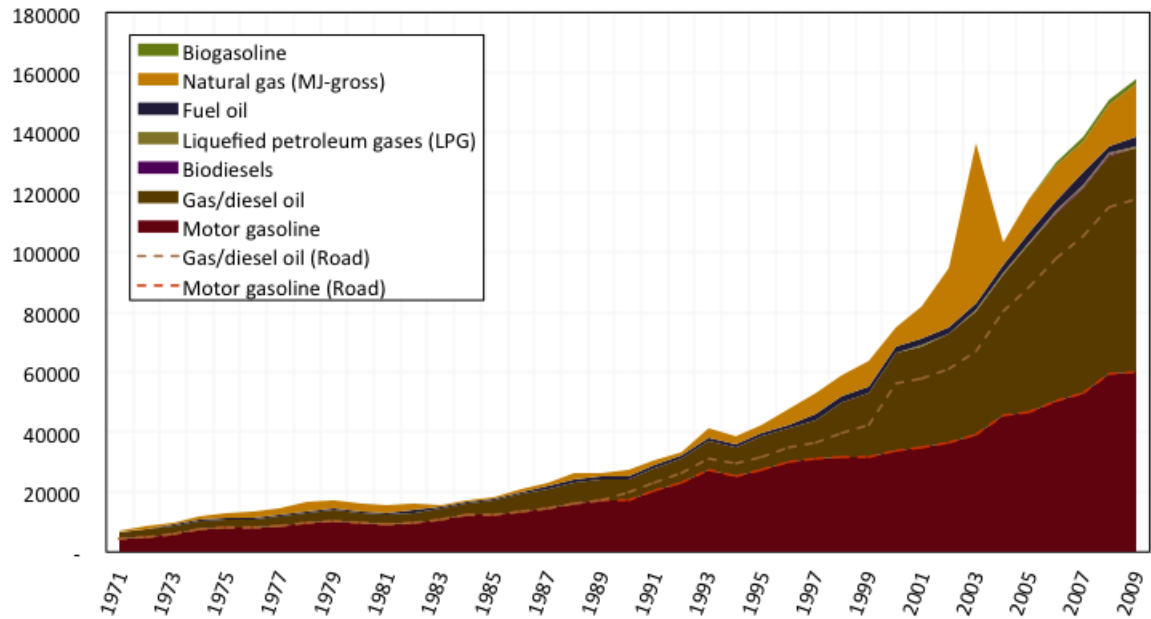


Figure 1-1: Historical Chinese transportation energy in million tons per year. Note: The spike in natural gas consumption in 2003 is an anomaly found in the original database source. Source: IEA (2012c).

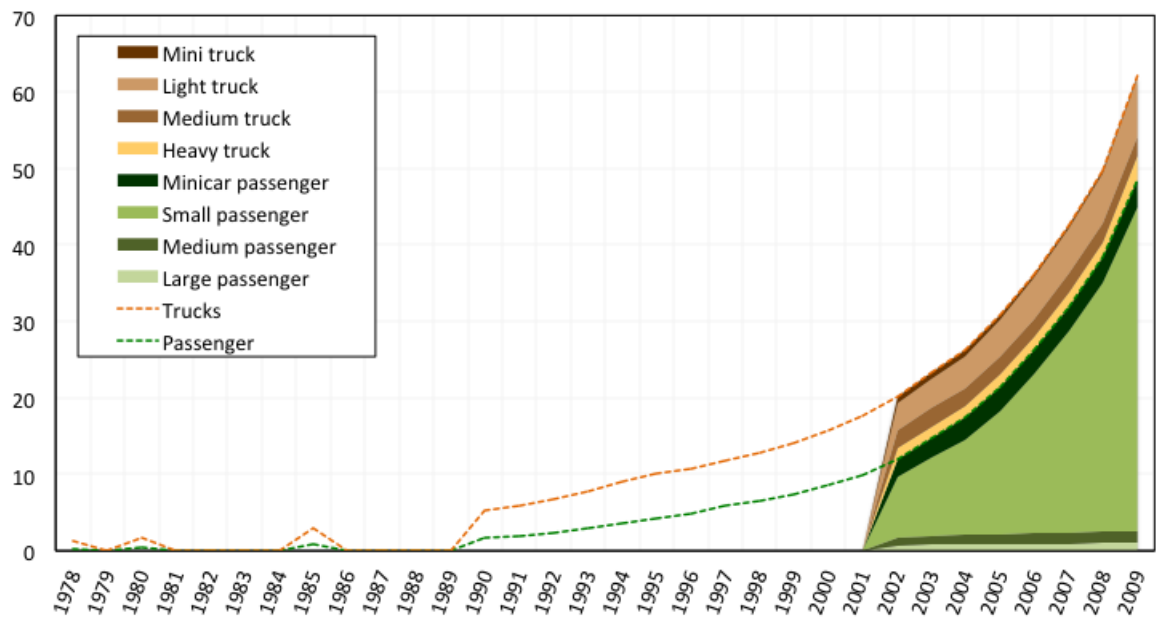


Figure 1-2: Historical Chinese vehicle stock in millions of vehicles per year. Source: China Statistical Yearbook (2011).

1.1.2 Transportation: a tenacious source of energy demand and CO₂ emissions

Although transportation energy research often focuses on the negative externalities of transportation, transportation itself carries many positive benefits. Access to a rapid form of transportation enhances mobility, letting an individual move faster from place to place. It can thus dramatically improve accessibility, the measure of an individual's access to desired opportunities (Lynch, 1984). More accessibility brings a greater diversity and number of jobs, entertainment and housing. However, the technology developed countries have adopted to fulfill rapid transportation desires is not wholly positive. The car, a favored form of personal transportation, carries many negative externalities that impact humans now and in the future. The challenge rapidly growing countries such as China face is minimizing these negative externalities while maximizing citizen accessibility (Wachs, 2010). In countries such as China, where hundreds of millions have no access to reliable transportation save walking, the potential benefits of improved mobility are vast.

Developed countries have adopted the personal automobile as a means of rapid transportation for a variety of reasons. The personal automobile is convenient and flexible; powering it has traditionally been cheap. Nevertheless, road transportation and car transportation in particular contribute to a range of negative environmental, social and economic impacts both in the short term and long term. Vehicle production itself consumes material and energy. Rising numbers of vehicles on the road compromise safety and contribute to the psychological and economic effects of high congestion. As discussed in the preceding section, vehicles consume large amounts of energy, which is not a limitless resource. Cars generally use gasoline or diesel for propulsion and governments consider dependence on these fuels a geopolitical and thus economic risk. In addition, burning these and other fuels emits carbon dioxide and other greenhouse gases that contribute to global warming and climate change with corresponding environmental, societal and economic impacts. Finally, vehicles also emit other pollutants such as NO_x, SO_x, and particulate matter that contribute to local air pollution and negative health impacts.

Economic theory explains these impacts are not internalized in the price of vehicle transportation and are therefore made worse than they otherwise would be if priced properly. Policymakers design and promote policies that minimize these market failures through pricing or regulating the externalities. In doing so, they generally choose among a number of different levers that impact automotive energy demand. Together, these levers create an identity that expresses the energy and environmental impacts of road transportation:

$$\text{Vehicle impacts} = f(\text{volume}) \times f(\text{use}) \times f(\text{efficiency}) \times f(\text{fuel}) \quad (1.1)$$

Vehicle impacts depend on the volume of vehicles, distance these vehicles drive, energy efficiency of these vehicles, and fuels these vehicles depend upon. The expression is a variant of the general transportation Activity-Mode share-Fuel intensity-Fuel source identity (Schipper et al., 2000) transportation energy researchers have popularized in literature throughout the previous decade. Thus, a policy intended to minimize the negative vehicle transportation impacts mentioned above would target one of these four levers. (Figure 1-3). Not all levers can target all impacts. To address vehicle congestion, policies should seek to alter the volume or use of vehicles. To mitigate negative consequences of global warming, policies can seek to reduce or alter volume, use, efficiency or fuels of vehicles. However, a rebound effect could cause a policy that specifically targets one lever to create spillover effects among other levers.¹

¹For example, banning odd numbered plates from driving on Mondays would target lower use but could cause citizens to purchase a second vehicle and increase vehicle volume.

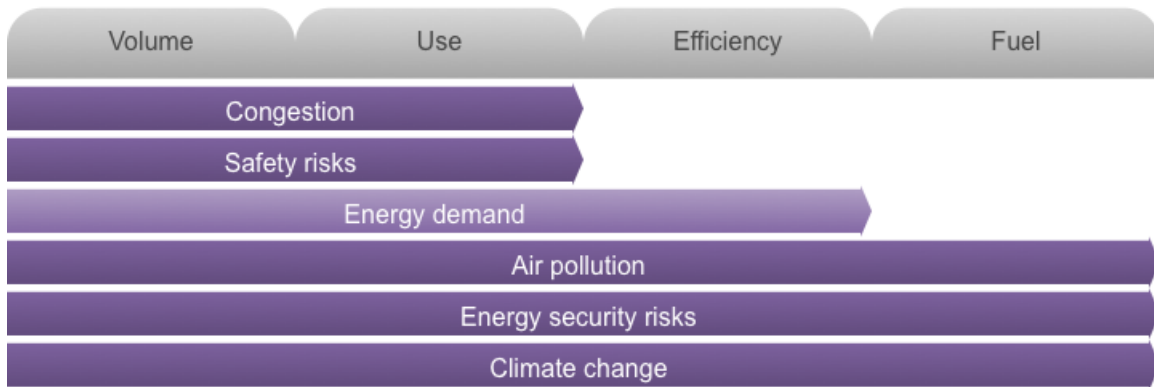


Figure 1-3: Vehicle impacts identity with negative impacts. The top bar describes the vehicle impacts identity while the arrows describe which portions of the vehicle identity policies seeking to affect a given externality can target. Energy demand is shaded separately because it is not negative per se.

Having adopted the personal automobile as the default mode of rapid transportation, curbing negative externalities is far easier in theory than in practice. First, once citizens have attained a high level of mobility, restricting vehicle travel is akin to reducing and restricting accessibility. Unless an equally fast and convenient mode of transportation were available, such a policy would decrease people’s quality of life by decreasing access to jobs, social pursuits, and recreational opportunities. It would run counter to the basic goal of most governments and countries. In many places, no equally flexible and far-reaching mode of transportation alternative currently exists. Therefore, policymakers commonly target the efficiency and fuel parts of the impacts identity. However, no equally good and cheap technology alternative exists to the basic internal combustion engine (ICE). Furthermore, the internal combustion engine automobile does not exist as a single technology, but as a technology embedded within a system. The technology is locked in to a system that encompasses road networks, automotive oriented development, fuel distribution networks, cultural imagery and more (Unruh, 2000). Shifting to an alternative solution would require not only the new technology be less expensive or better, but also that it be sufficiently better to overcome the inertia of the technology lock-in. The fourth, economic solution would be to price transportation in accordance with the emissions externalities they produce. While this could reduce mobility because transportation would become more expensive, such a Pigouvian tax would merely correct a market failure whose cost should already have been internalized. Although this approach would be efficient, it could inequitably distribute impacts across portions of the population and also face high political barriers. Finally, extricating a society from an automotive lifestyle is a complex task that requires long-range planning. However, governments and the individuals that steer them are generally evaluated upon short term and not long term results.

1.1.3 China’s transportation system: an opportunity to act now

China could acknowledge the difficulty of reducing the impacts of transportation and focus on mitigating energy use in other portions of the economy, especially as transportation energy is yet only a small portion of China’s total energy demand. Zhou et al. (2011) note that even if policies could effect significant changes, the impact on mitigating overall Chinese energy demand would be small. However, China has been a net crude oil importer since 1996 and imports now account for over half of China’s available crude oil (China Energy Statistical Yearbook, 2000-2002, 2007, 2010). Energy security remains a top

policy priority (Andrews-Speed, 2010). Second, serious air pollution in Chinese cities is due increasingly to motorized transportation and not coal combustion (Wang, 2011). Local air pollution has become a significant citizen concern in recent years and is becoming an important public policy issue. These two challenges are transportation specific and cannot be mitigated merely by reducing energy demand in the overall economy. China is urbanizing and its transportation sector energy consumption is growing quickly. In this light, China has a unique opportunity to act now: by creating the policy solutions that will avoid automotive technology lock-in, it might mitigate the worst effects of rapidly rising vehicle energy demand and emissions before they occur.

1.2 Research questions

The Chinese government has proposed various policy strategies to address and control the energy demand, fuel demand and emissions road transportation creates. These will often target different parts of the vehicle impacts identity in an effort to reduce overall energy demand, conventional and imported fuel, local air pollution, and CO₂ emissions. However, successfully addressing these vehicle transportation consequences will require evaluating said strategies and prioritizing them thereafter. Such an evaluation might consider potential impact, cost or political feasibility as criteria. This thesis compares different strategies according to potential impact in reducing energy demand, conventional fuel demand and CO₂ emissions. The thesis also considers the strategies in the context of current Chinese transportation and industry policy, investigating each strategy's political feasibility. To complete these two tasks, I pose and answer two sets of questions. The first set is technical in nature and seeks to better understand the problem; the second is policy oriented.

The technical half of the thesis builds a model in order to quantify future energy and emissions.

1. How will the future number, energy demand, fuel consumption and CO₂ emissions of light duty vehicles in China evolve?
2. Which are the most important drivers to determine future energy demand, fuel consumption and CO₂ emissions?

It is important to note already that the answer to the first question cannot be packaged and presented as one definitive future. As will become evident in Part II, Drivers of the fleet outputs, many factors that affect future energy demand and emissions (ownership, distance, fuel consumption etc.) are difficult to predict. As the follow-up question explains, it is how significant the factors are relative to each other that matters. The policy half of the thesis thereafter places the answers to the technical questions in context.

1. How well does the current policy orientation address the important determinants of future vehicle energy use?
2. How do political stakeholder interests pose institutional barriers to implementation on policies that address future vehicle energy use?

1.3 Thesis structure

The chapters that follow tackle the questions presented above in roughly chronological order. The technical portions of the thesis are presented in Chapter 3, Sections 4.1 and 4.2, sections in Chapters 4

through 7 entitled “Model implementation” and “Comparison across models”, and Chapter 8. The policy portions of the thesis are presented in Chapter 2, sections in Chapters 4 through 7 entitled “Progress and policies to date,” Section 6.1, and Chapter 9. A reader could choose to read only the technical portions or the policy portions of the thesis. However, the two are integrated as the policy analysis is intended to complement the technical analysis that defines the thesis structure.

The remaining chapters in Part I, Fleet modeling in China, focus on providing the necessary background for the chapters that follow. Chapter 2, Stakeholder priorities, presents a discussion of Chinese political structures that can affect relevant policy implementation. Chapter 3, The fleet model, motivates the choice of model and provides both a mathematical and schematic description.

Part II, Drivers of the fleet outputs, thereafter devotes one chapter each to discuss the major model inputs and the policy context each acts in. These are also the four components of the vehicle impacts identity as described in Section 1.1: Chapter 4, Vehicle ownership; Chapter 5, Vehicle use; Chapter 6, Vehicle technologies; and Chapter 7, Vehicle fuels. In each, I discuss model implementation and critically compare my future trends against those of other comparable models. In addition, I present a historical view of policies to date and for some policies, investigate how political and economic structures have impacted policy implementation.

Part III, Results and policy implications, delivers results and discusses the policy implications that follow. Results are two-part: Section 8.1 presents an aggressive yet feasible reference scenario for critical comparison against other fleet model results and Section 8.2 analyzes the relative importance of different drivers in controlling future automotive energy demand, automotive fuel demand and automotive CO₂ emissions growth. Chapter 9, Implications, thereafter ties the significance of these results to current Chinese society. It evaluates previously discussed government policy strategies both by ability to effect change and by likelihood of being stymied by political barriers to implementation. Chapter 10, Conclusions, summarizes the thesis, reviews the major findings, and offers final remarks.

Chapter 2

Stakeholder priorities

China is politically centralized, but economically and administratively decentralized. It was not always so, but fiscal reforms over the past thirty years have gradually assigned local governments more economic and administrative responsibility than is the norm worldwide. In 1988, the central government ended its formal responsibility for financially supporting local expenditures, returning to the Maoist ideology of “self-reliance” (Saich, 2008). Fiscal reforms in the early 1990s further transferred economic responsibility to local governments and extended them property rights over the local state-owned enterprises (SOE) – companies where the government is a majority shareholder – while also redirecting far more revenue to the central government (Baum and Shevchenko, 1999). Specifically, dismantling complete state ownership of corporations during the 1980s and letting SOEs compete in a marketplace had eroded their profits and thus also diminished the main source of government tax revenue. The new tax sharing system rerouted a majority of tax revenue to the central government, which then committed to redistributing a portion of this to the local governments (Wong, 2000). Nevertheless, richer areas tend to get proportionally larger transfers (Mountfield and Wong, 2005) and few local governments had enough.

A rich literature explores the effects of the fiscal reforms on the Chinese economy and society, as well as the resulting power balance between the central and local governments. When evaluating potential policies to control automotive energy demand growth, these political relationships may impose constraints on available policies and pose barriers to implementation. In this chapter, I explore relevant policy priorities and political relationships among central government, local governments, SOEs and Chinese citizens. Throughout the chapters that follow in Part II, I examine the effectiveness of existing policies that could control automotive energy demand growth. I examine policies through a bureaucratic process lens and see policy creation and implementation as effects of negotiation among different political actors Allison (1969). Indeed, Baum and Shevchenko (1999) argue that “central-provincial relations have increasingly been marked by bilateral bargaining and compromise rather than unilateral command and control” following fiscal reforms, even as they note that scholars disagree on who holds the bargaining power. I thereby argue that policies and behavior among various levels of government do not align in purpose and are at times contradictory. This may create insurmountable barriers to implementation for the policies I evaluate in Chapter 9.

I am not the first to suggest such an interpretation for the automotive industry. In his book *The Chinese Automobile Industry*, Eric Harwit views each Chinese bureaucratic organization as rational actor but argues those institutional leaders acting through bureaucratic processes (Harwit, 1995). Harwit identifies bargaining both within the central government and between central and local government.

Several authors have used “fragmented” to describe the automotive industry. In *Changing Lanes in China*, Thun takes a more nuanced approach (2006). Taking the codependence of firms and local governments as given, Thun draws attention to variation among political and economic structure of different local governments and how this affects automotive sector development. Thun also argues that central-local relations provide not only opportunities but also constraints for local governments. Chin (2010), however, after balancing the fragmented authoritarianism with the unified and strong state, adopts a position closer to Allison’s rational actor model. He argues that a strong centralized state has been able to effectively leverage foreign direct investment from multinational corporations, thus challenging the usual decentralized state interpretation of China’s economy.

2.1 National government

One of China’s central government top priorities is to ensure favorable conditions for continued economic growth and increasing prosperity among China’s citizens. To do so, it sets blueprints, standards and guidelines to shape economic development and social progress. However, while the central government sets plans, it leaves achieving these targets to the local governments (Liu and Salzberg, 2012). Indeed, China is vast and retaining oversight over all local government activity would be exceedingly difficult. Instead, the national government sets targets (for GDP growth, population growth etc.). It divides these up among the provinces, which then further divide the targets among local governments. Targets come in two forms: hard and soft. Officials at all levels must meet hard targets in order to be considered for promotion to a higher position (Saich, 2008).

To develop industries, the central government has retained elements of central planning from the past. Every five years since 1950, the government has promulgated a Five Year Plan that sets a vision for China’s development over the next five years. The national government named the automotive industry a “pillar industry” in 1986 (Thun, 2006) and sought to encourage private household car ownership (Mehndiratta et al., 2012). In the plans since, the government has continued to shine a spotlight on the automotive industry. In the twelfth Five Year Plan (2011-2015), the central government selected the “new energy vehicle” (NEV) industry of electric and plug-in hybrid electric vehicles as one of seven strategic sectors and funded research, development and pilot project commercialization. These seven sectors were to contribute 8% to GDP by 2015 (Li and Wang, 2012).

The national government will also coronate a select number of companies in a sector to be state “champions” handpicked to become undisputed leaders in the field. Market consolidation would make shape around these firms the small number of hubs that would help the Chinese automotive industry rise to success (Dunne, 2011). Political leaders in 1988 chose the “Three Big and Three Small” (San Da, San Xiao) companies to be First Auto Works (FAW), Second Auto Works (now Dongfeng), and Shanghai Automotive Industry Corporation (SAIC) for the big, and Beijing Automotive Industry Corporation (BAIC), Guangzhou Automotive Company (GAC), and Tianjin Auto for the small (Harwit, 1995). Since then, central government has continually pushed for industry consolidation into larger conglomerate groups to mimic Japanese and Korean successes, with limited success (see Chapter 6).

The government also sets guidelines for urban planning and transportation planning as well. For example, it reviews all the largest plans for cities, investment projects and land use conversion plan, as well establishing best standards for public transit and other urban services. However, inadequate national funding for these development projects means central government only partially monitors the progress (Liu and Salzberg, 2012).

To transition the economy to innovation-based sectors, the government spends research capital on

designated technologies. In order to promote innovation policies, the national government frequently supports demonstration projects in various cities. These projects encompass the strategic NEV industry. The “Tens of Cities, Thousands of Vehicles” project has sought to encourage many large cities across China to adopt electric vehicles among their government fleets and incentivize private electric vehicle purchases (see Chapter 6). In addition, since the 1990s, various ministries the national government has aided a number of provinces and cities to develop pilot low-carbon development cities to fulfill its priority of helping cities achieve greater sustainability. These demonstration projects are spread out across provinces and have achieved mixed success (see Chapter4).

The central government is also concerned with maintaining adequate resource supplies for strategic reasons. Grain is one such resource, and the central government strives to prevent the loss of agricultural land. Farmland per capita in China is only one-third of the world average and shrank 4% from 1978 to 1996 (Ho, 2001). The twelfth Five Year Plan includes a binding target not to reduce farmland reserves at all from the current level. The national government also works toward energy self-reliance. Andrews-Speed (2010) explains that these aspirations have a long history in China. Foreign companies are excluded from participating in China’s energy sector except when their expertise cannot be found within China’s borders. Such collaboration is expressly intended improve chances for future self-reliance. More recently, the dogged intent for energy security has only grown among government and citizens alike since China began importing oil in the mid 1990s.

2.2 Local governments

China’s local governments have a clear priority: economic development. Unlike local governments in Western countries, local governments in China are accountable and responsible for growing the local economy and jobs. In addition, while the central government sets standards and guidelines for services, local governments are responsible for delivering and managing these services. Nevertheless, local governments are limited in their ability to finance such services (Saich, 2008).

Chinese local governments are responsible for their entire economy to a greater extent than local governments in other countries. Mayors constantly compete against mayor in other cities and predecessors in their own cities (Liu and Salzberg, 2012). Furthermore, performance is measured almost solely upon GDP growth. If local officials do not meet the hard targets for tax revenues, GDP growth levels or family planning quotas (to maintain the one child policy), they receive no promotions or monetary rewards. Focus is placed squarely on attaining goals at maximum speed and quantity. Although Saich points out that higher government levels are testing new, holistic evaluation criteria, nationwide rollout is uncertain(Saich, 2008). Together, these performance metrics foster a focus on short term results to the detriment of long term sustainable planning.

Moreover, Chinese governments are limited in their ability to raise finances. Most local government revenues collected must go to the central government, but local governments are not allowed to exact property taxes on local citizens. Fiscal reforms have “pushed (or pulled)” . . . “governments into a variety of creative new partnerships with entrepreneurs and other emerging societal forces.” As a result, governments have sought sources of extrabudgetary revenues and employed “scores of administrative caches” to help them collect more revenue Baum and Shevchenko (1999). Baum and Shevchenko further argue that “a cadre’s value is increasingly measured by his or her ability to generate – and successfully tap into – new revenue streams.” These new revenue streams might include earmarked central government transfers for pilot projects, such as low carbon cities or electric vehicle projects. Neither do local governments have access to traditional Western methods of raising funds. Saich (2008) explains that

because governments are not allowed to issue bonds, their ability to borrow money is limited. Instead, governments rely on off-budget revenues that may total 20% of GDP and range from 30% to 70% percent of local government income. If this does not suffice, local governments set up municipal investment corporations that can borrow funds and thus finance the development projects governments rely upon for GDP growth.

One method of generating off-budget revenues is rural land conversion and subsequent land sales. I explore this literature and its implications for automotive travel in Chapter 4. Competition among cities likely exacerbates the incentives to sell land, generate revenue and build new developments and infrastructure. Bai and Qian (2010) find that highway infrastructure, a local government expenditure, has expanded far more rapidly than the centralized railways transportation infrastructure.

Even though policy directives are often set centrally, “policy implementation in China allows for flexibility and fine-tuning at the local level because the provincial government is often given the discretion to decide on the details and schedule of implementation” (Cheung, 1998). That is, central government policy is often vaguely worded, leaving local governments to interpret it (Winebrake et al., 2008). Sometimes the resulting local government experimentation goes too far: Cheung explains that provinces have been known to disobey and defy central government directives. In the automotive industry, Dunne describes the race among cities to become king of the automotive industry as “ruthless.” Each wants to become the “Detroit of China” (Dunne, 2011), and contrary to central government directives, this has led to a proliferation of several independent brand automotive companies. I explore this issue further in Chapter 6.

2.3 State-owned enterprises

State-owned firms grew out of China’s controlled past. In the 1980s, the central government partially privatized SOEs as it transitioned close to a market economy. Although many private firms exist today in China, SOEs still enjoy numerous perks. Although Stigler’s concept of regulatory capture occurs anywhere specialized interests can exert undue control over the policy agenda (Stigler, 1971), China’s political system exacerbates it. Although SOEs decide on day-to-day managerial decisions, the Chinese government retains the right to decide on mergers and acquisitions and appoint CEOs of public companies (Fan et al., 2007). Chin (2010) confirms that the government tends to do this in the large automotive SOEs.

Fan et al. (2007) use a CEOs status as a former or current government official as a proxy for political connection and conclude that companies with politically connected CEOs perform worse than those without. In addition, their boards are more often composed of government officials without relevant professional experience. This creates a situation where management extracts rent in order to fulfill objectives counter to the company’s profit maximizing interests. In fact, management may fulfill political local government objectives instead. The political-SOE connection works the other way as well. Many senior bureaucrats from the energy industry have graduated into powerful government positions (Andrews-Speed, 2010). Furthermore, Li et al. (2009) demonstrate that SOEs have easier access to long-term debt. However, they too find that being a state-owned firm is negatively correlated with firm performance.

These tight connections between industry and politics have implications on both local and national levels. Wong (2013b) explains how this has prevented tailpipe emissions standards from becoming more stringent. Even though diesel vehicles are the worst motorized polluters, Chinese diesel sulfur levels are 23 times as high as those in Europe. The oil industry SOEs have significant input on environmental

standards, several representatives sit on the committees researching fuel standards, and the committee is housed within an oil company. The Ministry of Environmental Protection cannot force the committees to adopt more stringent targets, and even if the committee does, Wong estimates the companies may very well flout the rules. Beyond regulatory capture, this example illustrates how formal political structures legitimize SOE interests.

In Chapters 4 and 6, I discuss how local governments cater to their own local SOEs.

2.4 Chinese citizens

Although Chinese citizens have no formal political power, they hold informal political power insofar as various government entities wish to maintain social stability. Wang (2008) argues the “popular pressure model” is frequently used to set the policy agenda in China today in contrast with the authoritarian methods of mass mobilization and unilateral decision-making of years past. By the new method, agenda initiators mobilize the popular opinion. A “focusing event” can help the agenda initiator appeal to mass media for in-depth coverage or instigate a vehement, passionate online response. This forces the issue to the fore of government attention. Mertha (2009) supports this view and demonstrates how NGOs and media can capture the policy-making process through examining a couple of hydropower dam case studies in southern China.

Local air pollution serves as a poignant example. Air quality in China’s major cities is very poor. In 2007, the average air quality of the 31 cities in China’s City Statistical Yearbook was 94 ug/m³ of PM 10¹ (China City Statistical Yearbook, 1997-1999, 2001-2005, 2007-2008). This compares with the WHO’s 2009 world average from 1098 major cities spanning all continents of 71 ug/m³ (WHO, 2011). The WHO recommends a safe level of PM 10 air pollution does not exceed annual average of 20 ug/m³ (WHO, 2005).

In January 2013, Beijing was hit with four toxic smog attacks and media coverage of the event indicates this could have served as a “focusing event.” The Beijing government reported levels of PM 2.5, even smaller and more dangerous than PM 10, exceeding 900 ug/m³. Citizens discussed the polluted situation endlessly online, and official media covered the episode in meticulous detail. Until recently, the Chinese news media has avoided candidly discussing pollution and only in 2013 did the Ministry of Environmental Protection order 74 cities to report PM 2.5 levels (Wong, 2013a). Thus, during the episode, many Western analysts marveled at this novel transparency. In response, both the Beijing government and the vice premier publicly pledged to take action. The vice premier promised to step up enforcement of environmental laws as part of the long term challenge to curb air pollution (Wu et al., 2013). The Beijing government committed to closing hundreds of heavily polluting plants, reforestation 66 000 hectares of land, replacing 44 000 aging coal fired heating systems, removing nearly 200 000 old vehicles from the road and implementing emergency control measures for extremely polluted days (Xin, 2013). Nevertheless, many barriers remain. As discussed above, the largest oil industry SOEs deter standards to tighten clean fuel standards. This is not surprising, as regulated fuel prices that strongly disincentivize any efforts to produce cleaner fuel through more expensive refining processes (Spegele and Ma, 2013). Even as local air pollution becomes a more pressing policy issue, the ability of the government to take unilateral action is not secured.

¹Particulate matter no more than 10 microns in diameter

Chapter 3

The fleet model

This fleet model builds off previous work completed in the “On the Road” group at MIT. This previous work created a fleet model of the US with base year 2007 that used sales growth rates and ratios of sold to scrapped vehicles to predict stock. An exponential decay function predicted annual Vehicle Miles Traveled (VMT) per vehicle. The model thereafter differentiated among naturally aspirated gasoline vehicles, turbo charged vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, and electric vehicles. Various research efforts applied and adapted this model to the US market (Bandivadekar et al., 2008), major European countries (Bodek and Heywood, 2008), and Japan (Nishimura, 2011). In Chapter 9, Implications, I also compare my results with another concurrent analysis of US fuel demand (Bastani et al., 2012).

For this thesis, I adapted the original model to suit the Chinese data and context. A scrappage function predicts future stock from sales. The base year is shifted forward to 2010. Previously, electric efficiency and plug-in hybrid electric power utilization rates were constant; I allow them to change over time. I add diesel as a potential powertrain option. Previously, future fuel consumption declined in percentage points per year; now I use ratios of future fuel consumption rates to base year fuel consumption rates to define rates of decline. The model can now incorporate alternative fuels such as methanol, ethanol, biodiesel and compressed natural gas (CNG). Future energy demand can be measured in both million tons of oil equivalent (mtoe) and billion liters of fuel. In addition, a researcher can adjust scenarios from the main page instead of working through all individual spreadsheets, thereby improving ease of use.

3.1 China fleet model literature review

Different research efforts have also created China-specific fleet models estimate vehicle energy demand. International organizations frequently also break out China from overall global projections. I will refer to these studies multiple times throughout the text to contextualize my assumptions and results, but I introduce most of these efforts here:

- In a series of four papers, a team at Tsinghua University led by Hong Huo built a detailed fleet model spanning all types of vehicles and building off a series of detailed field studies and surveys (Huo and Wang (2012); Huo et al. (2012c,a,b)). The model built a business-as-usual scenario and evaluated energy demand reductions for scenarios that varied powertrain mixes, fuel consumption and fuel mixes. This built off an earlier study at Argonne National Laboratory in the United States

(Wang et al. (2006); Huo et al. (2007)).

- A second Tsinghua research team published a pair of papers based on a passenger vehicle fleet model (Hao et al. (2011d,a)). It is the only previous model to model effects of policies constraining vehicle ownership and use. It also examines energy demand effects of fuel consumption improvements, vehicle downsizing, and electrification in order to inform future policy decisions.
- A third group at Tsinghua University also built a fleet model to explore the future energy demand effects of their previous extensive analysis on lifecycle emissions of alternative fuels (Ou et al., 2010b). The study examines future energy demand for all road transport and recommends future policy strategies.
- A British duo at University of London used the Stockholm Environment Institute’s LEAP tool to develop a fleet model that also examined effects of implementing alternative fuels (Yan and Crookes, 2009).
- Various international organizations use fleet models in global energy demand scenarios, including the International Council for Clean Transportation (ICCT) (Cristiano Facanha et al., 2012). Its model focuses on predicting future emissions and transport demand, not energy demand.
- The IEA’s 2012 World Energy Outlook bases its projections off a highly complex mobility model with a fleet model grounding its road transportation projections (IEA, 2012a). In its International Energy Outlook, the EIA also breaks out the China as a separate region (EIA, 2011).

3.2 Model presentation

The fleet model is best described through a diagram (Figure 3-1). The grey boxes denote fleet model inputs and the purple fleet model outputs.

The model generates four sequential outputs - stock, energy demand, fuel demand and CO₂ emissions - that are loosely based on the four levers of vehicle impacts identity. The first output, vehicle stock, corresponds with the *volume* portion of the vehicle impacts identity. The vehicle distance traveled input corresponds with the *use* portion of the vehicle impacts identity, while fuel consumption and powertrain mix together correspond with the *efficiency* portion. This generates the second energy demand output. I disaggregate energy demand by fuel to calculate the fuel demand output. Finally, specifying sources for different fuels corresponds with the *fuels* portion of the impacts identity and also generates the final CO₂ emissions output.

The bottom of the model diagram shows different ways to present output results. For example, I can express not only total light duty vehicle stock, but also total stock by component vehicle types. Similarly, I can express not only total fuel demand but also fuel demand for different vehicle types, different vehicle fuels or different vehicle powertrains. It may be relevant to know how much gasoline and diesel consumption alternative fuels displace, even if total energy demand remains unchanged.

3.3 Model equations

A series of equations underlie the schematic view of the model process:

$$Stock_{v,MY,CY} = Sales_{v,MY,CY} \times Survival_{v,MY,MY-CY} \quad (3.1)$$

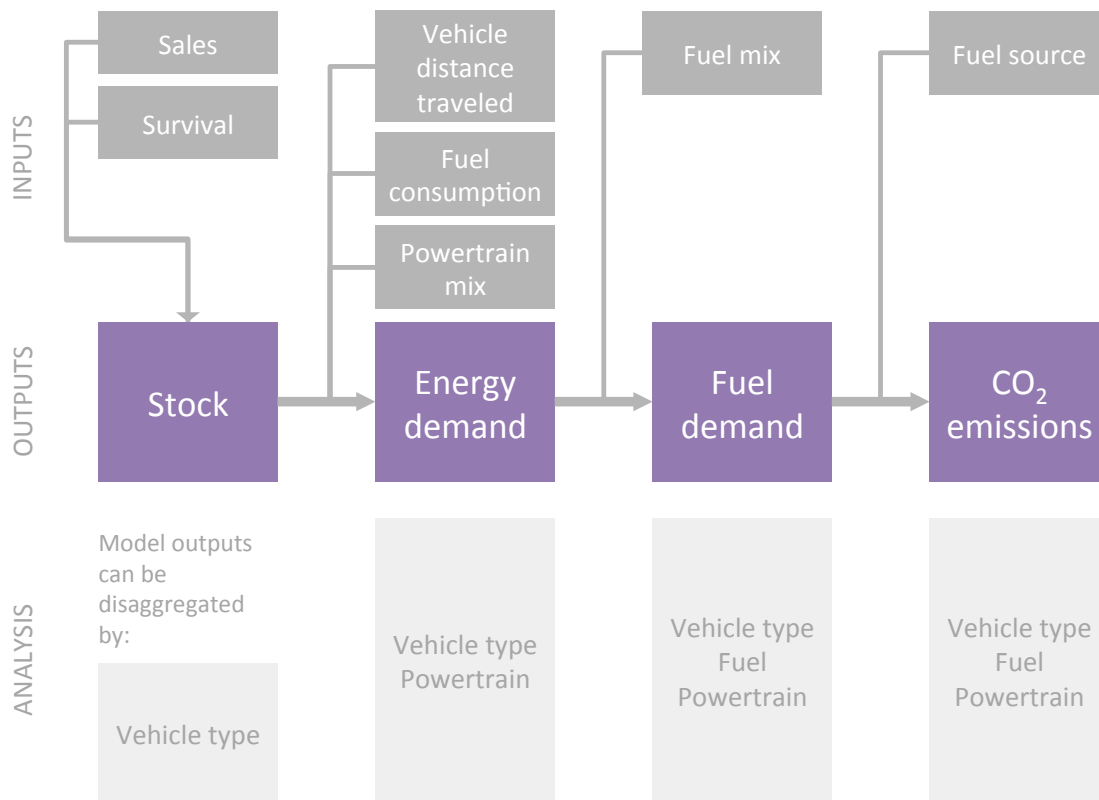


Figure 3-1: Model diagram.

The stock of vehicles for a given calendar year (CY), model year (MY) / age ($MY - CY$) and vehicle type (v) is calculated by multiplying the appropriate sales number with the appropriate survival ratio.

$$Energy\ Demand_{P,CY} = \sum_{MY,v} Stock_{v,MY,CY} \times VDT_{v,MY,MY-CY} \times Powertrain_{v,P,MY} \times FC_{v,P,MY} \quad (3.2)$$

Overall energy demand per vehicle powertrain (P) for a given calendar year is determined by multiplying together the number of vehicles in a year by how far each vehicle travels in a year (VDT) by the fuel each vehicle consumes to drive that distance. More specifically, the count of vehicles unique for a given model year, calendar year and vehicle type is multiplied by the VDT associated with that count. The marketshare mix for different powertrains for a given model year and vehicle type divides this count and thereafter associates each count of vehicles with its appropriate fuel consumption. Summing over model years and vehicle types gives energy demand per powertrain and calendar year.

$$Fuel\ Demand_{f,CY} = \sum_P Energy\ Demand_{P,CY} \times Fuel_{f,P,CY} \quad (3.3)$$

Annual fuel demand, broken down by fuel (f), is determined by multiplying $Fuel$, the fraction of powertrain energy demand supplied by a given fuel, by the energy demand for a powertrain.

$$Emissions_{CY} = \sum_{f,i} Fuel\ Demand_{f,CY} \times Source_{f,i,CY} \quad (3.4)$$

Emissions are determined by classifying each source by fuel and carbon intensity (i) and multiplying each fuel's average carbon intensity for a given year with that given year's fuel demand to generate overall emissions.

Equation 3.1 corresponds with Chapter 4, Vehicle ownership. Equation 3.2 corresponds with both Chapter 5, Vehicle use, and Chapter 6, Vehicle technologies. Equation 3.3 and Equation 3.4 correspond with Chapter 7, Vehicle fuels.

3.4 Sensitivity analysis

Several historical statistics and over a dozen assumptions inform future energy demand and emissions. While certain assumptions are fixed, others vary. Each such variable input has three potential sets of future values: reference, high and low. Each of the four chapters in Part II contains a "Model implementation" section that presents and explains these variables. Chapter 8 presents reference scenario future energy demand and emissions based upon the reference values for each variable input. In addition, Chapter 8 presents a sensitivity analysis. In this sensitivity analysis, all inputs are kept at reference values save one that adopts either its high or low values. Repeating this process for all variable inputs illustrates the relative importance of each driver.

3.5 Model limitations and justifications

As with any modeling technique, this approach to analyzing China's vehicle energy demand has limitations. First, it relies heavily on specific historical data as well as numerous input assumptions. Especially in China, amassing this data and understanding the local context that informs the input assumptions is

time-consuming and occasionally impossible. In addition, the data may be unreliable and the collection methods obscure. Third, the model lacks feedback mechanisms among various inputs. For example, decreasing fuel consumption might correlate with lower vehicle stock growth rates because technology costs will make vehicles more expensive and less affordable. However, the model includes no mechanism to automatically change vehicle sales in response to vehicle fuel consumption. Instead, I would have to adjust such responses manually. Finally, this is an engineering model and not an economic model. As such, it does not consider vehicle prices or consumer preferences for vehicle ownership. My judgment, based upon an expectation of how these values could evolve, informs the input assumptions that govern outcomes. As a final relevant consideration, the model results, discussed in Chapter 8, Results, are used to recommend future policy decisions. However, the results are also dependent on the model inputs, which in some cases acknowledge current policy. This interdependency could potentially cloud interpretation of results and I strive to make it as clear as possible.

The model's weaknesses are also its strengths. The input assumptions, while numerous, are transparent. It is easy to gauge the individual impact of one assumption. Second, because the model lacks complex feedback mechanisms, it is relatively easy to adjust: new alternative fuels or powertrains can be added when a specific objective calls for it. Finally, although the fleet model lacks economic inputs, it is well suited to model the command and control policies China's government readily adopts to influence vehicle output.

As stated in Section 1.2, the technical portion of the thesis seeks to understand how various factors influence future energy demand and emissions and which are the most important. Stated another way, this research question is more suited to an exploratory than a consolidative¹ model (Bankes, 1993). This model type is appropriate for identifying unexpected relationships among input factors, prioritizing strategies to address future vehicle energy demand and emissions, and isolating extreme cases that may justify immediate action. For example, the reference scenario is only the predicted future if each of the inputs grow at the expected rate. Although I predict the reference scenario results as a likely future among all future scenarios, it is unlikely to be the exact future. Interpreting the reference scenario result as stemming from a consolidative model is immature: there exist only about ten to fifteen years of reliable historical trends for the inputs and the eventual market uptake of disruptive powertrain and fuel technologies is unpredictable. Prompting action is another reason to use an exploratory model. Solely employing a predictive model approach can defer policy action (Sarewitz and Pielke, 1999). Instead, this model can help advance decisions before researchers have amassed all the possible data and statistics about China's future vehicle energy demand by preparing policymakers for a range of futures.

¹A model that predicts future values and events

Part II

Drivers of the fleet outputs

Chapter 4

Vehicle ownership

With certainty, China's vehicle stock will continue to grow. However, it is not certain how much it will continue to grow. Vehicle ownership depends on myriad factors, many of which are difficult to quantify. While population projections and GDP growth projections give an idea of how many people can afford to purchase a vehicle, the projections do not necessarily indicate how likely a person is to purchase a vehicle. This chapter explains the specific vehicle types into which I subdivide the light duty vehicle fleet, vehicle stock growth and policies to date, model stock projections, comparison with other models, and an overview model stock projection methods.

4.1 Vehicle types

4.1.1 Chinese classification systems

China has different methods of vehicle classification that remain inconsistent across agencies and history. The official country statistics from the China Statistical Yearbook classifies vehicles as freight or passenger vehicles. This corresponds with trucks or buses and cars, and since 2002 the Yearbook has further broken these categories into large, medium, small and mini categories. The statistics report both vehicle sales and vehicle stock, also reporting private vehicle stock (China Statistical Yearbook, 2011a) A minitruck weighs less than 1.8 metric tons (Wang et al., 2006). While smaller, this corresponds fairly well with the US light duty truck whose curb weight is less than 6000 pounds (Tit, 2011). The China City Statistical Yearbook reports information on all cities in China at the prefecture level of above, and includes taxi stock among their statistics (China City Statistical Yearbook, 1997-1999, 2001-2005, 2007-2008).

Since 2005, the China Association of Automobile Manufacturers (CAAM) and the China Automotive Technology Association Research Center (CATARC) have used a very different classification system based upon use and weight. The six categories are M1, M2, M3, N1, N2 and N3. M1 vehicles are passenger vehicles and M2, M3 and N vehicles are commercial vehicles (Huo and Wang, 2012), though because vehicles are classified by model, the distinction is not clear-cut: a taxi is often an M1 vehicle while a US pickup truck could be classified as an N1 vehicle. M1 vehicles are passenger cars, minivans with fewer than nine seats and sport-utility vehicles. M2 are passenger vehicles with nine or more seats but less than 5000 kg. M3 are passenger vehicles with nine or more seats but weighing more than 5000 kg. N1 are trucks weighing less than 3500 kg, N2 trucks weigh from 3500 to 12000 kg, while N3 are heavy duty trucks weighing more than 12000 kg (Huo et al., 2012a). The CATARC and CAAM China Automotive Industry Yearbook (CAIY) also provides data for sport-utility vehicles (SUV), multi-purpose



Figure 4-1: A “mianbaoche” in Beijing. Source: author.

vehicles (MPV) and crossover vehicles (China Automotive Industry Yearbook, 2011b).

4.1.2 Selected vehicle types

My goal in this study is to model the light duty vehicle fleet in China. The light duty vehicle fleet includes the non-freight and non-bus vehicles a private citizen would potentially purchase. This includes passenger cars, minitrucks and minibuses as reported in CAIY. Passenger cars and minitrucks correspond with the US light duty vehicle fleet of cars and light duty trucks while the minibus category is sufficiently large to warrant separate attention. While unknown in the US, the minibus “mianbaoche” category is modeled off the Japanese K-car (Figure 4-1; see description in Nishimura, 2011). CAAM and CATARC classify SUVs with passenger cars (China Automotive Industry Yearbook, 2011b) and not light trucks as in the US. This model retains that classification and therefore the Chinese minitruck category is far smaller than the US light duty truck category. Over the past decade, rising incomes and increasing private car purchases has shrunk the non-private car share of total car stock (Figure 4-2). Given different scrappage and use patterns, I separate private vehicles from non-private vehicles (see Appendix B, Private and non-private vehicles).

This model excludes all heavy duty vehicles but also certain other lighter vehicles. It does not include motorcycles or electric two-wheelers. This mode of transport is popular in China, with around 28 million gasoline and electric powered motorcycles, scooters and bicycles sold in 2006.¹ Local policies and public transit availability provide both encourage and discourage growth in two-wheeler stock (Weinert et al., 2008). Because it is unclear whether two-wheelers and light duty vehicles are complementary, substitute or unrelated goods and information on them is lacking, I exclude them from analysis. In addition, they have low fuel consumption. I also exclude the rural vehicle category from analysis. Used for low-speed goods transport in rural areas, China produced three times as many rural vehicles as passenger cars in 2002 (Sperling et al., 2005). Despite being generally small and privately owned, because they are used for freight, I do not include them among light duty vehicles. Finally, I exclude the “zhuliche” vehicles

¹This compares with 3.8 million passenger car sales (China Statistical Yearbook, 2011a)

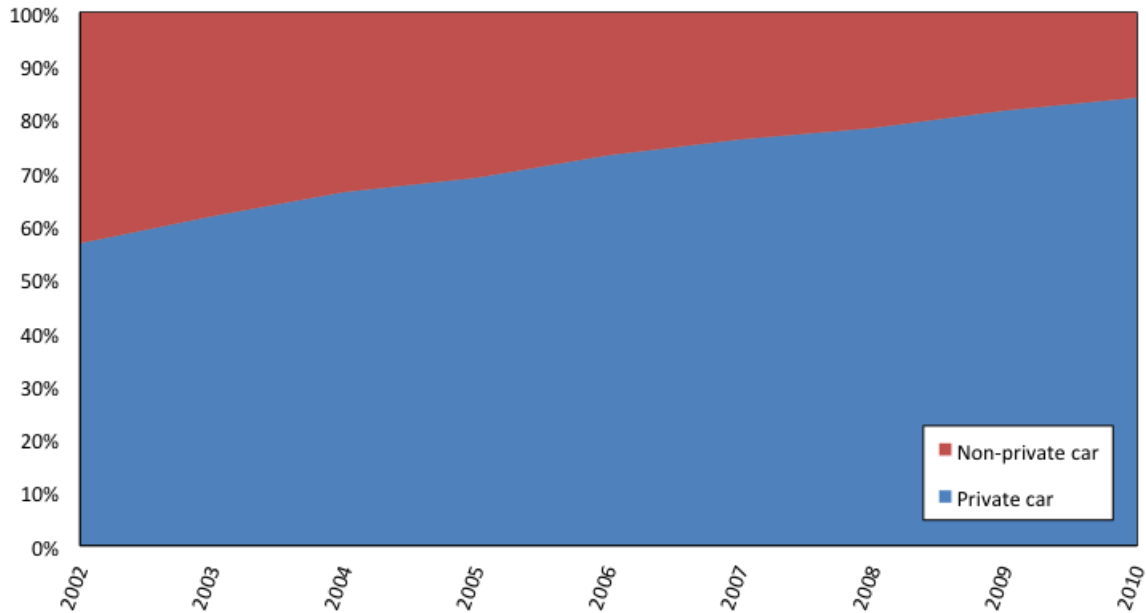


Figure 4-2: Ratio of private cars to non-private cars in China. Source: China Statistical Yearbook (2011a).

commonly found as taxis in Chinese cities (Figure 4-3). Because they run on small, lead-acid batteries, these three-wheelers have more in common with two-wheelers than with passenger cars.

4.1.3 Comparison across models

Other fleet modelers examine the entire Chinese vehicle fleet, but break up the light duty vehicle fleet in different ways. Yan and Crookes (2009) model light duty trucks, minitrucks, passenger cars, taxis and minivans, and Ou et al. (2010b) passenger cars, minitrucks, minivans, light duty trucks and motorcycles. My “minibus” category corresponds with their “minivan” category. Huo and Wang (2012); Huo et al. (2012c,a,b) identify private light duty vehicles, business light duty vehicles, taxis and light duty trucks. The light duty vehicle and light duty truck categories include larger and heavier vehicles than my corresponding passenger car, minitruck and minibus categories do. Hao et al. (2011d) only model passenger vehicles and split out private passenger vehicles, business passenger vehicles and taxis. Business passenger vehicles and taxis correspond with my non-private car category.

4.2 Historical sales and stock

Vehicle stock

Until the mid 1990s, vehicles in China were few and far between. Figure 4-4 traces historical passenger car stock. Taxis, in fact a subset of non-private cars, made up the lion’s share of all cars in the mid 1990s and 36% of the non-private car stock in 2001. However, numbers of taxis have remained constant while non-private cars and especially private cars have proliferated (see Appendix C, Stock). These growth curves imply that China’s passenger car fleet is unusually young; my analysis shows the average Chinese private car was only around four years old in 2010. If growth continues at this pace, the light duty vehicle fleet could rapidly absorb new technologies. However, China’s passenger vehicle stock is unlikely



Figure 4-3: A 3-wheeled Chinese “zhuliche” in Beijing. Source: author.

to continue increasing at the same dramatic rate. By this argument, China should introducing new and disruptive technologies into the vehicle fleet now before it locks onto conventional, gasoline-driven, ICE cars of regular size and materials.

Vehicle sales

Vehicle sales have shot up at similar speeds (Figure 4-5). While minitruck, minibus and non-private car sales have steadily increased, private passenger cars have fueled overall growth.² From 2000 to 2010, car sales increased from 0.6 million to 9 million passenger cars per year, an annual 31.58% sales growth rate increase. Nevertheless, pace of growth has been variable: over 55% from 2002 to 2003 to not even 7% from 2007 to 2008. The considerable volatility in car sales in the past decade makes it difficult to predict future sales.

Projections

Forecasting future vehicle sales is difficult, especially in the near term. Over the past decade, analysts have consistently underestimated the relentless acceleration of Chinese vehicle sales. This holds true across academic and industry forecasts. To illustrate this, I gathered articles published in the English-language Chinese newspaper “China Daily” between January 1, 2000 and December 31, 2009 citing sales forecasts for the year 2010 (Figure 4-6; see Appendix D for a complete list). Forecasts do grow increasingly accurate as 2010 approaches, but less than five years prior in 2006, a forecast of 6 million passenger car sales in 2010 underestimates by 37% true sales of 9.49 million passenger cars. Meanwhile, the average 2005 forecast for total 2010 vehicle sales at 9.47 million underestimates true sales of 18.06 million by 48%. Various factors explain the discrepancies between 2005 forecasts and 2010 sales. First, relative vehicles prices declined steadily throughout the decade (Huo and Wang, 2012), potentially because several foreign vehicle manufacturers entered China and many new domestic automakers gained strength. In addition, temporary favorable sales policies in 2009 and 2010 temporarily halved vehicle

²I derive private and non-private car sales from the China Statistical Yearbook and the CAIY in Appendix B.

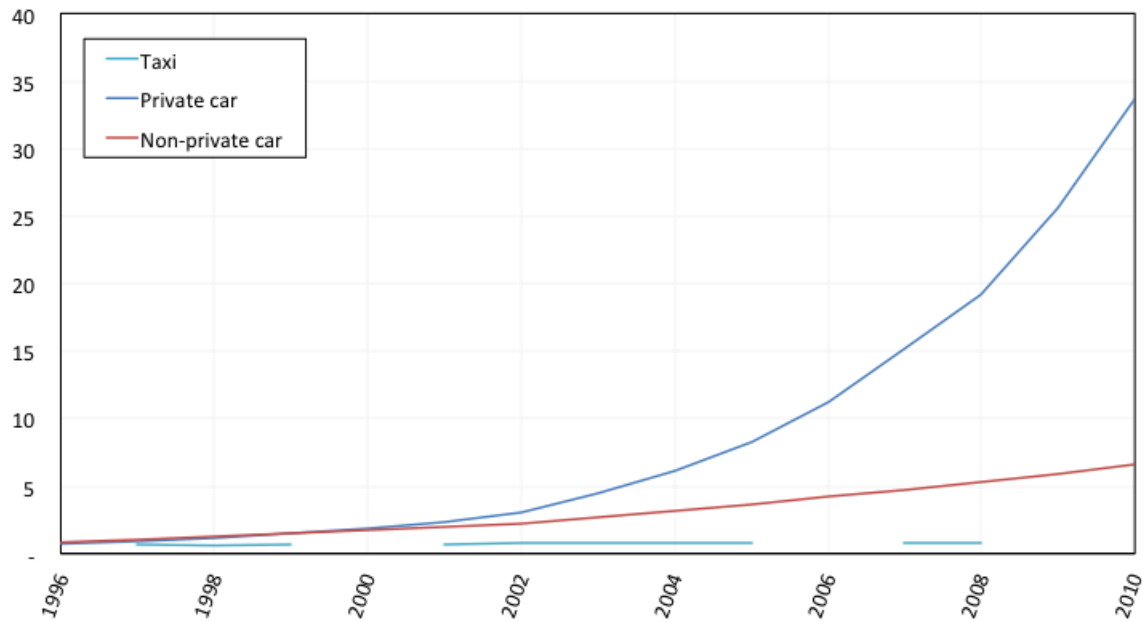


Figure 4-4: Historical Chinese passenger car stock in millions of vehicles per year. Source: China City Statistical Yearbook (1997-1999, 2001-2005, 2007-1997-1999, 2001-2005, 2007-2008); China Statistical Yearbook (2011a); China Automotive Industry Yearbook (2011b); and author analysis.

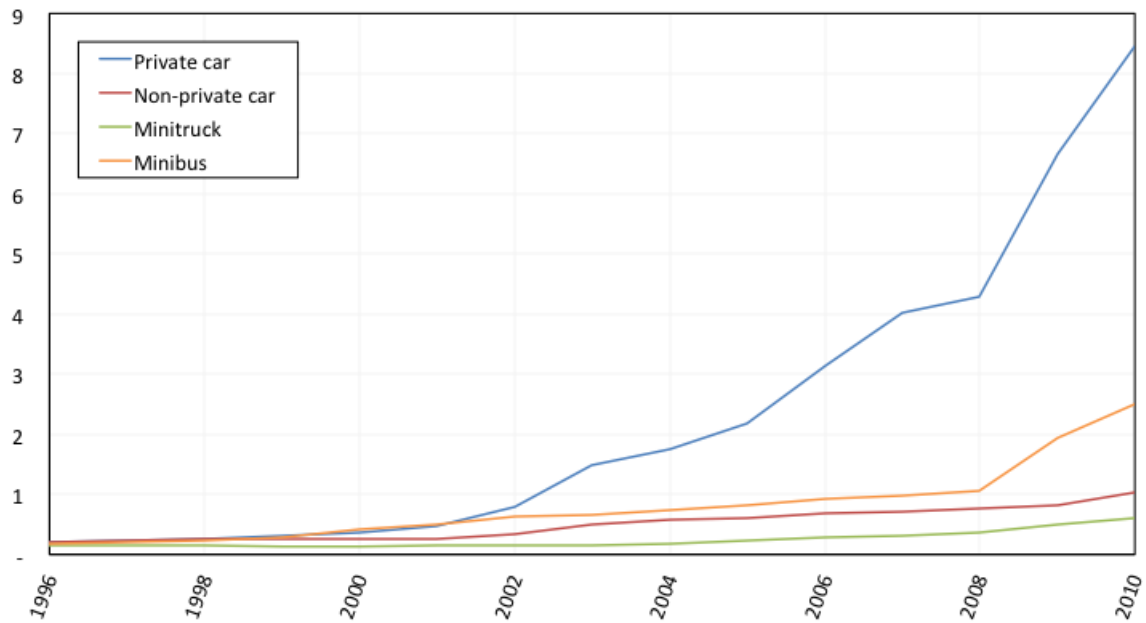


Figure 4-5: Historical light duty vehicle sales in millions of vehicles per year. Source: China Automotive Industry Yearbook (2011b).

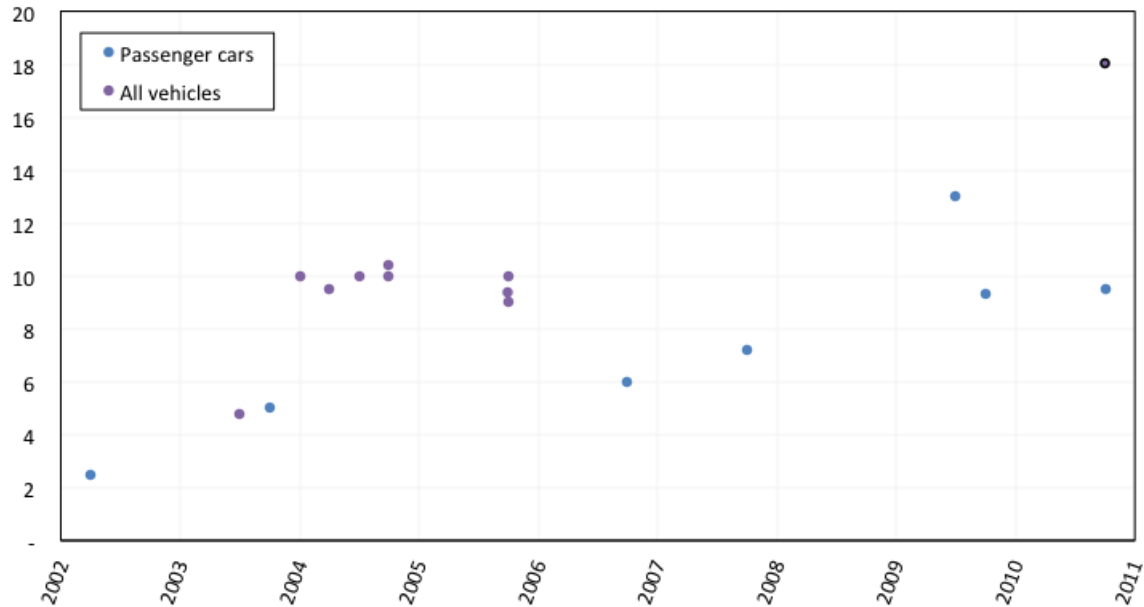


Figure 4-6: Predictions for 2010 vehicle sales in China in millions of vehicles. Source: author analysis for China data articles. The two markers at the end of 2010 are true sales figures.

taxes for small cars and subsidized rural light vehicle purchases (State Council,2009). I do not suggest Chinese vehicles sales in 2018 will differ from current projections by half, but illustrate how volatile future vehicle sales are on short time horizons. Therefore, it is difficult to gauge the accuracy of future long term sales forecasts generated in vehicle fleet modeling with any mid or short term results.

4.3 Progress and policies to date

Worldwide, vehicle ownership has historically linked closely with per capita income (Dargay et al. (2007)). Thus, as China’s goal is to develop economically, vehicle ownership will also increase. However, although vehicle ownership correlates well with income per capita, vehicle ownership in some countries is nonetheless higher or lower than Dargay et al.’s predicted levels. For instance, car ownership in the US has historically been higher than at comparative income levels in Japan or Germany (Dargay et al. (2007)) even though all three countries are major automobile producers. The challenge for China, then, is to craft policies that increase per capita income levels while encouraging only modest automotive ownership.

A country’s vehicle stock also depends on innumerable other variables. Both the ability, need and desire to purchase a vehicle factor in, as do demographics. Considering just the light duty vehicle fleet, an individual’s ability to purchase a vehicle will depend on income, relative vehicle price, and fuel price. Across a whole population, not only average income but also income distribution will be important. Second, an individual’s need to purchase a vehicle depend on where she lives and what her environment resembles. Population density, urbanization, land use policy, comparative utility of other modes of transportation may all be relevant factors. Third, cultural norms that dictate how desirable vehicle ownership is may alter the desire to purchase a vehicle even if one does not need it. Finally, demographic factors translate the likelihood that a given individual will purchase a vehicle to total vehicle stock. Not only is total population important, but so is the proportion of population of driving

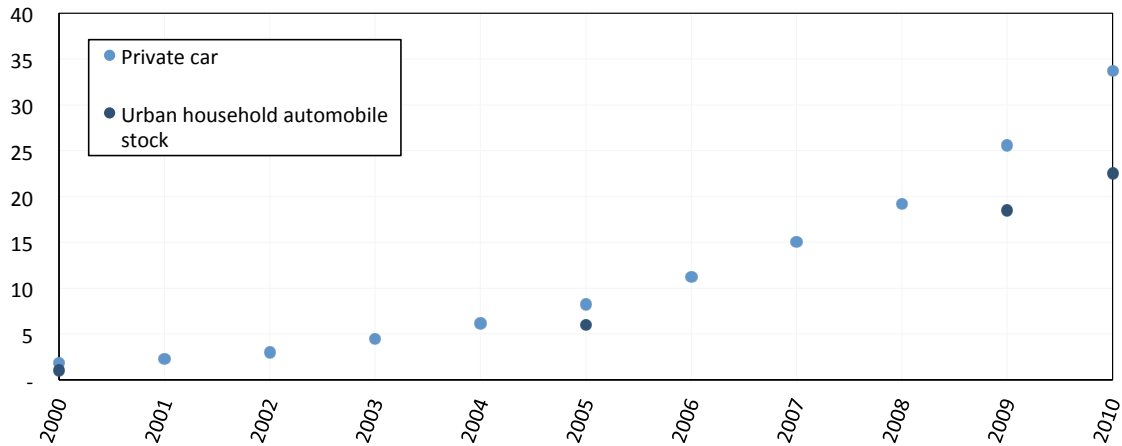


Figure 4-7: Private car and urban household vehicle stock in millions of vehicles per year. Source: author analysis from China Statistical Yearbook, 2011 and China Automotive Industry Yearbook, 2011, and author analysis from China Statistical Yearbook, 2011, respectively.

age. Family structures and gender can also influence the size of the potential vehicle owning population. This section examines policies to date that discourage or encourage an individual's need to purchase a vehicle. I examine demographics and cultural norms in Section 4.6.

4.3.1 The built environment

In developed countries, auto ownership is higher in rural areas than in urban areas (see Dargay (2002) for instance). So far, China has showed the reverse trend: vehicle ownership is much higher in urban households than rural households. This is reasonable because urban incomes in China are far higher than rural incomes. Eventually, when rural income distributions allow a majority of residents to purchase vehicles, rural automotive ownership may quickly surpass urban automotive ownership. Nevertheless, the current pattern of ownership in China, where urban private household vehicle stock constitutes a majority of private cars (Figure 4-7) indicates that understanding the drivers or urban automotive ownership in China is key to understanding overall automotive ownership. The trends also hold true across provinces; rural household vehicle ownership is consistently lower than urban household vehicle ownership (Figure 4-8). Moreover, because poorer provinces do not even measure rural household vehicle ownership, this sample of eight provinces includes many of the richest provinces. On a household basis, ownership is even lower.

China is rapidly urbanizing, but determining the effect of urbanization on vehicle ownership and use is difficult. Evidence indicates that increasing urbanization in a middle income country does increase energy use per capita (Poumanyong and Kaneko, 2010). Urban residents are much richer than rural residents in China, and it is logical they use more energy. However, the design and shape of the city may also play a role. A rich literature has explored the relationship between urban form and vehicle ownership and vehicle use on both the macroscale and microscale. At the macroscale, several studies have found strong correlation between rising urban densities and declining vehicle use and vehicle fuel demand ((Newman and Kenworthy, 1989; Kenworthy and Laube, 1999, 1996)). These macroscale measurements, of course, give little insight into the specific urban form conducive to low automotive ownership and vehicle use. Therefore, they offer no prescriptive solutions for how China should develop. Microscale studies try to measure how diversity and design of cities affect urban form as well.

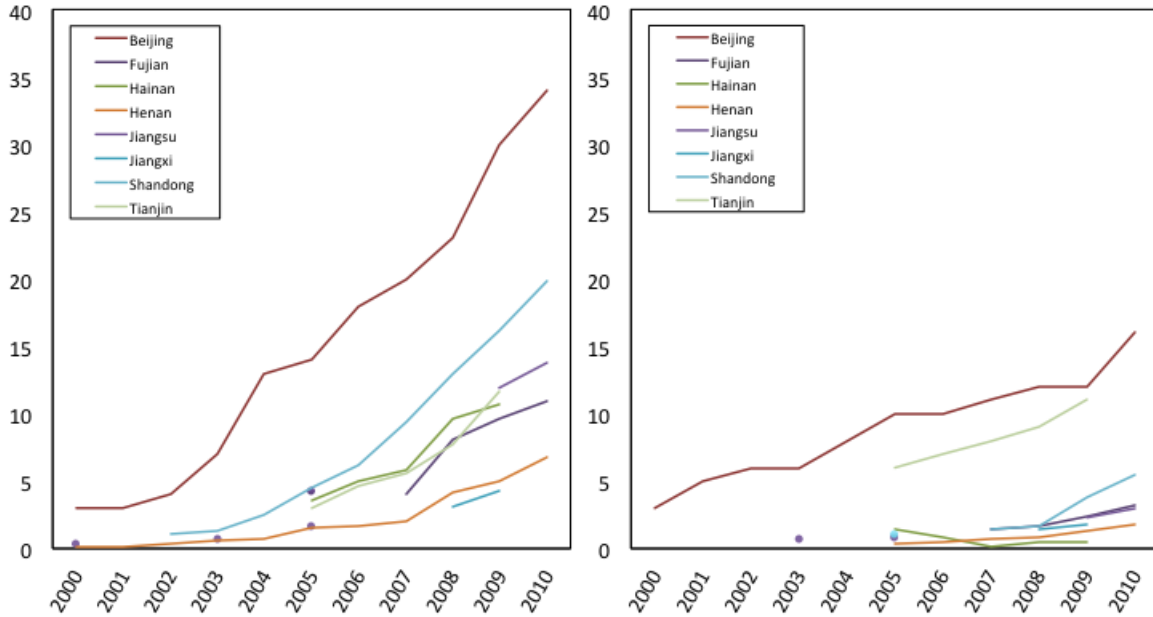


Figure 4-8: Urban and rural household vehicle ownership in eight provinces in vehicles owned per 100 households. Source: Beijing provincial yearbook (2011); Fujian provincial yearbook (2011); Hainan provincial yearbook (2011); Henan provincial yearbook (2011); Jiangsu provincial yearbook (2011); Jiangxi provincial yearbook (2011); Shandong provincial yearbook (2011); Tianjin provincial yearbook (2011) .

Studies indicate that although effects exist, they are smaller than expected (Crane, 2000). Other studies indicate that diversity and design influence automotive travel behavior more than density (Ewing and Cervero, 2010). While crude, density matters across a large population, but the design of individual neighborhoods is crucial as well. In this section, I examine urban densities in China, forces that encourage Chinese city sprawl, and policies that encourage automotive ownership and use.

Urban densities

Chinese cities have traditionally had very high population densities, but urban density is quickly declining (Figure 4-9). The six major cities of Beijing, Shanghai, Tianjin, Guangzhou, Hangzhou and Ningbo had an average population density of 164 people per hectare in 1990 and 146 people per hectare in 1995 (Kenworthy and Hu, 2002). This small set contained a notable density range from 251 persons per hectare in 1990 in Shanghai to 119 persons per hectare in Guangzhou in 1995. Two more recent studies used a wider dataset of cities to estimate population densities in 2000. An analysis of population densities in 2000 in the 41 largest cities in China and four provincial capitals found urban population densities to range between 68.13 persons per hectare (Huhehot) and 211.74 persons per hectare (Wuhan) and found a median population density of 107.39 persons/hectare (Suzhou) (Chen et al., 2008). Another recent study analyzed a much larger sample of 135 cities, and found a lower density of 94.6 persons per hectare with values ranging from 40 persons/hectare (Kalamyi) to 220 persons/hectare (Fuzhou City) (Tan et al., 2008). Finally, Liu et al. (2012) find that in 2008, the average population density for 30 cities in China was 95.5 persons/hectare. The data thus indicates that Chinese urban population density decreased from 1990 to 1995 to 2000, a trend in line with development worldwide. Second, the larger datasets include smaller cities the smaller datasets do not, and the larger datasets' average or median

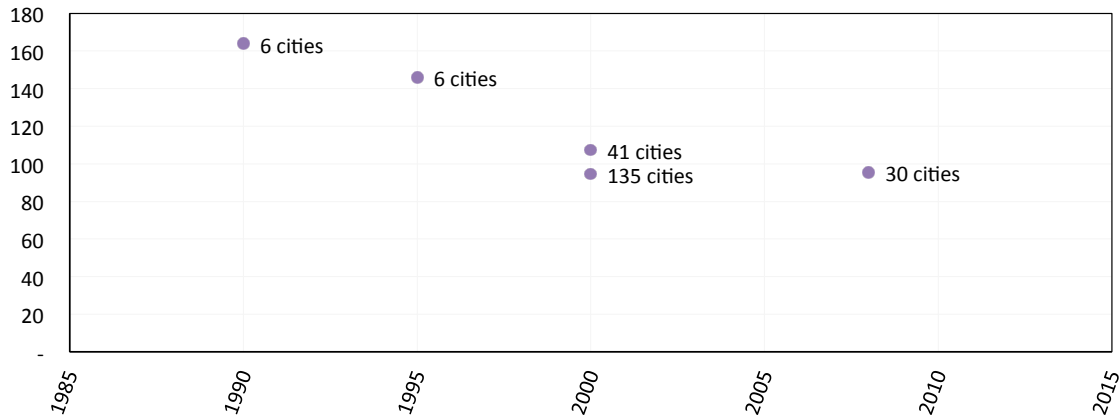


Figure 4-9: Urban densities in China in persons per hectare. Labels refer to the number of cities used analyzed for datapoint. Source: Kenworthy and Hu (2002); Chen et al. (2008); Tan et al. (2008); Liu et al. (2012).

population densities tend to be smaller. This indicates that in China, urban density rises with increasing population size.

Both urban population and city size are difficult to measure in China. Zhou and Ma (2005) provide the best explanation to date for how various statistical agencies measure China’s urban population. China has traditionally divided its citizens into agricultural and non-agricultural workers. While the concept originally reflected reality, many “agricultural” citizens will now live in urban environments. Thus, equating non-agricultural workers with urban residents will undercount the true population of urbanites. However, counting the official urban population with urban residents will create an overcount. In China, the urban population includes all people living within the administrative boundaries of a city, which includes land that is not built up and therefore descriptively rural. In addition, China’s citizens are also formally attached to one location through a “hukou.” If a person moves to a new city, he is considered a migrant and not officially part of the host city. Various studies examine how this has prevented rural to urban migration patterns, has dictated which cities grow, and which cities remain static (Bosker et al., 2012; Au and Henderson, 2006; Xu and Zhu, 2009). All these consideration matter when measuring urban densities in China.

It is therefore worthwhile to briefly discuss methodology for the urban density studies. Both Chen et al. (2008) and Tan et al. (2008) explicitly state they use the non-agricultural population statistic, which counts the urban population in the city proper and exurban districts. Tan et al. (2008) also measure population density with only the city population data to calculate population density and find a higher population density of 131.5 persons/hectare. Kenworthy and Hu (2002) do not specify which population statistic they use, but it is likely the non-agricultural population as it is the one reported in statistical yearbooks. Both Kenworthy and Hu (2002) and Tan et al. (2008) adjusted the data for built up area.

Land-use policy

China’s unique approach to land property rights motivates a political explanation for urban sprawl. While governments own all urban land in their jurisdiction, rural land is collectively owned. The government cannot sell its land outright, but can offer long-term leases. Tian and Ma (2009) explain that the system encourages local governments are pressured to oversupply land leases in order to capture

short term revenues. Recall from Chapter 2 that local governments are underfunded and limited in the ability to raise taxes. Local government can sell land use rights, and Tian and Ma (2009) cite evidence that these sales accounted for 15.9% of local government revenues between 2000 and 2006. These sales contribute to sprawl. Tian and Ma (2009) demonstrate that urban land expansion in China far outpaced urban population growth between 1990 and 1995, and continued to do so by 10% until 2005. The gap narrowed in large part because the central government mandated that all local governments use an auction and tender system to lease land instead of the previous artificial allocation through negotiation. The new market based allocation increased prices over the previous artificial allocation, but did not retard land leases.

When an actor is only compensated financially for new developments, there is no incentive to further develop existing land (Yang et al., 2007). Local governments are in this position because they cannot exact property taxes but receive a lump sum payment when land is initially leased. Thus, to retain a steady stream of revenue, a governments must continually seek new sources of land to develop. Local governments can expand city borders by absorbing rural land. Because rural citizens have little power, local governments can easily undercompensate farmers and expropriate the land (Ding, 2007; Yew, 2012; Yue et al., 2012). The governments can thereafter lease this newly acquired land at higher prices than they obtained it.

The result is urban sprawl of a particular type. While in the West sprawl is often characterized by large, low-density residential suburbia, in China it consists of “leapfrog” developments unconnected to the rest of urban development containing large industrial parks, university campuses, or half-urbanized villages. This “leapfrog” growth comprised 50.55% of Hangzhou’s growth from 1995 to 2005 as Hangzhou grew from 1.44 million to 4.1 million people and 96 km² to 314km² (Yue et al., 2012). It can also consist of residential developments. These are customarily built as highrise towers with high population density.

The central and local governments view land supply different. To local governments it represents a financial resource. To the central government, it is the resource that must feed the population (Zhang, 2000). The central government feels China has a shortage of farmland (Lichtenberg and Ding, 2009) and as localities expand, cultivated land shrinks. Nevertheless, cities continue to expand. For example, Shanghai grew by over 4000 ha per year from 1979 to 2008, but two-thirds of the acquired land originated as cropland (Zhang et al., 2011). An amendment to the 1998 land management law required State Council approval for converting any farmland, cultivated land over 35 hectares and any land over 70 hectares. A 2006 notice required budgets to include land use revenues for inspection by higher levels of government in another attempt to curb excessive land use right sales (Tian and Ma, 2009).

Nevertheless, land use right sales have constituted 30 to 70 percent of local government revenues recently Yew (2012), increasing dependency on this resource. With the central government policies in place, how does land expansion continue? Yue et al. (2012) explain that local governments create land use plans subject to central government oversight. Central government oversight operations, however, are underfunded and it is easy for local governments to frequently revise plans and reserve less and less land for agricultural uses.

Several more specific mechanisms increase unnecessary urban development. In order to capture additional revenue from land, governments will often build public infrastructure before leasing land in order to drive up prices (Yew, 2012). This can lead to unnecessary construction. Many local governments will also build large public spaces – because the cost of land for the government is close to zero, marginal costs of large developments are small. Yang et al. (2007) write that city government’s “monopolistic role in the land market” has led many to build “government buildings as luxurious as the Capitol of the

United States.” Actual government spending, they write, is decoupled from spending on public services and needs, partially because the cadre system rewards such spending.

Fierce competition among cities to elevate their urban centers to cosmopolitan icons as well as incentives for local politicians to gain recognition and seek advancement also contribute to excess urban development projects (Yew, 2012). This competition pushes cities to cater to local industries in order to ensure economic development and job growth (for which local governments are responsible). Yue et al. (2012) explain that local governments often acquiesce with industrial enterprises who want to locate business in an area not planned to be urban. Previously, urban governments would often cater to these companies to locate by offering low land prices: Yue et al. (2012) find that while average industrial land prices were just 8.3% of average residential land prices in Hangzhou in 2004 – 559 yuan / m² vs. 6735 yuan/m². Since then, however, national policy has required governments to sell land through auctions (Yang et al., 2007). Finally, local governments have also zealously engineered large development zones thought to attract industrialization and foreign investment. The unfortunate result is extra and half-empty infrastructure, as well as isolated and oversized development zones (Yew, 2012).

All sprawl will not necessarily push up automobile ownership. Yue et al. (2012) relate that Zhejiang university sold its old, urban campus in order to relocate on the outskirts of Hangzhou. The sold land has been reconverted to high-end commercial land use. Considering that university students in China are unlikely to own vehicles, the effect on automotive travel behavior of this particular suburbanization is questionable. A few studies on specific cities in China have therefore tried to model transport behavior resulting from land use changes. Various city-specific studies have used integrated land use-transport models to simulate these actions. Zhou et al. (2012) examine what happens with transportation energy on urban Xiamen Island if development continues and the population grows much richer compared with a scenario that promotes mixed land uses and economic incentives to develop and encourage public transportation. The former increases transportation CO₂ emissions by more than 10%, the latter decreases it by about 5%. As more integrated land-use transport planning studies like this enter the literature, it will be interesting to see how urban design in China contributes to transportation energy use.

Low-carbon cities

In the publication *Sustainable Low-carbon City Development in China*, (Baeumler et al., 2012) overview eco-city projects in China. Both the Ministry of Environmental Protection and the Ministry of Housing and Rural-Urban Development have developed eco-city standards that Baeumler et al. argue will incentivize cities to develop towards these goals. At the same time, they criticize the standards for keeping a narrow focus on physical indicators.

Eco-cities are the demonstration projects for low-carbon city concepts both the national government and select pilot provinces have worked to build in the past decade. In 2009, the Ministry of Housing and Rural-Urban Development selected thirteen cities and districts as pilot projects. In 2010, the National Development and Reform Commission (NDRC) selected five provinces and eight cities to set their next Five Year Plan with climate change in mind. These cities have crafted development plans, selected performance indicators, and identified key priorities. Nevertheless, many initiatives have failed because of financial constraints, lack of local government attention, mismanagement or failure to adapt to local conditions. In particular, the authors point out the “Ecologically Sustainable” village in Huangbaiyu, Benxi, Liaoning was a poor village before plans were drawn up to build up new state-of-the-art green houses. But villagers refused to live in the houses because the yards were too small for animals while many homes were built with car garages, an unaffordable luxury for the farmers. In conclusion, Baeum-

ler et al. opine that eco-city demonstration projects can be beneficial on the road to low-carbon cities, but are not as easy and foolproof to implement as developers and officials may think. It is not enough for the central government to allocate money to projects without ensuring that local governments have the ability, capacity and incentives to see the projects through.

Automotive friendly policies

On a smaller scale, China has also encouraged automotive development. Many cities have banned two-wheelers, implicitly encouraging motor vehicle use as a form of rapid private transportation. 148 cities in China had banned gasoline two-wheelers in 2006, many citing air pollution concerns. A number of cities have also banned electric two-wheelers, citing safety concerns and desires to improve traffic flow Weinert et al. (2008). This implies that traffic safety officials prioritized automobile traffic flow to other traffic flow. This is not unquestionably obvious. In fact, in his book *Fighting Traffic*, Norton (2011) describes how in the 1920s the US socially reconstructed streets from belonging to people to belonging to cars. That cities in China are doing so now with two-wheelers and cars indicates that China may be tending towards a city design where automobiles take priority over pedestrians, bicycles and low-speed motorized vehicles like two-wheelers.

Density of new Chinese developments exceed new developed world developments (Mehndiratta et al., 2012). Nevertheless, travel behavior is not only a matter of density; design matters as well. This can refer to street width, building layouts, or development layouts. Consider setbacks, the minimum distance from building to road curb. Chinese municipalities traditionally dictate distances of five to fifteen meters. Nevertheless, cities have proposed setback distances of forty meters for primary arterial roads, citing safety in the case of natural disasters. This would create very large building to building distances that encourage automotive reliance (Mehndiratta et al., 2012). As anybody who has spent time China will know, this type of street planning is common. Major streets in Beijing are often very wide, have white metal barriers to prevent unwanted pedestrian crossings, and large, infrequently spaced pedestrian overpasses. In addition, new developments in China, even if they are dense, are often built on large, isolated blocks. These have limited number of entrances and promote automotive access (Cervero and Day, 2008).

Parking practice in Chinese cities favors automotive use. First, parking enforcement is lax in many cities and it is easy to spot cars parked on sidewalks. Mehndiratta et al. (2012) explains this is due to institutional fragmentation - traffic police enforce laws only on streets while a different divisions manages sidewalks, but this division often lacks the authority to give parking fines. In addition, Mehndiratta et al. explain that building codes specify minimum levels of parking provision and that government bodies set parking prices, making them unnaturally low.

4.3.2 Transportation system development

Beyond land-use, the transportation system China develops is equally important in dictating future travel patterns. If China restricts automotive ownership or automotive use, it must provide good contexts for alternative transportation systems in order to provide its citizens with high levels of accessibility. Until this point, undue attention has been given to roadway development at the detriment of public transportation development.

Roadway development

Infrastructure development is neither a wholly central government nor local government affair. Bai and Qian (2010) show that while railway investment has remained centrally planned and growth in business volume has lagged GDP growth, highway investment burden rests with local governments and growth in highway length has exceeded GDP growth. Industry aids local governments in funding highway expansion, often foreseeing the lucrative toll collection that can accompany it. While low rates of return on railway investments due to low prices make profit-minded investors uninterested in railway infrastructure, rates of return on investment for highways is much higher. Return on investment for twelve publicly listed highway companies was 10.5%.

Furthermore, the system is highly sensitive to regulatory capture and overinvestment. The companies that invest in highway infrastructure, while profit-driven, are also often majority government held. The close connection between local government and local companies creates strong incentives to overdevelop and oversupply highway infrastructure (Bai and Qian, 2010).

Public transportation development

It is difficult to know whether China undersupplies public transit or not. Yang et al. (2007) argue it does: while city governments can rake in revenues with land development, transit development is by itself not profitable. Transportation planning is an afterthought: many cities have no dedicated transportation planning staff but route other city officials as needed. Thus, when a city expands to a new area, it only routes rail lines for central institutions. This leaves gaps in the transportation system in new developments and encourages private paratransit operators or reliance on two-wheelers and automobiles. By treating transportation planning as an afterthought, transit services remain delayed and undersupplied. (Zhang, 2007) describes that although Beijing has quickly developed rail-transit networks and new housing communities have developed next to these networks, business has not followed and these have developed into pure commuting neighborhoods. Stations furthermore often fail to integrate into the local neighborhood, creating unnecessarily long transfers and confusing walkways paths.

4.3.3 Demand management interventions

Despite new roadway and public transportation infrastructure, congestion in Chinese cities has rapidly expanded during the previous decade. Average speeds on major arteries in Beijing fell from 45 kmph in 1994 to 12 kmph in 2003 (Cervero and Day, 2008). Wang et al. (2008) find that rush hour in Beijing can reduce automotive travel speeds on freeways by half. Peak hour speeds on arterial roads range from 23 to 39 kmph, reduced from off-peak average speeds by 11% to 35%.

To mitigate this congestion, a handful of large Chinese cities have set caps on the annual number of new vehicles allowed onto roads. Shanghai curtailed its private vehicle sales with an auction in 1994. The city government released about 10 000 plates every month to private vehicles (Wang, 2010). Commissioned to the Shanghai International Auction Company, citizens can enter the auction in person or online (Feng and Ma, 2010). The auctions have become more expensive and competitive in recent years: 26 526 people vied for one of 9 500 plates released this past July, paying on average 58 271 yuan (\$9,140) to obtain one (Shi, 2012). This is more than the price of cheap domestically manufactured cars.

Beijing adopted a similar policy at the beginning of 2011, sharply curtailing its vehicle sales by more than half: the capital registered almost 900 000 new vehicles in 2010, but just around 400 000 in 2011

(China Statistical Yearbook, 2011a). In Beijing's policy, aspiring private vehicle owners may enter the lottery free of charge and winners are randomly selected once a month.

Citizen response is generally negative to these policies, especially the Shanghai plate quota, and the government appears to allow for policy leakage for just this reason (Chen and Zhao, 2013). That said, as a result of this policy, at the end of 2009, Shanghai had about 3 times fewer vehicles per capita than Beijing: 72 to 212 vehicles per 1000 people (Hao et al., 2011b). Car plate quotas are nevertheless vulnerable to side effects. Any major city in China has a large proportion of publicly owned vehicles, and cities with large proportions of publicly owned (government and state enterprise) vehicles achieve smaller effects private vehicle license plate quotas. For example, though Beijing had 2.5 times as many vehicles as Shanghai in 2010, Beijing had 782 100 publicly owned vehicles to Shanghai's 718 000 publicly owned vehicles (China Statistical Yearbook, 2011), suggesting Shanghai's policy had not restricted public sector vehicle growth. In addition, despite restricting driving during rush hour to only Shanghai-plated vehicles, a significant number of Shanghai residents purchased vehicles in nearby cities to circumvent the sales cap, although no formal statistics are available (Wang, 2010). One estimate sets it at 10% of vehicles (Hao et al., 2011b).

The main impediment towards widely implementing this policy is likely to be central government response. If just ten cities restrict their automotive sales by 200 000 vehicles annually, this represents over 2 million loss in vehicle sales (as sales would likely have increased without a cap) - 10% decrease in the Chinese vehicle market. At this point, the central government might step in to protect automotive sales.

4.4 Model implementation

Projecting vehicle stock by incorporating quantitative projections of all the drivers presented in the preceding Section 4.3 is unrealistic. However, normalizing vehicle stock to population enables me to compare vehicle stock across different countries. Among the 34 OECD countries, for example, it is unusual to have more than 600 vehicles per 1000 capita or fewer than 400 vehicles per 1000 capita. The United States, at 797 vehicles per 1000 capita, is highest but Finland, Canada, Greece, Italy, Australia, New Zealand, Luxembourg, and Iceland also have rates above 600. Turkey, with 155 vehicles per 1000 capita, is lowest, but Chile, Mexico, Israel, Hungary, South Korea and Slovakia also have rates below 400 (World Data Bank, 2013). The statistics for OECD countries are useful because although they do not represent all the wealthiest countries, they exclude the wealthy island nations and other very small countries that are unrepresentative for China's future.

For model implementation, I set three alternatives for Chinese vehicle ownership in 2050: 400 vehicles / 1000 capita as a low projection, 500 vehicles / 1000 capita as a reference projection and 600 vehicles / 1000 capita as a high projection. The reference scenario projection is lower than the current OECD average of 564 vehicles per 1000 people (World Data Bank, 2013), but considering China's current high urban population density and income disparities, a lower ownership rate is reasonable.

The three relevant model inputs are base year vehicle sales, percentage point annual sales growth rates, and survival curves. Survival curves represent the fraction of vehicles that survive as a vehicle ages (Figure 4-10). I use a decay function using average vehicle age and rate of scrappage to model this relationship. These values can be determined with field studies or by fitting appropriate values to historical sales and stock. I assume survival rates are constant over time (see Appendix B, Vehicle scrappage, for further explanation). With fixed survival curves and base year vehicle sales, I set annual sales growth rates for five and then ten year increments to achieve desired ownership rates in 2050. I

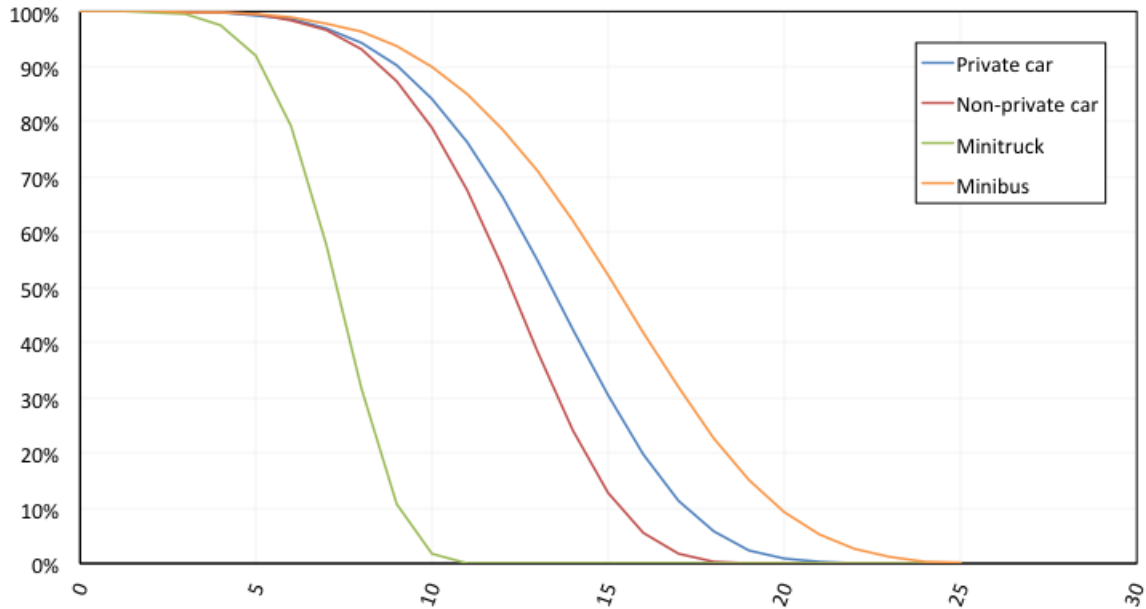


Figure 4-10: Light duty vehicle survival curves by vehicle age.

supplement my light duty vehicle stock projections with heavy duty vehicle stock projections from Ou et al. (2010b) and population forecasts from UNESCAP (2012) to measure projected future vehicle per 1000 capita values. I assume sales growth rates will slow over time because lower predicted economic growth and future declining population are unlikely to sustain high sales rates. I also assume sales growth rates are consistent among all four vehicle types (see Appendix B, Vehicle sales, for a detailed explanation).

These projected future sales, combined with survival curves, generate predicted future stock (Figure 4-11).

In all cases, most growth in vehicle stock occurs before 2030. Future sales growth exhibits kinks because I lower sales growth rate projections in five and ten year intervals, but continually slows down throughout the model timeframe. Future vehicle stock can also be disaggregated according to vehicle type or powertrain as described in 4.1 and 6.5.2. Minibuses and private cars continue to dominate vehicle stock. Diesels will compose a very small portion of future vehicle stock, while electrified powertrains will slowly gain acceptance, especially after 2030. Meanwhile, turbocharged vehicles will replace NA-SI vehicles as the most common ICE vehicle between 2030 and 2040.

4.5 Comparison across models

Other China fleet models use a variety of techniques to project future vehicle stock and arrive at similar, but not identical, projections that range from 375 to 575 million vehicles in 2050 (Figure 4-13). This study's reference case projection is among the highest of all studies. Hao et al. (2011d) exceeds the projection while Meyer et al. (2007) and Huo and Wang (2012) come close. Similar to this study, two other studies also set percentage increases in sales growth rates in five and ten year intervals: Ou et al. (2010b) and Yan and Crookes (2009). However, neither study pegs these numbers to a target future stock as this study does, although Yan and Crookes explain they attempted to mimic the periods of rapid

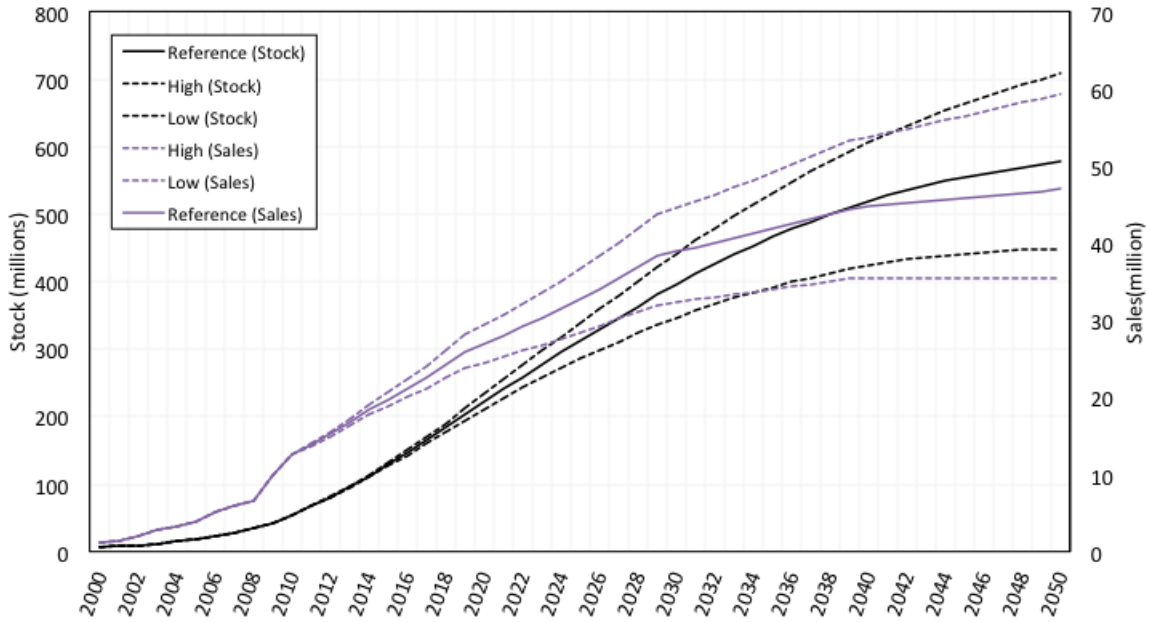


Figure 4-11: Future light duty vehicle sales and stock.

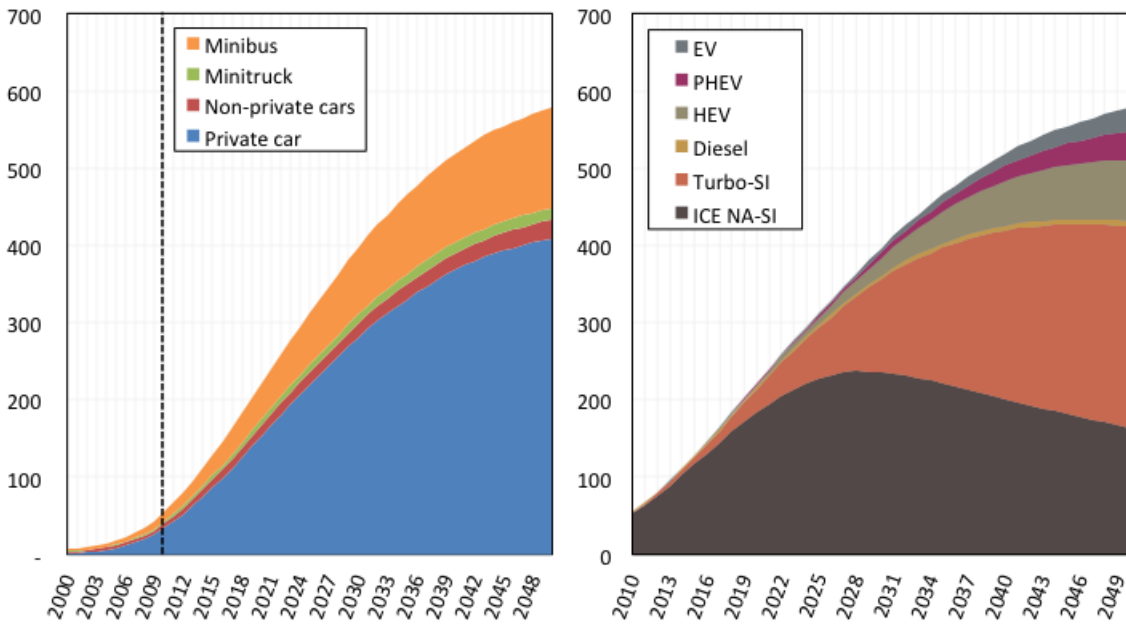


Figure 4-12: Future light duty vehicle stock by vehicle type and by powertrain in millions of vehicles.

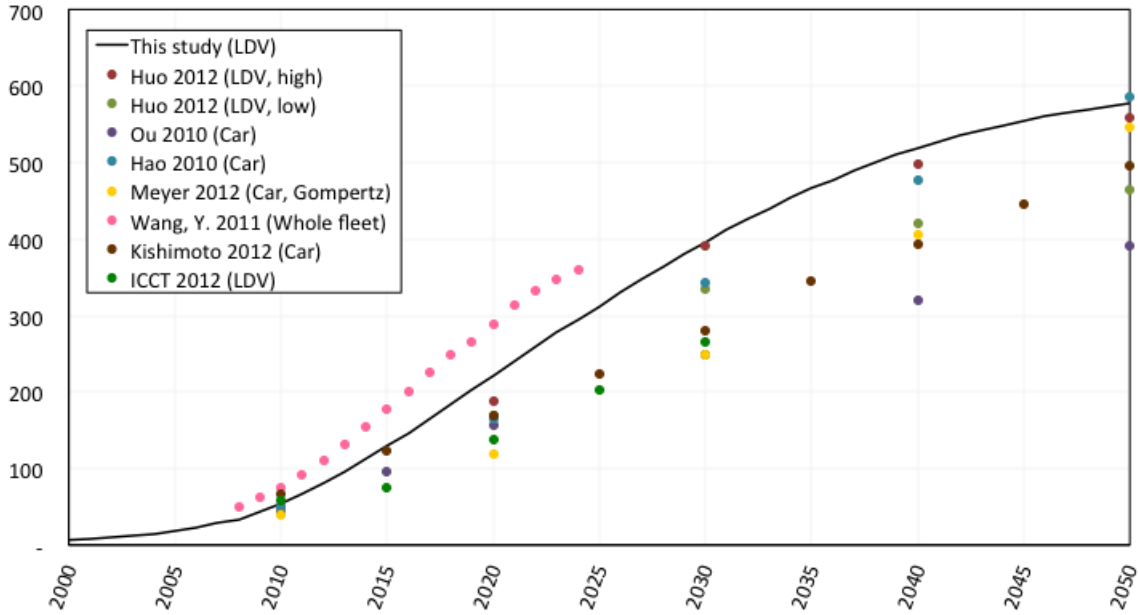


Figure 4-13: Stock comparison across models in millions of vehicles.

motorization followed by slowing vehicles sales growth other countries have historically experienced. Other techniques explicitly index vehicle stock against developed countries' historical experiences, use a economy-wide economic model to extract vehicle stock, or relate vehicle ownership to equations based on economic indicators.

Historically, large countries with domestic automotive industries have undergone expansive and brief periods of motorization. Wang et al. (2011b) average out motorization trends from seven large, automotive-industry countries and use the resulting trend to project China's vehicle sales growth. This generates a more accelerated growth curve in the coming fifteen years than do other methods. This may indicate that most projections underestimate the rate at which rapid motorization can occur.

Kishimoto et al. (2012) extract vehicle stock from their analysis of future Chinese household travel energy demand using a recursive-dynamic general equilibrium model. The model generates money spent on own modes of transport which the researchers convert then to passenger car numbers.

Income is the most important factor in vehicle purchases and many studies use the so-called Gompertz equation to model this relationship. Huo and Wang (2012) devise a method taking into account ownership in different income brackets, relative vehicle prices and population. Hao et al. (2011d) use different methods for different types of vehicles. For private household vehicles, they take rural and urban vehicle ownership of different income brackets, relative vehicle prices and population into account. For taxis, they assume vehicle density increases over time to a saturation point, while government and business vehicles increase in line with GDP growth. Meyer et al. (2007) do a complete global stock projection based on multiple regions, of which China is one. They assume North America is representative of vehicle ownership saturation. It is worth noting that they also employ other stock projection techniques that also predict far lower ownership in China than does the Gompertz curve method.

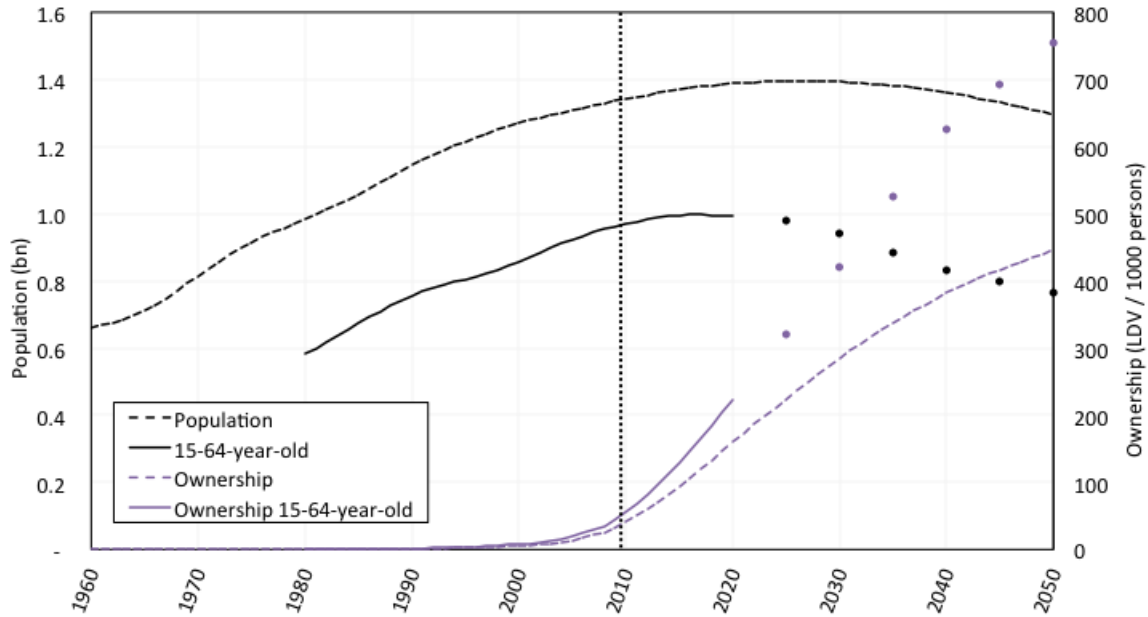


Figure 4-14: Population and driving age population projections. Source: UNESCAP (2012) and author analysis.

4.6 Other determinants of vehicle ownership

As mentioned previously, the desire to own a car and underlying population can also affect vehicle ownership.

4.6.1 Demographics

Demographics determine the size of the potential vehicle buying population in China. Total population represents the most basic demographic indicator and this model incorporated vehicle population projections into pegging future vehicle ownership to that of other countries. Projections indicate that China's population will peak at 1.40 billion in 2026 and decline thereafter, surpassing 0.5% per year by 2046 (UNESCAP, 2012). Were it not for population decline, sales growth rates could have been higher to achieve the same ownership levels.

Other demographic factors, however, can also affect future vehicle stock. As China's population ages, the population of eligible drivers will shrink. The number of 15-64-year-olds in China will peak in 2016 at 1.00 billion (Figure 4-14). Analyzing the UNESCAP projections suggest this section of population will decline more rapidly than the overall population: more than 1% annually between 2030 and 2040 and nearly 1% between 2025 and 2030 as well as after 2040. This decline should depress vehicle purchases in China. However, changing family and housing structures could also increase vehicle ownership. Zhang and Goza (2005) point out that while elderly care has traditionally been a family responsibility. However, the one-child policy has shifted the multigenerational family structure and parents are less likely to live with grown children than before. An increasing number of small households could increase vehicle purchases.

4.6.2 Culture

A population's ability and need to purchase a vehicle are important vehicle stock determinants, but so is desire. The utility a person derives from a vehicle can be divided into functional and symbolic utility, where functional utility reflects the need for a car and the improved accessibility that car provides whereas symbolic utility reflects the social stature or other non-accessibility related benefits one derives. Lu (2008) explains that in rapidly developing China, becoming wealthy and purchasing the luxury goods that can accompany this lifestyle is an important life goal. Students are no exception (Zhu et al., 2012).

The "three most-wanted" has traditionally described the most desirable consumer goods in China. While it included a bike and watch in the 1950, it now includes housing, an automobile and a kids education (Peo). This affects mate selection as well. Many young urban Chinese men today lament the harsh financial criteria against which they are judged for potential marriage suitability. On a reality TV dating program, a model caused a social media stir for defending choosing a rich partner but an unhappy relationship rather than the reverse (Sebag-Montefiore, 2012), while a 30-old-Beijing resident recalls arriving to dates by public transportation and purposefully leaving the car at home to find a woman interested in more than his financial standing (Jacobs, 2011). A "perfect mate" must have "a car, an apartment, a good salary and, preferably, a tall stature" (Sebag-Montefiore, 2012) or be able to provide these items at time of marriage (Lim, 2013). Because owning a car in China symbolizes affluence and stability, its value extends beyond an intrinsic, monetary sticker price. The social currency the car brings a family social standing and a single man a better chance of finding a wife. The desire for car ownership will push up number of vehicles in China. The elasticity of vehicle ownership in China will be lower than if the cultural importance of vehicle ownership were smaller. This concept has been integrated into a predictive vehicle ownership model (Wu et al., 1999). It will be important to incorporate this concept into future China vehicle ownership models.

Chapter 5

Vehicle use

Once an individual owns a vehicle, the marginal cost of using the vehicle compared with its purchase price is low, and individuals will drive it. Nevertheless, countries differ in average annual distance driven per vehicle (VDT). Several factors can affect VDT and many are similar to those that affect ownership itself: the built environment, availability of public transportation, cost of driving, and culture. In addition, policies that influence the cost of driving will also affect vehicle use: these include fuel prices, road prices (congestion charging, toll roads, and parking pricing) or road availability (road bans). This chapter examines the current Chinese policies increase the cost of driving in China, describes VDT trend implementation in the model, and compares the trends with those of other studies.

5.1 Progress and policies to date

Before 2000, when taxis and government vehicles comprised a majority of China's passenger car fleet, annual VDT per vehicle in China was high compared with that of other countries. Taxis, for example, are constantly on the road and can easily surpass 100,000 km per year. However, the average annual VDT of passenger cars in China dropped quickly between 2000 and 2010, coinciding with the advent and rise of private citizen car ownership. Although China has not collected official statistics on vehicle distance traveled, several researchers have sampled vehicles in different cities in China over the past decade and recorded evidence for this trend (Huo et al., 2012c; Hao et al., 2011a; Vehicle Emissions Control Center, 2010; see Appendix C, VDT). These studies have also noted a clear difference in VDT between private cars and non-private cars, as well as evidence that taxi VDT continues to grow.

Few policies in China directly target VDT from an energy consumption perspective. Instead, cities such as Beijing have implemented vehicle driving bans for certain days of the week as an attempt to curb severe congestion and mitigate local air pollution. For the Olympic Games in 2008, Beijing restricted 50% of vehicles from driving on its roads between July 1st and September 20th. Vehicles with an odd-numbered license plate could only drive on odd-numbered calendar days, while special purpose vehicles, transit buses and taxis were exempt. The Beijing government has continued the policy, instituting a 20% restriction by matching a given weekday with two license plate final digits, with the same exemptions as before. Digit pairs rotate about every month to make difficult to circumvent the ban with two vehicles. Meanwhile, 30% of government vehicles were forbidden from driving on each weekday. Since 2010, this restriction has been implemented during peak driving hours (Hao et al., 2011b). In the rest of China, driving bans have slowly gained in popularity among larger cities with populations of a couple million

inhabitants. As of March this year, Beijing, Chengdu, Hangzhou, Lanzhou, Guiyang and Changchun had all implemented some form of driving ban (Ma, 2012). That said, the effectiveness of these policies are still in question. Following the Olympics, during one day per week bans, flows on main street were reduced by 4.1% and on the ring roads by 2.8%, while passenger flow on public transport increased by 20.8% (Hao et al., 2011b). Hao further estimates that up to 30% of vehicles purchased in Beijing since the driving bans were intended to circumvent the restriction. Although Beijing's vehicle purchase restrictions now limit this policy, it is easy to think of other possible rebound effects. For example, they may retain a secondary old vehicle longer to have a back-up option on restricted days or rent a vehicle. In addition, people may substitute planned drives on weekends or other non-banned days. In other words, it's questionable what effect driving ban restrictions would have on reducing total VDT. Hao et al. (2011b)'s estimates suggest that effects are not 20% (from banning 20% of license plates), but rather on the order of 5%. Even if many cities were to adopt such a policy, the overall effect would be small.

China lacks policies that price driving in order to discourage it. The exception is China's expressways that link different cities together and carry high tolls on par with those of many developed countries (Hu et al., 2010). Partially because these expressways carry such high tolls, policymakers have been hesitant to add further driving charges in the form of fuel taxes (Winebrake et al., 2008). A proposed fuel tax in the late 1990s was derailed due to central and local government tensions. Wong (2000) explains that the Ministry of Finance wished to consolidate the patchwork of local fees on vehicle purchases and use into a fuel tax that would be redistributed to local governments. The localities, however, were suspicious of the central government's promises after the tax redistribution scheme in 1994 had left them with far lower budgets. Lack of local government support created an institutional barrier to fuel pricing, and the case exemplifies how Chinese politics is based upon mutual agreement and bargaining rather than unilateral action.

In the early 2000s, fuel prices in China were on par with those in the US in the early 2000s. In 2005, they surpassed those in the US, but in 2010 remained one third lower than those in Europe (Mehndiratta et al., 2012). Now, local governments retain the right to tax fuel at optional rates of 30%, 50% or 80%, which is still low in comparison with most European countries (Hu et al., 2010).

5.2 Model implementation

VDT is commonly reported as a fleetwide average annual distance traveled per vehicle. While no official statistics are available, I approximated average results from other studies that relied on field surveys to set appropriate historical VDT values (Huo et al. (2012c); Hao et al. (2011a); Table C-4). These studies separate taxis from non-private cars and I reaggregated them to correspond with my non-private car category. Information on private cars, non-private cars and taxis is more abundant than for minitrucks or minibuses. I use the data available for minitrucks and assumed its VDT over the past decade showed a similar declining trend as cars. I assume minibus VDT will resemble non-private car VDT. Unlike private cars, minibuses are frequently used for utilitarian purposes: transporting many people or much material. See Appendix C, VDT, for details.

Concerning future VDT, it is reasonable that average annual VDT will continue to drop for all vehicle types. Chinese private car VDT was above that of most other OECD countries in 2010 at around 16000 km/vehicle/year while non-private car VDT was far higher. For future VDT, I set a reference, higher and lower projection (Figure 5-2). To develop these, I benchmarked future Chinese private passenger car VDT against current average annual car VDT for OECD countries sourced from Euromonitor (2013). 10000, 13000 and 16000 km/vehicle/year are the model predicted 2050 low, reference and high sce-

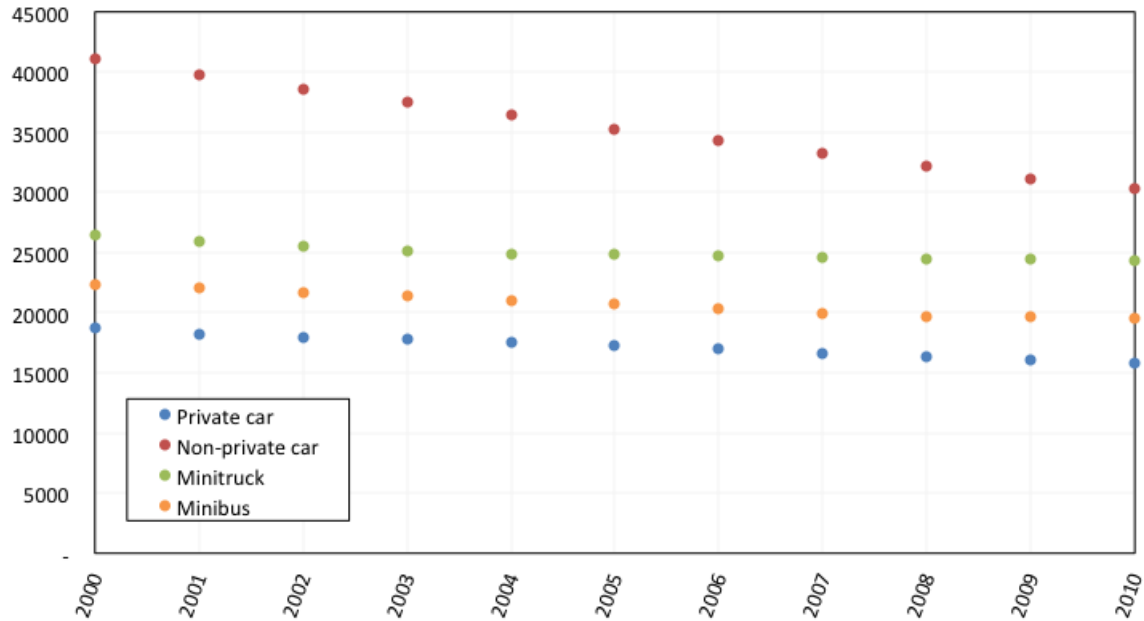


Figure 5-1: Chinese light duty vehicle VDT in km per vehicle per year.

nario predictions. In 2010, Mexico, South Korea, Slovakia, Turkey, Hungary, Poland and Spain had car VDT values below 10000 km per year, while the Netherlands, Ireland, Austria and the USA had values above 16000 km per year. The OECD average was 13618 km/vehicle/year and has been falling since a peak of 14774 km/vehicle/year in 2003. For all scenarios, I assumed the majority of change in average annual VDT would occur before 2030.

I include no explicit feedback mechanism between ownership and VDT. Although during the past fifteen years rising ownership in China has correlated with falling VDT per vehicle per year, this trend does not hold across OECD countries. Analysis of both the Euromonitor (2013) and World Data Bank(2013) shows little correlation between OECD countries' car ownership and per vehicle VDT.

For the model, average annual VDT is an aggregate measure because it differentiates VDT by model year and vehicle age. This means the group of five-year-old private cars sold in 2005 have a unique annual average VDT per vehicle associated to the group. This allows me to accurately incorporate the tendency for vehicles to be driven fewer kilometers as they age. An exponential decay equation models this relationship with a mileage degradation rate as a decay factor and a new car VDT. The model keeps mileage degradation constant at 5% per year (see B for details) and uses a percentage point annual change in new car VDT to incorporate changes over time. I set these percentage point annual change values in five or ten year increments for each vehicle type so the fleetwide average annual VDT for each vehicle type I thereafter calculate accords with the target scenario projection values in 2050 defined above (see Appendix B, Vehicle distance traveled, for details).

In this process, I disaggregate car VDT projections into private cars and non-private cars but ensure the weighted average average annual VDT equals the target values. Non-private cars include not only government and company vehicles, but also taxis. Non-private car VDT is sensitive to taxi VDT: although they will make up less than 10% of non-private vehicles, their average annual VDT is over 100000 km. Nonetheless, as I benchmark projections to set values, I assume taxi VDT will settle at 110,000 km/year/vehicle and compose 5% of the non-private vehicle fleet. I then combine the weighted average of non-taxi and taxi non-private cars with private car VDT to achieve 2050 target car VDT values (see

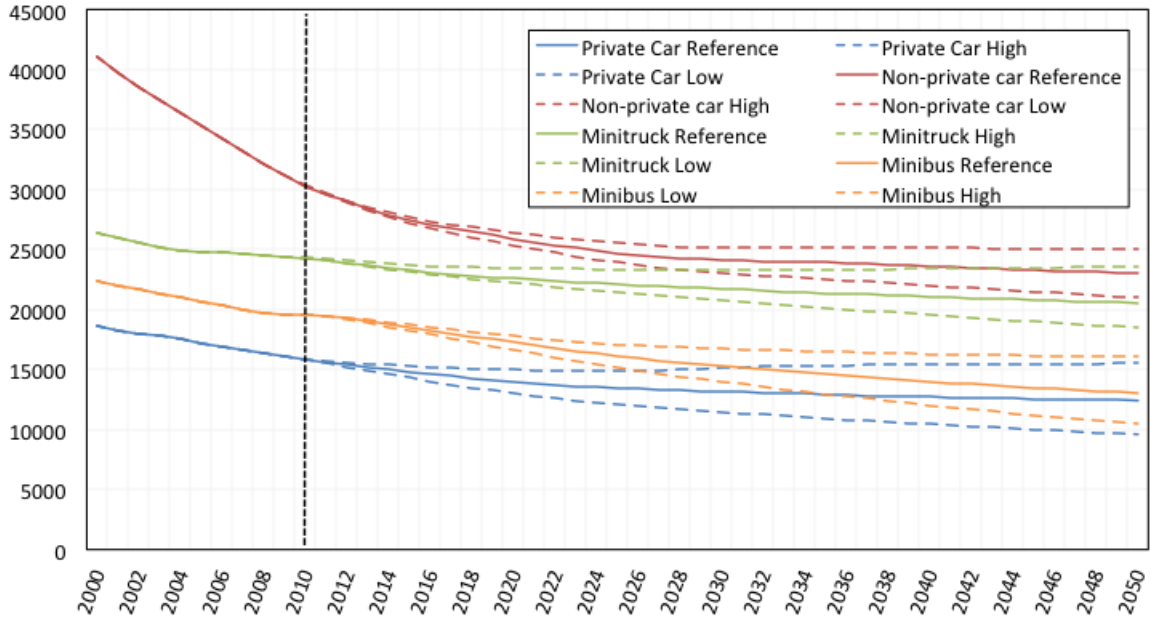


Figure 5-2: Future light duty vehicle VDT in km per vehicle per year.

Appendix B, Vehicle distance traveled, for details). I assume minibus VDT will be similar to average car VDT and minitruck VDT will remain higher than car VDT but also drop (see Figure 5-2).

5.3 Comparison across models

My projections for VDT trends are similar to those of other research teams. Huo et al. (2012b) have a high and low use projection for passenger cars at 9900 km and 13600 km in 2050, Hao et al. (2011a) project 12000 km in 2050, while Ou et al. (2010b) have the highest projection at 15000 km in 2050. That said, Hao et al. (2011a) allow for lower VDT in one of their scenarios that specifically targets VDT. My upper and lower extreme VDT projections bound these projections, while the reference VDT projection is only slightly lower than the average of the three other research teams' 2050 projections.

Chapter 6

Vehicle technologies

Automotive ownership and use comprise the first half of the vehicle impacts identity. Vehicle efficiency and fuel intensity define the second half. Policy often targets these latter two characteristics more directly, even if policy is inherent in both. This chapter begins by examining how local and national government interests have shaped the Chinese automotive industry. It then systematically examines fuel consumption progress and policies to date. The third section of the chapter uses a dataset compiled from the Ministry of Industry and Information Technology (MIIT) to compare joint venture (JV) and domestic brand vehicles. After reviewing alternative powertrain progress and policies to date, the chapter discusses model implementation and compares chosen values with other modeling efforts.

6.1 The industry perspective

6.1.1 Automotive industry development

During the years of industrial state planning in China, a few hand-picked automotive manufacturers produced the nation's vehicles. Many of these SOEs live on today as the "Three Big" (San Da): First Automotive Works (FAW), Dongfeng, and Shanghai Automotive Industry Corporation (SAIC) (Harwit, 1995). Nevertheless, in the late 1970s and early 1980s, the national government attached little priority to the automotive industry as it was focused on developing the agricultural sector and rural industry (Chin, 2010, pp 53). The existing companies produced trucks. Passenger car production made up no more than 2% of national output in any year before 1979, and accounted for over 5% first in 1988 (World Motor Vehicle Data, 1990). The firms that manufactured vehicles did so inefficiently: in 1987 China had the world's largest motor vehicle industry in terms of employment (1.2 million), but one of the world's smallest in terms of output (400 000 units). Chinese automotive labor productivity was one sixtieth that of Japan (Womack, 1987, pp 31-32). Womack further describes a tour at a Beijing Truck Plant I tour where skilled machinists used individual tools to create identical parts. Nevertheless, data shows that 1990 marked a definitive upward shift the passenger car segment's importance in the Chinese automobile industry. The passenger car segment's importance grew rapidly to top 25% of sales in 1994 and 50% of sales in 2001 (Ward's, 2009, 2011-2012).

China's passenger car market was nonexistent for long because private cars were seen as an unnecessary luxury good (Oliver et al., 2009). When China loosened trade controls in the 1970s and 1980s, demand for imported passenger cars and light trucks bounded upwards. The Chinese government's solution was to develop indigenous truck manufacturing capabilities and establish JV firms with for-

eign automotive manufacturers in order to access desirable foreign models (Chin, 2010, pp 54). China awarded the first JV approval to Beijing Automotive Industry Corporation (BAIC) and American Motor Company (AMC) in 1983 to produce Jeeps. The national government approved Shanghai Volkswagen in 1984 and Guangzhou Peugeot Automotive Corporation (GPAC) in 1985 (Thun, 2006, pp 136-137). Unfortunately, both Beijing Jeep and GPAC went sour and the parent companies terminated cooperation.

Womack blames the Chinese government for imposing burdens on the foreign firms that prevented them from applying their own, tested “foreign” practices. For instance, requirements to “reuse existing facilities and tools made it difficult or impossible to lay out plants in a world-class manner” (Womack, 1987). Chin (2010) also points out after the most successful automotive firms of the day snubbed China’s high demands to enter a risky, unproven domestic market, two of the three firms who did invest were in financial trouble. They could not devote the attention necessary to establish the robust local supply chains required for long term success but relied on importing complete vehicle kits (Chin, 2010, pp 66-72). This is only a partial explanation, because institutional relationships in China contributed to Shanghai’s success in establishing a local network where Beijing and Guangzhou failed. Each municipality had received central government approval to fulfill the vision of developing a domestic Chinese automotive industry. When implementing this vision, Thun argues that Shanghai’s close ties with the central government ensured effective communication and cooperation. Shanghai’s complete control over its automotive sector also enabled it to steer necessary supply chain investments. Beijing and Guangzhou, however, were unwilling or unable to fulfill this central government vision. In Beijing’s case, authorities declined to favor local supply firms and invest the time to develop their organization capabilities. In Guangzhou’s case, they had other, more lucrative industries to invest in. (Thun, 2006, ch 5). Meanwhile, “lack of coordination on the Chinese side, between central authorities and local representatives” prevented the Chinese firms from effectively bargaining with foreign firms to receive the skills, training and expertise they needed to develop a strong automotive industry (Chin, 2010, pp 76). By the mid-1990s, China only produced nine car models (Oliver et al., 2009). China’s automotive industry was still small and not yet entered a period of significant, sustained growth. It was already clear, however, that the existence of a central government vision did not necessarily translate into local government implementation.

The central government prioritized the automotive industry gradually. It was designated a “pillar industry” in 1986 and goals included consolidating the industry under central control, prioritizing passenger cars, developing local capability, and partnering with international firms (Thun, 2006, pp 55). These goals were formalized in the 1994 “Automotive Industry Policy” that sought to imitate Japanese and Korean success and avoid the overinvestment and duplication that could result from “unregulated market competition.” Between 2000 and 2010, the central government would consolidate the industry into 3-4 large, internationally competitive conglomerates by offering priority access to finances, financial markets and foreign investment (Chin, 2010, pp 112). This national policy also laid out the JV policy where the Chinese partner had to have at least a 50% stake in order to retain “state power” and “promote national goals” (Chin, 2010, pp 116). This bold vision formed the start of a continual central government commitment to the automotive sector.

The automotive sector grew. In 2002, it employed 1.57 million Chinese and accounted for 5% of manufacturing industry employment and 6.1% of manufacturing industry value (Gallagher, 2006). However, the JV ownership structure had not produced desired results. The Chinese government had hoped JV partnerships would create a means and incentive for foreign vehicle manufacturers to transfer new and cleaner technology to their local partners, but foreign companies transferred only outdated products to local partners. (Gallagher, 2006). Transferring outdated products allowed foreign compa-

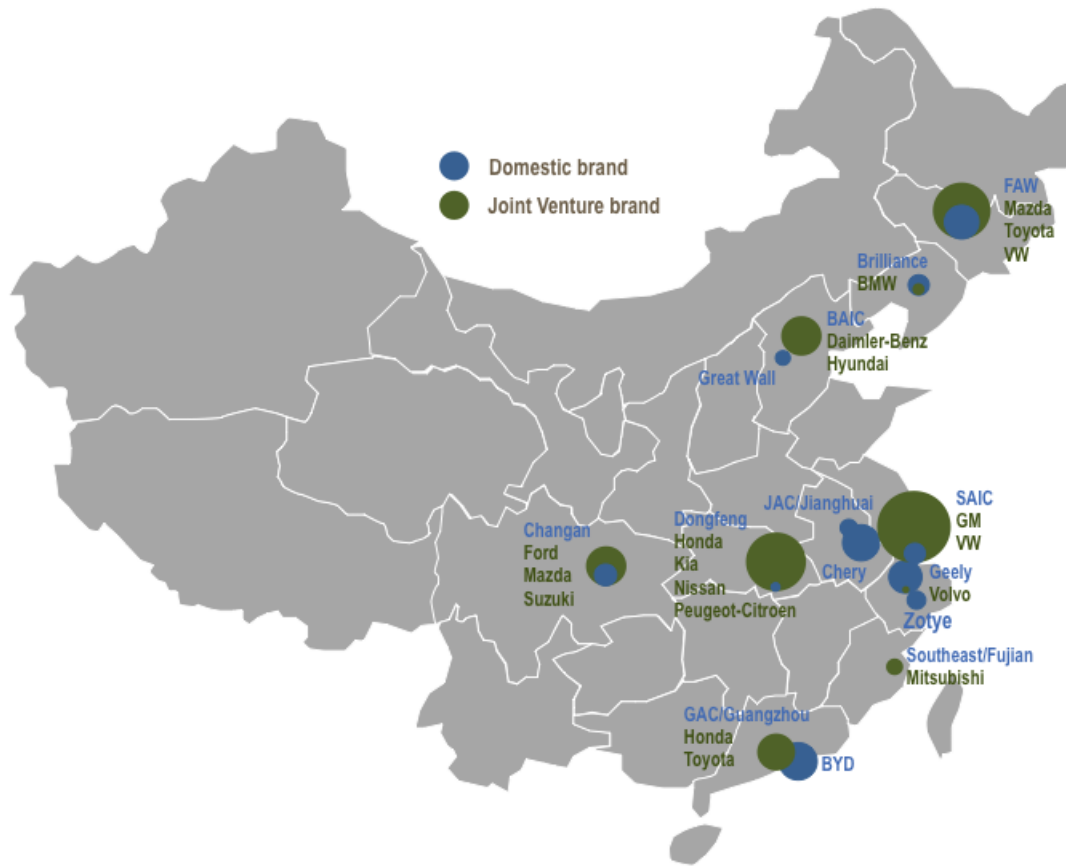


Figure 6-1: Chinese passenger car production volume 2010, divided by manufacturer. Geographic locations correspond with domestic company headquarters, and foreign partners in any joint ventures are listed below. (Volvo is the exception; Geely wholly owns Volvo). Circle size corresponds with relative marketshare, and joint venture and domestic brands are grouped together. Source: Ward’s World Automotive Data, 2009, 2011-2012.

nies to extract more profitable years from aging models, while transferring knowledge and proprietary innovations to a potential future competitor was entirely irrational. Concerning clean vehicle technology regulation, Gallagher further argues the government was locked in a “vicious circle” where they were reluctant to impose fuel consumption or emissions limits for fear of jeopardizing the commercial viability of the domestic brands, but that the lack of such policies created insufficient incentives for foreign JV partners to transfer clean technology. As described in Section 8.2, the government eventually did impose these standards. However, as standards now grow even tighter, it is plausible that concerns over hurting domestic brands may once again delay action.

6.1.2 Current Chinese automotive companies

Two words describe the Chinese automotive industry: large, but fragmented (Figure 6-1). Nine domestic automotive companies produce passenger cars with a JV partner, and their headquarters are spread out among nine different provinces, in stark contrast to the strong regional Midwestern concentration found in the United States. A full 20 companies hold over a one percent marketshare (Ward’s World Automotive Data, 2009, 2011-2012) with headquarters spread over twelve provinces and factories located in many more. The largest Chinese car conglomerate today, SAIC, produces only 23.8% of China’s cars. In

addition, it is evident that JV brands still account for the majority of Chinese car sales. In fact, the most successful domestic brands are those unattached to a joint venture. This evidence shows that national government intentions for large SOEs to develop into strong automotive brands has gone awry as it is the independent and purely domestic automanufacturers who have developed the successful home-grown brands. The following section examines how national government vision and local government implementation has led to this outcome.

The central government designed the JV model to allow foreign entrants access to the Chinese market while developing SOE expertise and technology. This has indeed resulted in remarkable gains as Chinese passenger car production has sharply increased and many luxury models are now produced in China. However, “for Chinese state planners... realizing world-class quality and productivity standards inside China is not enough. The nationality of the firms matters” (Chin, 2010, pp 207). Unfortunately, the structure among the SOEs, local governments and central government has not produced the desired incentives to create strong domestic brands. Chin quotes a former head of FAW, who blames the “JV structure” for encouraging management to concentrate on selling profitable JV cars instead of investing R&D into domestic brands. Chinese SOEs abandoned R&D efforts in the 1990s, instead transferring skilled engineers and managers to the JVs in order to use the JVs protected status to overprice the models and gain handsome profits (Chin, 2010, 209-210). This is logical. Foreign firms had little incentive to transfer state-of-the-art technologies to China or train Chinese partners to produce top-notch vehicles and become future competitors. As municipalities largely owned the SOEs, they could reap easy revenues from the setup, and logically had little incentive to invest in costly R&D. Because the national government had decided the limited number of who could and who could not sell vehicles in China, the resulting near monopoly conditions, coupled with quickly rising sales, created few reasons to invest. National government vision and local government priorities failed to align - the local governments were content with steady profits. Chin relates that the general manager of FAW said “we have no time to do development now as we are very busy ... producing Jetta and Bora. We should wait some 20 years to have strong development capabilities” (Chin, 2010, 211).

Even if the national Chinese government could keep unwanted foreign brands from manufacturing in China, it could not prevent enterprising local companies from seizing the opportunity. These new entrants were not content to wait twenty years to develop Chinese brands. These independent automakers focus on the low end market that has benefitted from the rise of an urban Chinese middle class. The group includes Chery Automobile, BYD Auto and Zhejiang Geely. Because the central government strictly regulates companies that are and are not allowed to manufacture vehicles, these companies have often had to defy the system in order to pursue their business. Hessler relates that Chery built their first automotive assembly line in secret, only asking the national government for a manufacturing license after their successfully producing their first vehicles. This infuriated the government and Shanghai-VW who had negotiated contracts with supposedly exclusive suppliers (Hessler (2005)). Dunne writes bluntly that “officials in charge of the automotive industry gave car production licenses only to companies featured in the central government plans. Chery was never part of the official plan.” Yet Wuhu’s local government successfully lobbied the central government to successively allow Chery to produce engines, produce vehicles but only sell them only in Wuhu, and produce vehicles and sell them in China (Dunne, 2011, pp 125-131). Local governments can defy central government directives. While the central government may unilaterally set automotive policy, promulgating is not implementing. In addition, Chery, in combination with other independent brands, have shown themselves to be ambitious and risk-taking: BYD touts electric vehicle ambitions (Dunne, 2011, pp 207) while Chery has aggressively begun selling vehicles abroad (Chin, 2010, pp 191-192). Their ambitious behavior has paid off: they produce

the most successful domestic brands (Figure 6-1). Besides showcasing the disconnect between central government and local government interests, the mavericks' success also shows that central government planning is underperforming local government initiatives.

Not all vehicle manufacturers in China have been so successful. Industry defragmentation is also evident in the “long tail” of dozens of dysfunctional or defunct automotive manufacturers. Many were former automotive components or other industrial components manufacturers. Consolidating these is one of the national government’s thorniest headaches, but has so far proved unsuccessful. In the 1980s, attempts to rationalize existing assembly and components manufacturers into a limited number of designated product lines and assembly facilities and compensate the municipalities losing assembly operations did not work (Womack, 1987). Womack notes that “decision making on investments, products, and foreign tie ups now seems more than ever to be at the provincial, municipal, and even enterprise level.” However, as noted in Chapter 2, these years were when local governments were given both greater ownership over SOEs and greater financial burdens to provide economic growth and jobs in their home districts. The central government may have wanted to consolidate the automotive industry, but local governments pushed back. Thun describes that local governments might prohibit products produced outside their jurisdiction, levy extra fees on these out-of-district vehicle sales, or require SOEs and government bodies to purchase vehicles from the local manufacturing factory only (Thun, 2006, pp 58-59). Recall from Chapter 4 that non-private vehicles comprised a majority of sales at the time: this last requirement could significantly impact overall vehicle purchases. In addition, although only the central government could issue licenses to sell vehicles nationwide, local governments could provide authorization for production and sales within their own jurisdiction (Thun, 2006, pp 59). They did so and the number of automakers continued to grow. According to Gallagher, there were over 100 automotive manufacturers in China in 2005, the same number there was in the US in 1914. But while there were only a dozen manufacturers in the US in 1924 and three controlled 90% of sales (Gallagher, 2006), dozens of Chinese vehicle manufacturers remain. Granted, the automobile industry was still nascent worldwide in the early 20th century, but the lack of consolidation can also be attributed to economic and government structure. The automotive industry is a source of pride as a pillar industry, receives significant national support through R&D and demonstration programs (see Section 6.4.3), and employs millions of workers. Furthermore, the vehicle industry is growing quickly, and as local governments own SOEs, they can profit from investing in their local SOEs. It is no surprise that national government intentions to consolidate the industry have thus far been unsuccessful. Local governments have strong interests in maintaining their automotive companies. Unfortunately, because many Chinese companies lack the critical mass necessary for economies of scale, this industry defragmentation itself is a barrier to greater research, innovation and development.

Meanwhile, domestic manufacturers struggle to achieve decent passenger car marketshares. In 2003, they accounted for less than 20% of Chinese car sales (Oliver et al., 2009). Share of manufacturing output has increased somewhat faster from 10% in 2002 to 42.5% in 2005 (Chin, 2010, 183). Analysis of Ward’s World Automotive Data reveals that passenger car market shares have held relatively steady from 2007 and accounted for 30.3% of sales in 2010. Domestic brand share of light trucks are much higher and have varied between 70% and 90% of sales between 2007 and 2010 (Ward’s, 2009, 2011-2012). Though domestic brand sales have topped 30% in recent years as was the goal outlined in the “Automobile Industry and Restructuring and Revitalization Plan” (2009), they have not achieved the 40% the plan set as a future goal.

For the domestic Chinese automotive industry, it was beneficial that national government attempts to consolidate it have thus far failed - the rise of Chery, Geely, BYD and other independent automakers

would not have been possible under unilateral state control. Some analysts argue this is part of the solution. The Ministry of Science and Technology urges central government support be distributed among the successful independent companies such as Chery and Geely rather than concentrated among JVs and their SOE parents (Chin, 2010).

Developing a strong, internationally competitive automotive industry remains an important national goal for China, and has been so for over a decade (Gallagher, 2006). There is still progress to be made. As the remainder of this Chapter shows, the inherent technology levels of domestic Chinese manufacturers still lag that of JV counterparts. Meanwhile, grand central government plans to catalyze a thriving electric vehicle industry have short-circuited. Can the national government simultaneously consolidate the industry and raise the domestic brand sales marketshare while tightening fuel standards and promoting electric vehicles? We don't know yet.

6.2 Progress and policies to date: fuel consumption

6.2.1 First and second phase fuel consumption targets

In the mid 2000s, the Chinese central government concluded fuel consumption standards were necessary as a measure to control conventional fuel demand growth (Wang et al., 2010). Concerns over energy security (see 2) and a need to keep pace with foreign government regulation in order to eventually export vehicles may also have played a large part. Oliver et al. (2009) argue the Chinese government initially focused regulation on passenger vehicles because of international precedence and the segment's fast rate of growth among vehicles.

The first set of standards took effect for new models on July 1, 2005 and for continuing models on July 1, 2006. This set of standards did not require automakers to make undue adjustments in model lineups but rather sped up the retirement of outdated models (Wagner et al., 2009). The second set of standards that took effect for new models on January 1, 2008 and for continuing models on January 1, 2009 did require technical improvements. Both standards created sixteen weight classes ranging from below 750 kg to above 1500 kg. All car models had to adhere to the standard in their class, or else not be manufactured and produced (Wagner et al., 2009). Oliver et al. (2009) point out the standards are designed to be easier to meet for lighter vehicles than heavier vehicles, and (Wang et al., 2010)), who contributed to designing the policy, confirms this. The purpose of this, Wang et al. (2010) explains, was to discourage the proliferation of large, heavy cars. The policy was thus beneficial to Chinese domestic automotive manufacturers who have the largest comparative marketshares among small cars

The standards were, however, easier to meet for vehicles with special structures: SUVs, vehicles with three or more rows, and vehicles with automatic transmission. Vehicles with three or more rows of seats are largely designed for transporting passengers or goods in rural areas and as such are given more lenient standards (Wang et al., 2010).

6.2.2 Progress to date

The fleet fuel economy in China improved in the mid-2000s in response to China's first fuel economy standards. Early efforts to document fuel economy in China are sparse, and results contradict each other. Using a 1998 model year database with label fuel consumption values¹ and a 28% derived adjustment factor for passenger cars, He et al. (2005) calculated on-road passenger vehicle fuel consumption² to

¹Fuel consumption as tested by an idealized drive cycle

²Fuel consumption in real conditions, taking terrain, traffic and other considerations into account

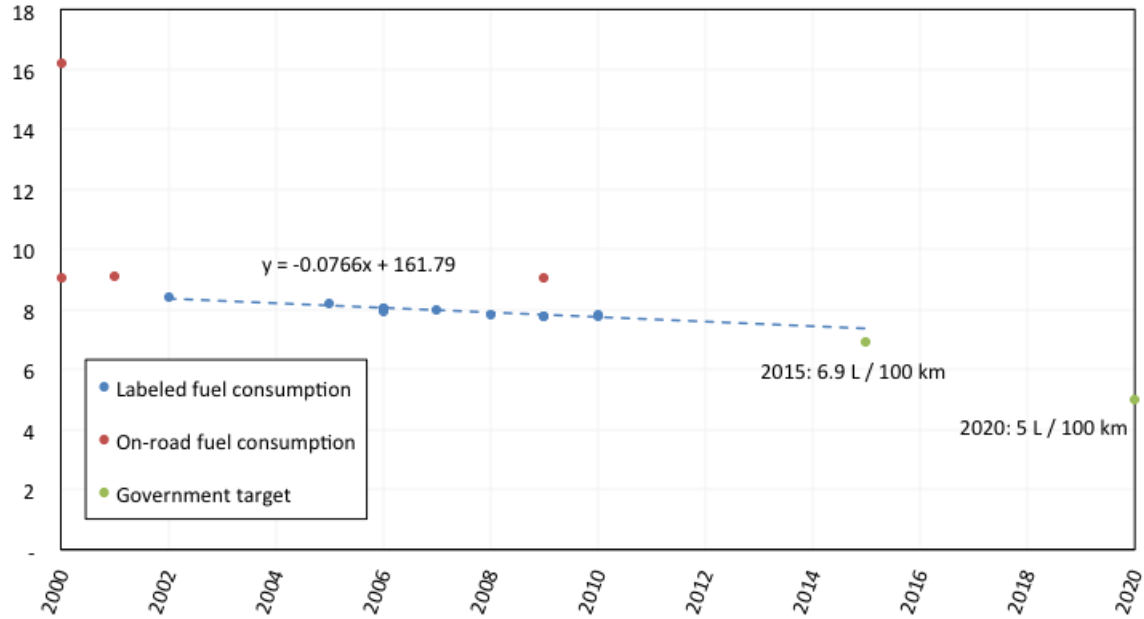


Figure 6-2: Passenger car fuel consumption in L / 100 km.

9.07 L / 100 km for 1997 – 2002 vehicles. Two years later, Wang et al. (2007) used 16.2 L / 100 km for the fleet wide on-road passenger vehicle fuel consumption in 2000. Because of the significant discrepancy in these values, I use no model year 2000 fuel consumption in the model calibration.

Numerous studies on passenger cars since 2002 show declining fuel consumption (Figure 6-2). Regarding on-road fuel consumption, CATARC calculated 9.11 L / 100 km as on-road passenger vehicle fuel consumption in 2002 (Wang et al., 2010), but the methodology used is unclear. Ten years later, Huo et al. (2011) found on-road fuel consumption to be 9.06 L / 100km, using an identified 15.5% adjustment factor from label fuel consumption. For label fuel consumption, data points are rich since 2002. Knörr and Dunnebeil authored a report with 8.4 L / 100 km as the passenger vehicle fuel consumption in China in 2002 (Knörr and Dunnebeil, 2008). Following this, MIIT began publishing batches of information of vehicle characteristics for each variant of each model approved for sale on the Chinese market. By corresponding this data set with sales data available through the Chinese Automotive Industry Yearbook, it is possible to determine fleet wide fuel consumption. The ICCT in An et al. (2007) reported 8.17 L / 100 km for model year 2005. For model year 2006, calculations clustered around 8 L / 100 km: studies cited 8.06 L / 100 km (Wang et al., 2010), 8.05 L / 100 km (An et al., 2007) and 7.95 L / 100 km (Wagner et al., 2009). The Innovation Center for Energy and Transportation (ICET) has compiled an annual study of Chinese fleet-wide fuel consumption from 2007 (An et al., 2011). Meanwhile, Huo et al. (2011) calculated model year 2009 fuel consumption as 7.8 L / 100 km and a recent ICCT analysis measured the same value for 2010 (He and Tu, 2012). The seven years of reported fleet wide fuel consumption statistics for passenger cars cluster well around a linear trendline. This derived trendline is used to model fuel consumption for the "private cars" and "non-private cars" in the model for all years preceding and including 2010 (see Appendix B, Future fuel consumption, for further explanation).

6.2.3 Third phase fuel consumption targets

Recently promulgated policies have announced ambitious fuel consumption targets. The State Council officially announced the upcoming targets in July, 2012. The new targets require an average corporate label fuel consumption of 6.9 L / 100 km in 2015 and 5 L / 100 km in 2020 (State Council, 2012). While the previous fuel economy standards were weight based, the new fuel economy standards are modeled on the US Corporate Average Fuel Economy standards. The new standards will put China on par with newly released standards in the US and EU standards (Cristiano Facanha et al., 2012). Both targets may prove difficult to meet: the former because it is merely two years away, a very short time span in an automotive development cycle, and the latter because many companies are not near this target. Both JV and domestic brands may struggle - JV brands focus on the larger passenger market while Chinese domestic brands focus on small cars (He and Tu, 2012). JV brands will either have to adopt much more stringent technology among their existing product lines or downsize their vehicles and vehicle engines and compete in new market segments. Chinese firms, meanwhile, already produce small vehicles. They will have to improve their technology and may face stiffer JV competition. In addition, more technology will raise average vehicle prices, potentially putting Chinese firms at a disadvantage because low prices is a major part of many domestic brands' value proposition.

While it seems contradictory that the national Chinese government would support a policy that could harm their domestic automotive industry, the policy is necessary. The national government wants to develop an internationally competitive automotive industry. To do so, it must conform to the international regulatory norm. Because the US and the EU have already independently set their targets, China is therefore responding. In regulatory parlance, the Chinese government is converging its policies to highest common denominator (Murphy, 2002). By the same argument, one reason the US and the EU may have adopted stricter policies is specifically to shield their markets from international entrants.

6.2.4 Stakeholder analysis of proposed policies

Even if the national government supports these policies, support may not be unanimous across all stakeholders (Figure 6-3). Additionally, policy responses may change over time. For instance, if the majority of domestic companies consistently fail fuel consumption standards, the national government may intervene and lighten the standards. In another scenario, domestic companies may be able to adhere to standards, but must concentrate on only small engine vehicles to do so. In this case, JV companies might regain marketshares they have lost over the previous five years and the national government may lighten standards to allow domestic companies to compete. Fuel consumption targets, while aggressive, may not be met. Hence the model also does not assume they will be met but uses a different method to set future fuel consumption values.

Local governments are not equal. The most successful Chinese domestic companies that have succeeded in selling cheap vehicles to first-time car buyers may be able to continue to do so. However, domestic companies on average will oppose the policy. They do well in the cheaper side of the market but the new regulations will require them to invest in more expensive technology and increase vehicle cost. JV firms will have a mixed response to the policy. While they must develop the technology in home markets to meet regulations, in China they have been able to focus on larger vehicles. Depending on how the policy will be formulated, this may place pressure on JV firms to start gaining market shares in the small vehicle segment, an area they are not as strong in. However, because they must meet high US standards, they will push for high standards in China as well.

In many other industrial sectors, Chinese manufacturing has been able to achieve cost savings and

Stakeholder	Response	Comments
National government	Positive	<ul style="list-style-type: none"> • Necessary to decrease international oil reliance • Necessary to prepare for future international automotive export
Local government	Depends	<ul style="list-style-type: none"> • If the province or city has a local domestic, but weaker, automotive manufacturer, likely to be very negatively opposed • Indifferent if no automotive manufacturer • Positive if strong domestic automotive manufacturer
Domestic firms	Depends	<ul style="list-style-type: none"> • Manufacturers concentrated on small vehicles (Chery, Geely) could fare well • Manufacturers concentrated on large vehicles (Great Wall) will not • Generally negative; most countries firms export to do not have high standards
Foreign firms	Depends	<ul style="list-style-type: none"> • Not consulted in policy process • May force shift in product mix towards smaller vehicles; have concentrated on larger sedans and luxury vehicles • Other international regulations are also tightened already

Figure 6-3: Stakeholder analysis for new fuel consumption targets.

more efficient production processes (solar and wind energy, for example). Some researchers suggest because China has reached success by concentrating resources in other industrial sectors such as military technology and spacecraft, it is the lack of effort that has prevented this in the automotive sector (Gallagher, 2006). Almost ten years after that analysis, the Chinese domestic vehicle industry has not caught up. It is possible that the first and second phase targets were not stringent enough to induce a flurry of innovation. However, rising fuel consumption standards are hard to marry with cost savings. In addition, the automotive sector may be industry but it creates consumer products. A formula of cost saving and production processes may not be enough to succeed in a consumer oriented sector.

6.2.5 Other industry policies

In addition to fuel economy standards, the Chinese government has set sliding vehicle sales taxes according to vehicle engine size (Table 6-1). This serves two benefits: just as relatively tougher standards on large vehicles encourage sales of smaller vehicles, so do higher sales taxes on larger vehicles. In addition, as Chinese manufacturers dominate sales of small vehicles, it benefits domestic firms. Nevertheless, this policy has questionably achieved its intended effects as marketshares for vehicles with engine displacements over 2.5 L did not sharply decline in 2006 when tax rates doubled. While after lowering the tax rate for vehicles with a 1 - 1.5 L engine grew the relative marketshare grew, the low tax rate for vehicles with engines smaller than 1 L has not improved their marketshare noticeably after 2008. It still hovers around 10% (Oliver et al., 2009).

Engine size (cc)	Before 4/1/2006	4/1/2006-8/31/2008	After 9/1/2008
<1000	3	3	1
1000-1500	5	3	3
1500-2000	5	5	5
2000-2500	8	9	9
2500-3000	8	12	12
3000-4000	8	15	25
4000+	8	20	40

Table 6-1: Vehicle sales taxes and engine size marketshares. Source: Wagner et al. (2009).

6.3 Vehicle fleet characteristics

Technology analysis

Countries regulate vehicle fuel consumption, but the independent variables that companies manipulate as they produce vehicles does not include vehicle fuel consumption. Rather, they include vehicle weight, vehicle power, vehicle engine displacement, transmission type, and others. For example, all else being equal, increasing vehicle weight increases vehicle fuel consumption, as does increasing vehicle power or vehicle engine displacement. All else being equal, switching to an automatic transmission will consume more fuel. Other dependent variables co-exist with fuel consumption as tradeoffs: shorter acceleration times are associated with worse fuel consumption and vice versa. Fuel consumption, then, is a function of these independent variables and could be expressed as $fuel\ consumption = f(weight) \times f(engine\ technology)$ where engine technology includes vehicle power, vehicle engine displacement, transmission type etc.

The existence of a technology gap between Chinese domestic brand firms and JV firms is qualitatively implicit in previous work. Some more recent work has begun to explore this difference quantitatively. ICET has yearly published a corporate average fuel consumption review by company and type of company in China, dividing out Chinese independent brand firms, Chinese SOE conglomerates and JV firms from each other (An et al., 2011). Their work shows how performance can vary astonishingly among companies. However, it does not include other variables such as weight or power which may also vary significantly among companies. The ICCT recently conducted a sales-weighted analysis of the vehicle characteristics and technologies of passenger cars present in China (He and Tu, 2012). This is the first comprehensive English language report to include statistics on engine size, power, and weight. The purpose of the study was to compare the Chinese passenger fleet with the foreign passenger fleets; hence, the study only separates domestically produced Chinese passenger cars from imported vehicles and bypasses the domestic/JV brand categorization.

However, merely examining fuel consumption differences among Chinese and JV companies does not suffice. All companies must adhere to the weight-based fuel consumption standards, and differences therefore reflect positioning among market segments. If the data for vehicle weight, power, engine displacement and fuel consumption exists, it should be possible to explore deeper and quantify the technology gap in between the two types of companies.

In this section, I will show that although vehicle fuel consumption for Chinese and JV brand vehicles in China is similar, there exists an engine technology gap between the two. Unfortunately, with the available data, it is not possible to comment on whether this potential technology gap is due to engineering and innovation capability, or targeting less affluent consumers. The necessary price data would have to be gathered separately.

Data sources for vehicles characteristics

MIIT ensures vehicles meet standards and certifies them for sale. In 2006 when the first Chinese fuel economy standards took effect, the NDRC began publishing data on all approved vehicles. Since 2010, MIIT uploads this information online. I have collected complete time series data for 2006, 2007, 2010, 2011 and 2012 (NDRCNDR; NDR; 2013, 2013). In 2006, the dataset includes company, model, model variant, weight and fuel consumption. 2007 adds transmission but excludes model. From 2010, data is split by company, model, variant, weight, power, engine displacement, transmission, fuel consumption and month. I manually add a classification for company type: domestic, joint venture or imported. I classify companies according to the name: Chery is Chinese and domestic, FAW-Toyota contains Chinese and foreign brand names and is a JV, while Porsche is foreign and imported.

The data is not sales-weighted. Because I am interested in the technology level of companies and not the market uptake, this shortcoming does not compromise the findings. Nevertheless, potential errors could influence the data. The database includes every variant of every vehicle model. However, some companies include many variants per model and others hardly any; this would skew data in favor of companies that favor many variants per model. To correct for this, I first analyzed the data on both a per-variant and a per-model basis. For the per-model basis, I averaged each of the vehicle characteristics for a given model across the variants. Very few differences in results arose. Second, because firms with many variants per model are usually domestic, firms with few variants per model are JV and I analyze the two categories separately, I minimize, but do not eliminate, errors in the variant-based approach. I proceeded with the variant-based analysis.

Weight, power and other characteristics

Imported cars account for just 4.2% of overall sales (He and Tu, 2012). These vehicles are also luxury vehicles. The list of foreign automotive manufacturers that export to China includes Audi, BMW, Lamborghini, Roll Royce, Ferrari, Maserati, Porsche and Jaguar. A more standard automotive manufacturer such as Toyota will import luxury brands even if the majority of its vehicles are produced locally with an SOE partner. The basic characteristics of an imported car stand out: compared with the average JV car produced for the Chinese market, the imported vehicle is over 300 kg heavier, its engine is 1200 cc larger and 74 kW stronger, and its fuel consumption is 2.3 L / 100 km worse (Figure 6-4). Because imported vehicles only comprise a small portion of sales in China and they are unrepresentative of the average Chinese passenger vehicle, I exclude them from further analysis.

The differences between the Chinese brand and JV vehicles are more subtle. The average domestic vehicle weighs 1421 kg, while the average JV vehicle weighs 33 kg less at 1387 kg (Figure 6-4). However, JV engines are larger than domestic engines - 1843 vs 1725 cc, respectively. Given that weight is similar, fuel consumption should be as well. It is: 8 L / 100 km for domestic brand vehicles and 7.86 L / 100 km for JV vehicles. However, even if weight, engine displacement and fuel consumption vary little between the vehicle classes, power does. The average JV engine is 25% more powerful than the average domestic brand engine: 101 kW vs 82 kW. With this discrepancy in engine power one would expect fuel consumption of JV vehicles to be worse. Instead, the discrepancy in engine power and lack of discrepancy in fuel consumption and weight support the conclusion that there exists a difference in engine technology. That is, JV engines are more efficient than their domestic counterparts.

Indeed, the average specific power (power divided by engine displacement) of JV engines is 28% better than the average specific power of domestic engines (Figure 6-5). The histograms show that certain domestic brand vehicles have high specific power, while certain imported models have low specific

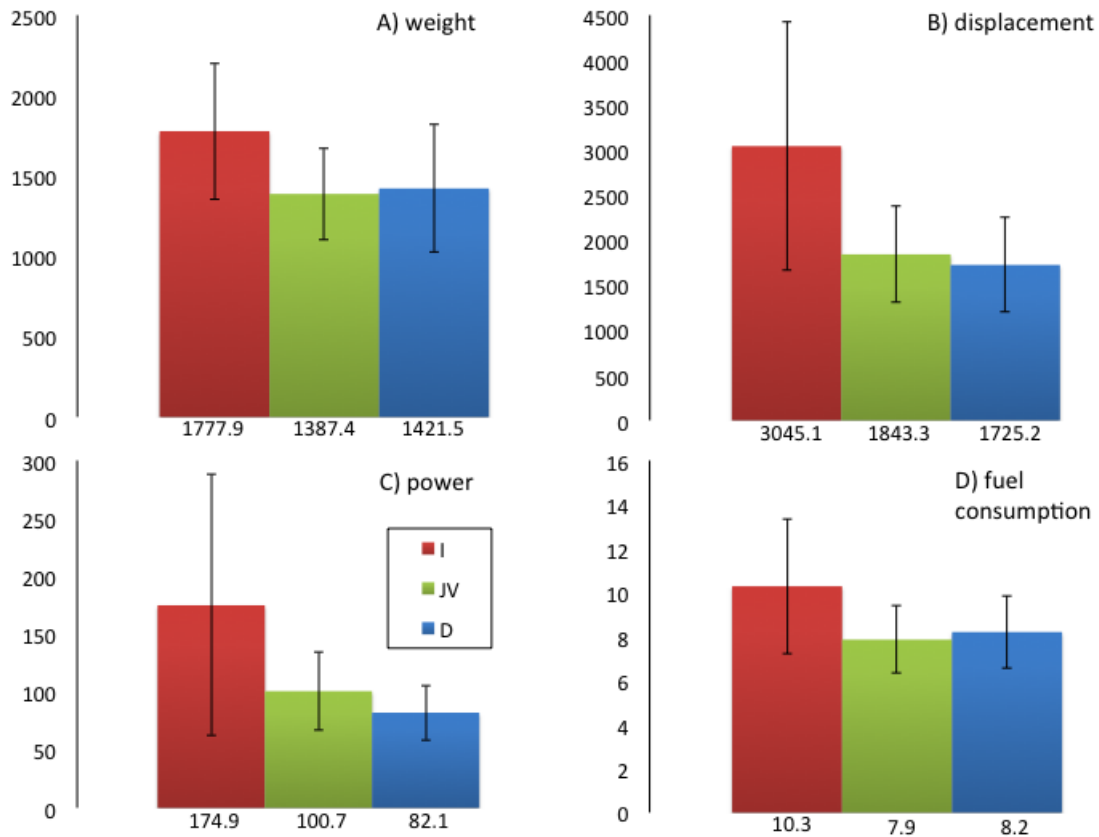


Figure 6-4: Passenger car weight, engine displacement, power and fuel consumption. Clockwise from top left: A) vehicle weight in kg, B) vehicle engine displacement in cc, C) vehicle power in kW, and D) vehicle combined fuel consumption in L / 100 km. Blue denotes domestic brand vehicles, red imported vehicles and green joint venture vehicles. Column height refers to average values and errors bars mark one standard deviation.

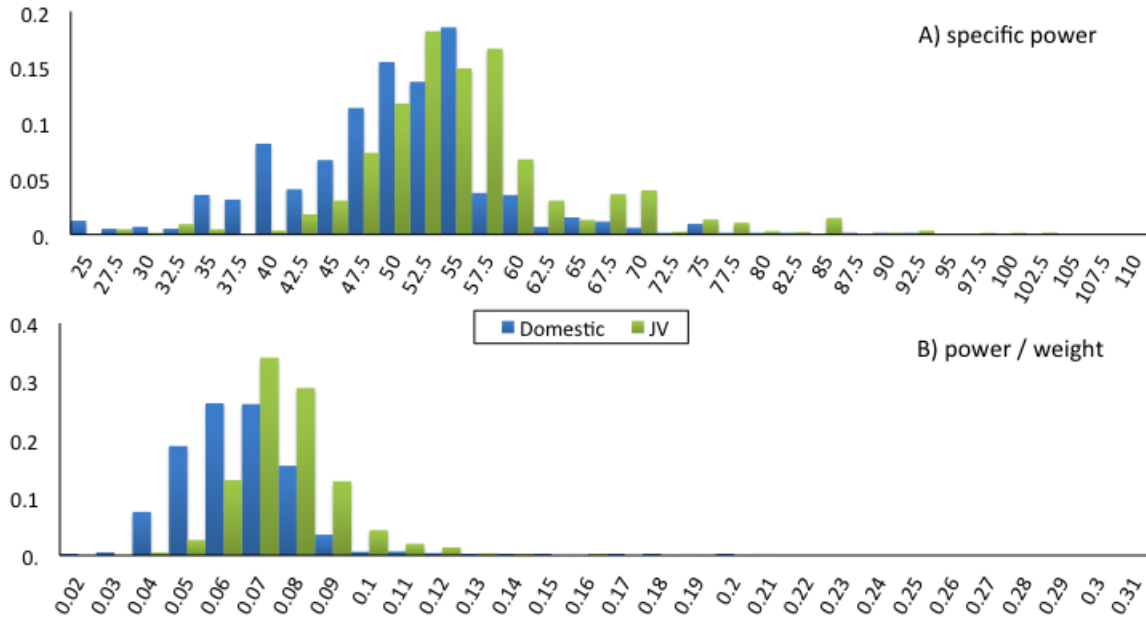


Figure 6-5: Passenger car specific power and specific weight. A) specific power, measured as power (kW) / engine displacement (L) and B) specific weight, measured as power (kW) / weight (kg).

power. Certainly, differences in engine technology between JV and domestic companies do not hold true across all companies or all vehicles: certain domestic companies are more technologically advanced, or choose to provide larger engines with more power. On average though, a given JV car will have a stronger engine than a given domestic brand car.

Distributions

Figure 6-6 and 6-7 show distributions of pairs of variables for domestic brand and JV brand passenger vehicles. Graphs A, B and D use all vehicles released in 2010 - 2012; graph C also includes model years 2006 and 2007. As is clear from graph C, both domestic and JV vehicles achieve similar fuel consumption for a given vehicle weight class. Because Chinese fuel consumption standards require every vehicle of a certain weight class to attain a corresponding fuel consumption, this is entirely logical. However, the slope of the JV weight-fuel consumption relationship is steeper by 22%. At higher weights, JV vehicles consume more fuel. This could be indicative of JV models using more aggressive engines (shorter acceleration times). At lower weights, JV vehicles consume less fuel, but the difference is negligible. All these effects could be due to differences in engine size, engine power, or engine technology. Graph A gives some indication of the differences: JV brand vehicle engines are more powerful than their domestic brand counterparts for a given weight. For small vehicles around 1000 kg, the difference is small or non-existent because these vehicles are generally inexpensive and rely on simple engine technology. Heavier vehicles, however, often contain more powerful engines and therefore need more advanced technology to keep fuel consumption low. Because JV engines are more powerful than the domestic alternatives at the same weight, these engines therefore must use more advanced technology to achieve the same fuel consumption limit. Graph B shows the same trend for engine displacement: JV engines are larger for a given vehicle weight. These JV engines are also not only larger than their domestic brand counterparts, but also more energy intensive (Graph D), which confirms the observations of specific power from the

previous histograms. These trends hold up over time, even as both domestic and JV firms have decreased fuel consumption.

Regression analysis

Various studies have applied regression analyses on vehicle characteristics to the US vehicle fleet for a variety of different purposes. (Knittel, 2012) examined what US passenger car fuel consumption would be if technology advances over the previous three decades had been used to improve fuel economy and not increase power and (Mackenzie and Heywood, 2012) developed an improved methodology for estimating vehicle acceleration

Here, I use the technique to derive a relationship among fuel consumption and various parameters that influence it (Equation 6.1). I relate fuel consumption to weight, power, specific power, origin and transmission. “Origin” refers to whether a vehicle is domestic or JV, where the default is JV. The default transmission is AMT. Unsurprisingly, nearly the variables are significant in predicting fuel consumption (Figure 6-8). By this estimate, all else being equal, a JV vehicle decreases $\ln(FC)$ by 0.057, meaning it decreases fuel consumption by 0.15 L / 100 km. The difference in average characteristics was 0.3 L / 100 km. However, the difference in the regression analysis does not take into account differences contained within the other variables: choices of transmission, differences in power, and differences in displacement. The analysis here is a first attempt at quantifying the differences among domestic and JV cars in China; many more questions remain to be investigated. Nevertheless, it is clear that there exists an engine technology gap between Chinese and JV cars. Some is attributable to choices in engine size. But much is attributable to engine efficiency in the form of specific power and other technology differences. As the central Chinese government tightens fuel consumption standards, domestic car manufacturers may be at a technology disadvantage.

$$\ln(FC) = a_0 + a_1 \ln(\text{weight}) + a_2 \ln(\text{power}) + a_3 \left(\frac{\text{power}}{\text{displacement}} \right) + a_4 \text{transmission} + a_5 \text{origin} + a_6 (\ln(\text{weight}) \times \ln(\text{power})) \quad (6.1)$$

6.4 Progress and policies to date: powertrain technologies

Among the established powertrains, passenger car fleets in China have been traditionally gasoline dependent. A number of these are increasingly turbocharged. Meanwhile, the Chinese government has strongly pushed for the proliferation of “New Energy Vehicles” (NEV) for over a decade. This section examines the current marketshare balance of different powertrains.

6.4.1 Turbocharged vehicles

Available studies suggest turbocharged gasoline ICE vehicles are more prominent in the Chinese sales mix (7%) than in the US light duty vehicle sales mix (3%) or the EU passenger car sales mix (4%) (He and Tu, 2012).³ Turbocharged vehicles are likely more popular in China because vehicle sales taxes increase with vehicle engine size. Because turbocharged engines deliver the same power for a smaller volume, the difference in sales tax can offset the increased technology cost. He and Tu (2012) identify

³That said, the study also reports that 16% of the European gasoline-powered passenger car fleet is turbocharged. The Chinese car fleet is almost entirely gasoline-powered

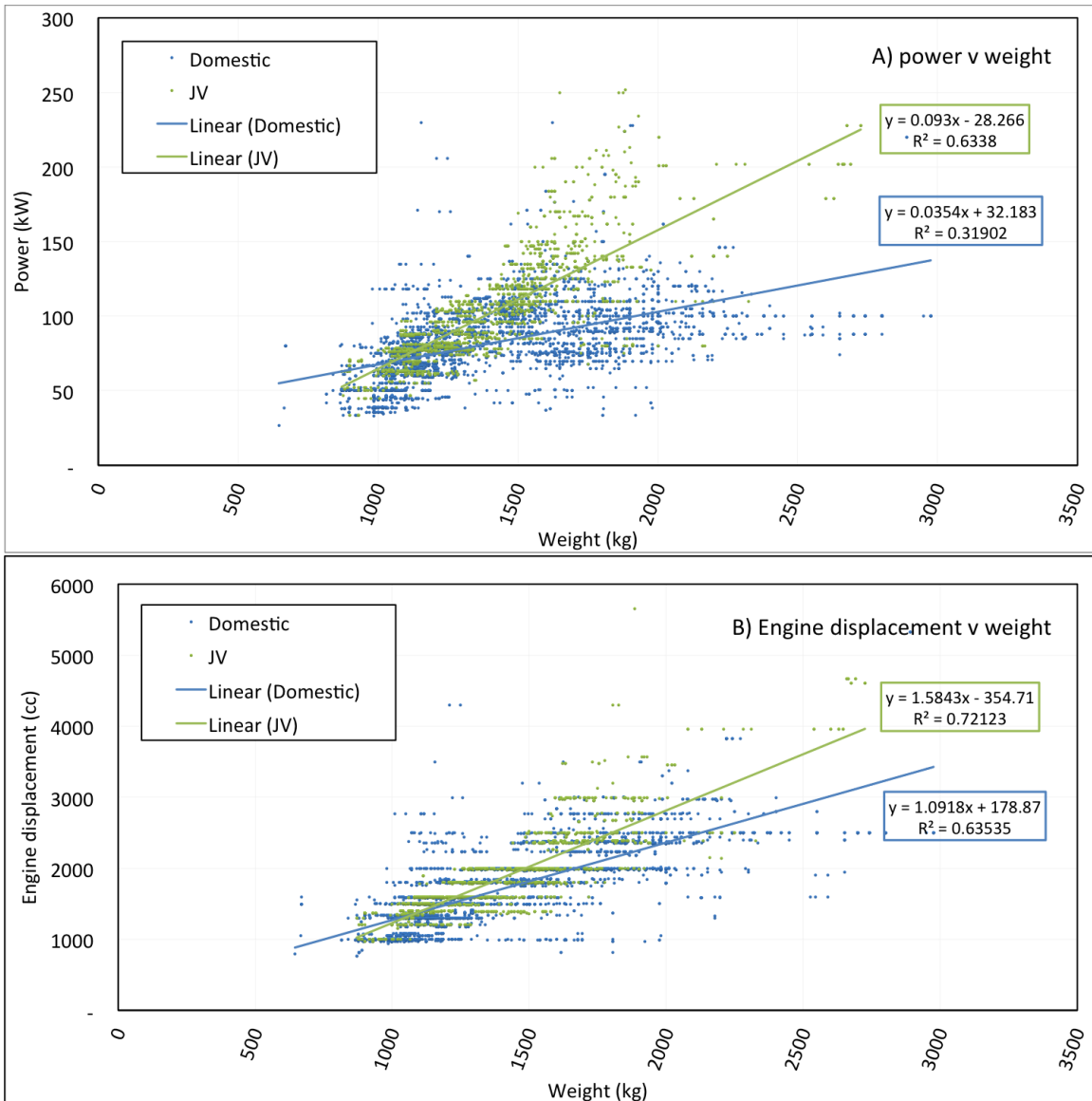


Figure 6-6: Passenger car power, engine displacement, weight, fuel consumption distributions. Simple linear regressions are applied to the blue domestic brand model variants and green joint venture model variants.

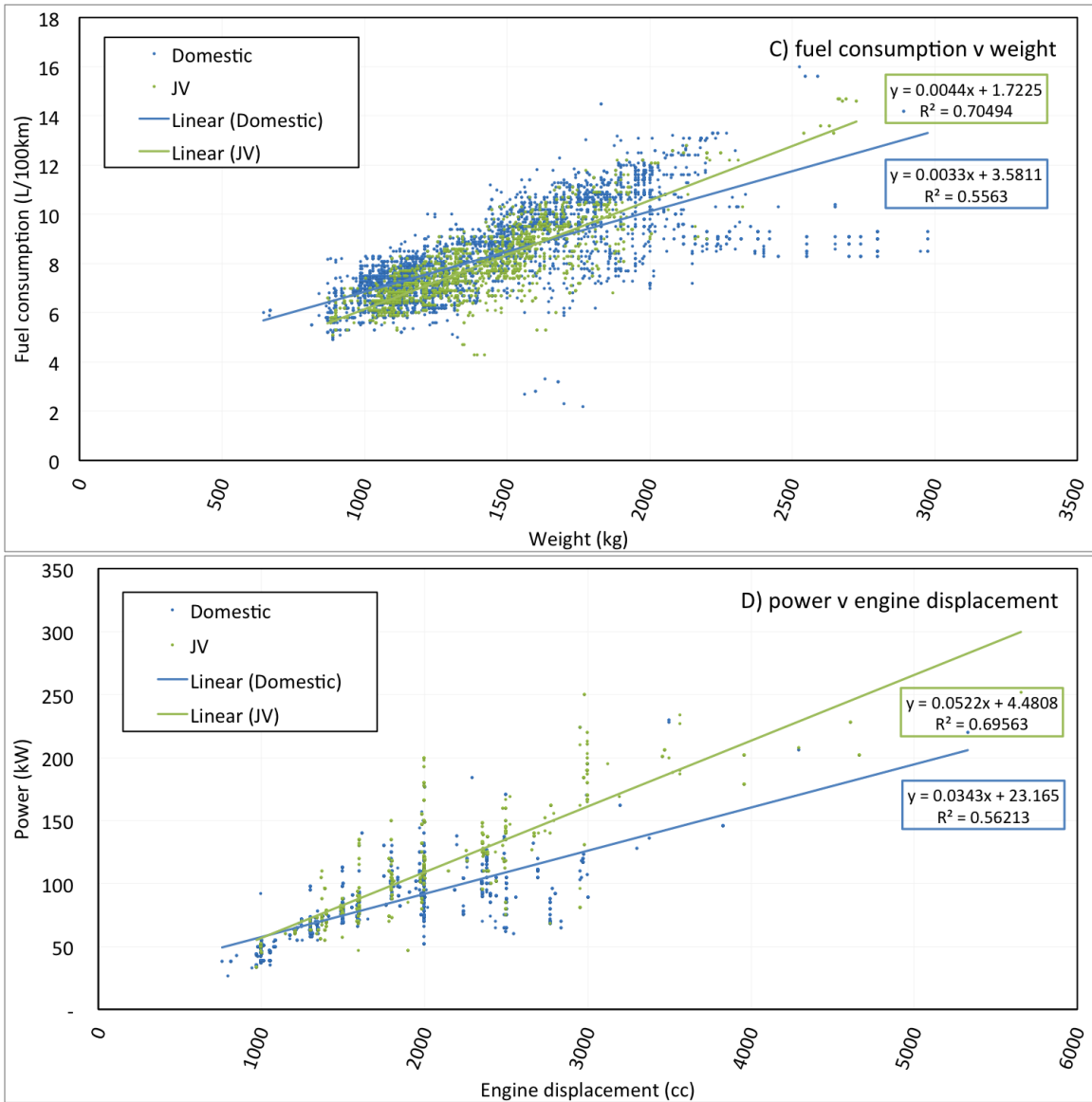


Figure 6-7: Passenger car power, engine displacement, weight, fuel consumption distributions. Simple linear regressions are applied to the blue domestic brand model variants and green joint venture model variants.

Vehicle weight class	Share of LDTs	Gasoline	Diesel
<1800 kg	24.5%	77%	23%
1800 - 3500 kg	38.8%	21%	79%
3500 - 4500 kg	22.9%	0%	100%
4500 - 6000 kg	13.9%	0%	100%
All LDTs	100%	26.9%	73.1%

Table 6-2: 2009 light duty truck gasoline and diesel marketshares. Source: Huo et al. (2012a).

duty vehicles (Huo et al., 2012a). Furthermore, sulfur content in diesel is more than thirty times higher in China than in Europe (Wang et al., 2011a), making it difficult for diesel passenger vehicles to meet emissions standards. Finally, China has experienced diesel fuel shortages (Wang et al., 2011a), making it difficult to start a passenger car market for diesel fuel. Conversely, light duty trucks have increasingly begun relying on diesel. Diesel powered 55% of light duty trucks in 1997, but 91% of light duty trucks in 2007 (Ou et al., 2010b). However, the fuel shares are not evenly distributed among light duty vehicle weight classes (See Figure 6-2). Gasoline powertrains dominate the small light duty truck fleet, but are nonexistent among trucks weighing more than 3500 kg. Because this model only considers light duty trucks weighing less than 1800 kg, the diesel share for these minitrucks is hence only 23%.

6.4.3 New energy vehicles

In China, the term “New Energy Vehicle” (NEV) generally refers to electric vehicles (EV), plug-in hybrid electric vehicles (PHEV), hybrid electric vehicles (HEV), and fuel cell vehicles. Occasionally, it also refers to alternative fuel vehicles (Gong et al., 2012). Developing these vehicles has captivated the national Chinese government since the mid-1990s because they represent a chance to “leapfrog” past other automotive technologies toward clean energy transportation (Gallagher, 2006).

China’s government includes fuel cell vehicles among new energy vehicles, and prioritized them among NEVs during the 11th FYP (2006 - 2010) during which it invested 21% of the “863 program” budget, or 23 million USD, into fuel cell vehicles (Gong et al., 2012). However, both vehicle production costs and the cost of hydrogen refueling infrastructure remain prohibitively high, making imminent adoption unlikely and long-term adoption uncertain (Yao et al., 2011). Refueling stations, for instance, have been limited to fuel cell vehicle demonstrations during the 2008 Beijing Olympics and 2010 Shanghai World Expo, and among the 14 models certified for production, very few have been produced (Gong et al., 2012). Because fuel cell vehicles in China have not yet entered a commercial phase, I exclude them from analysis. Even if they could reach technological maturity within the next decade or two, widespread adoption would still be many decades away.

Therefore, in this study, I equate new energy vehicles with vehicles using electrified powertrains. This includes full hybrid electric vehicle (not mild start and stop hybrids), PHEVs and EVs. I address alternative fuel vehicles in Chapter 7.

The first policy developments in clean energy vehicles appeared during the 9th Five Year Plan period between 1995 and 2000, but the first five years of the new millennium during the 10th Five Year Plan kicked off extensive R&D programs. The “863 program” firmly established electric vehicles as a key research and development technology, and various levels of government devoted \$290 million in funding. The 11th Five Year Plan extended these ambitions. Finally, in 2010, the State Council selected NEVs as one of China’s seven strategic emerging industries and the Ministry of Science and Technology announced a target electric vehicle fleet of one million in 2015 (Gong et al., 2012).

These are lofty ambitions. To achieve them, the national government partnered with several local city governments in the Tens of Cities, Thousands of Vehicles Project, begun in 2009. The ten cities of Beijing, Changchun, Chongqing, Dalian, Hangzhou, Hefei, Jinan, Shanghai, Shenzhen and Wuhan formed the inaugural group (World Bank,2011). The total group of 25 jointly set up goals to roll out over 50 000 NEVs into public fleets, with Shenzhen's goal of 9 000 leading the pack (Gong et al., 2012). The second stage of the program extended incentive policies to private citizens to purchase electric cars in six cities. The central government pledged 60 000 RMB and 50 000 RMB to subsidize electric and plug-in hybrid electric vehicle purchases. Many of the local cities pledged to completely or partially match these subsidies (World Bank,2011). The goals for private vehicles were more ambitious, totaling almost 130 000 cars across all demonstration cities (Gong et al., 2012).

Even though NEV production grew sharply from around 100 vehicles in 2005 to over 7000 vehicles in 2010, cities had met only 26% of the total target for public fleets by October 2011, sixteen months before the end of the program. Moreover, even less progress had been made on private car goals: Shenzhen had achieved 3.2% of the target, Hangzhou 0.8% (Gong et al., 2012).

Why have these goals proven so difficult to meet? Even if NEV technology is commercial, especially for HEV technology, technology does not suffice. One, new energy vehicles remain more expensive than their conventional vehicle counterparts. Consumers are unwilling to pay the difference because NEV do not enhance vehicle functionality. Battery costs are declining and the World Bank estimates prices will decline 60% by 2020 from 2010 to 1 300 to 2 000 RMB per kWh. This would reduce a new vehicle battery to RMB 34 000 to RMB 50 000 (World Bank,2011). However, even in 2020, optimistic battery cost estimates would still double the cost of one of China's cheap but popular cars, assuming car prices do not decline. Granted, luxury cars account for a large portion of the Chinese car fleet, and electric batteries would account for a lower fraction of the vehicle cost.

Second, charging infrastructure remains scarce. This may not be an issue for fleet vehicles, but for widespread adoption private vehicles must transition to electric powertrains. Gong et al. (2012) report that Shenzhen is rapidly expanding electric vehicle charging stations and had installed 62 poles by August 2011. In a ten million inhabitant city, 62 poles is still a small number. Dispersed and scarce charging infrastructure will deter consumers from electric vehicle purchases. Especially in China, installing public infrastructure is key because most Chinese live in apartment buildings and home charging in a private garage is not an option.

Three, the electric vehicle industry is defragmented and held captive by special interests, hindering effective innovation. Sun (2012) points out that if the central government continues to push research funding into research institutions and SOEs, private enterprises and non-key enterprises will have no access to policy funds, distorting the market environment. As I argued in Section 6.1, it is precisely the non-key automotive enterprises that have been more innovative in developing and growing domestic brands. This would suggest that they would be better equipped to effectively use research funds. In addition, NEV production is extremely defragmented. Gong et al. (2012) report that only 3 of the provinces with NEV pilot demonstration programs do not have their own NEV vehicle makers and models. Two other provinces have no demonstration programs, but do have NEV vehicle makers. However, only 45% of automotive manufacturers with certified electric car models and 55% of bus manufacturers with certified models are actually producing these vehicles (Gong et al., 2012). Sun explains that local governments consider their own automotive SOEs key to building this future growth industry (Sun, 2012). This evidence suggests that local governments in provinces with designated NEV pilot cities direct the central government funds to their local automotive manufacturers. Thus, the NEV industry has grown but become severely defragmented. However, there is a very small demand in each province for NEV

Scenario	2010	2030	2050
Reference	7.72	6.08	4.54
Low		6.41	5.10
High		5.06	3.40

Table 6-3: Future fleetwide label fuel consumption. Expressed in L / 100 km.

products, meaning many designed vehicles never enter production. The distortive effects of regulatory capture are readily apparent: both the automotive manufacturer and the local government that owns the automotive manufacturer benefit from the national government program. On a national scale, however, this amounts to pork barrel spending and retards the development of a strong Chinese NEV industry.

The national Chinese government remains resolute. Even if only the cumulative NEV production totaled just 22 000 by August 2011 (Gong et al., 2012), goals remain high. In July 2012, the State Council published the “Development Plan for the Energy Saving and New Energy Vehicle Industry” which confirmed cumulative production and sales goals of 500 000 PHEVs and EVs by 2015, a production capacity target of 2 million PHEVs and EVs by 2020, and cumulative sales of 5 million vehicles by 2020 (State Council,2012).

6.5 Fleet model implementation

6.5.1 Fuel consumption

I calculate the average model year 2010 car label fuel consumption in China to 7.72 L / 100 km, light truck label fuel consumption to 7.93 L / 100 km, and adjusted on-road car fuel consumption to 9.01 L / 100 km (see Appendix B, Future fuel consumption). For the eight years prior, fuel consumption had been improving 0.77% per year. I therefore assume in a reference scenario fuel consumption improvements for NA-SI engines will be slightly more modest across the course of the coming forty years than between 2002 and 2010 while I assume fuel consumption improvements in the high and low scenarios are a little less than double and a little more than half the observed fuel consumption improvements between 2002 and 2010. As modeled, this corresponds with fuel consumption decreases of -0.57% per year, -1.27% per year and -0.27% per year (See Figure 6-9). I use fixed relative fuel consumptions among powertrains to calculate future fuel consumptions for other powertrains, and adopt a separate projection for electric engine efficiency improvements (see Appendix B, Relative powertrain fuel consumption).

Two ways to examine how aggressive these factors are is to calculate average fuel consumption for the entire fleet for distinct years in the future and compare this with the baseline (Table 6-3). This takes the powertrain mix assumptions in the next section, 6.5.2, into account. I do not include the energy EVs consume and count only the portion of PHEV fuel consumption gasoline powers. I can also judge aggressiveness by comparing fleetwide fuel consumption forecasts against how much they advance or postpone achieving target fuel consumption under the third round of fuel consumption targets (See Table 6-4). Neither the reference, high, nor low scenario projections achieve the government targets without delay. Of course, this assumes only reference scenario values for alternative powertrain adoption. Quicker or slower alternative powertrain adoption will also contribute to achieving government fuel consumption targets with less or more delay.

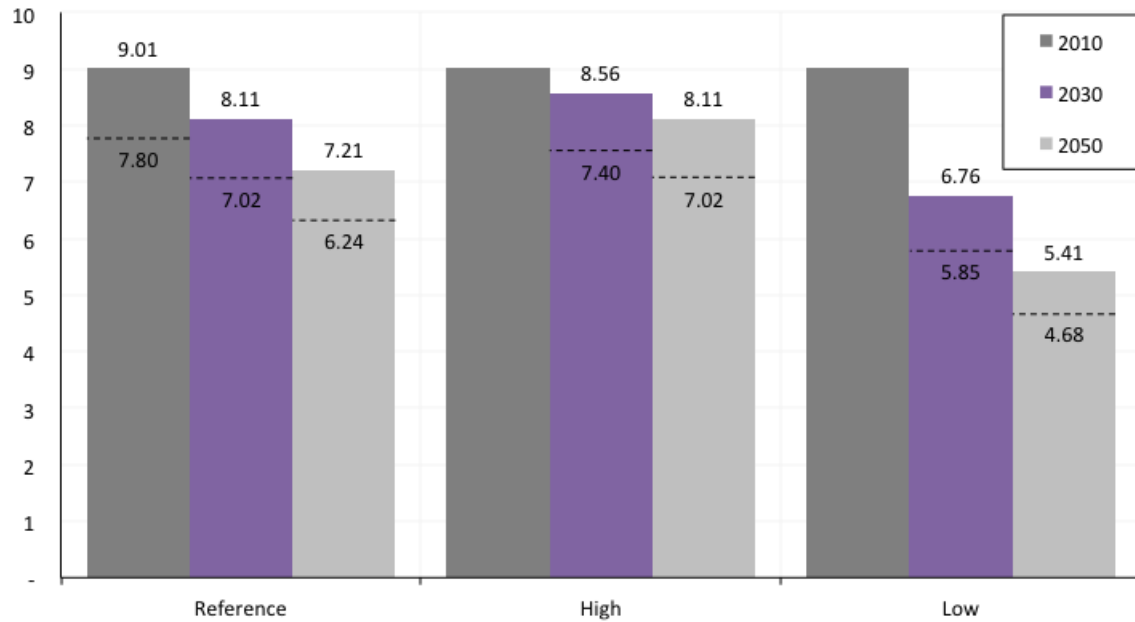


Figure 6-9: Future car fuel consumption in L / 100 km. The bars represent on-road fuel consumption, the lines label fuel consumption.

Scenario	6.9 L / 100 km	5 L / 100 km
Reference	2022: 7 years	2044: 34 years
Low	2018: 3 years	2031: 11 years
High	2025: 10 years	does not reach

Table 6-4: Years by which scenarios postpone government fuel consumption targets. Targets are 6.9 L / 100 km in 2015 and 5 L / 100 km in 2020. Read as: “year target is achieved: years by which target is delayed”.

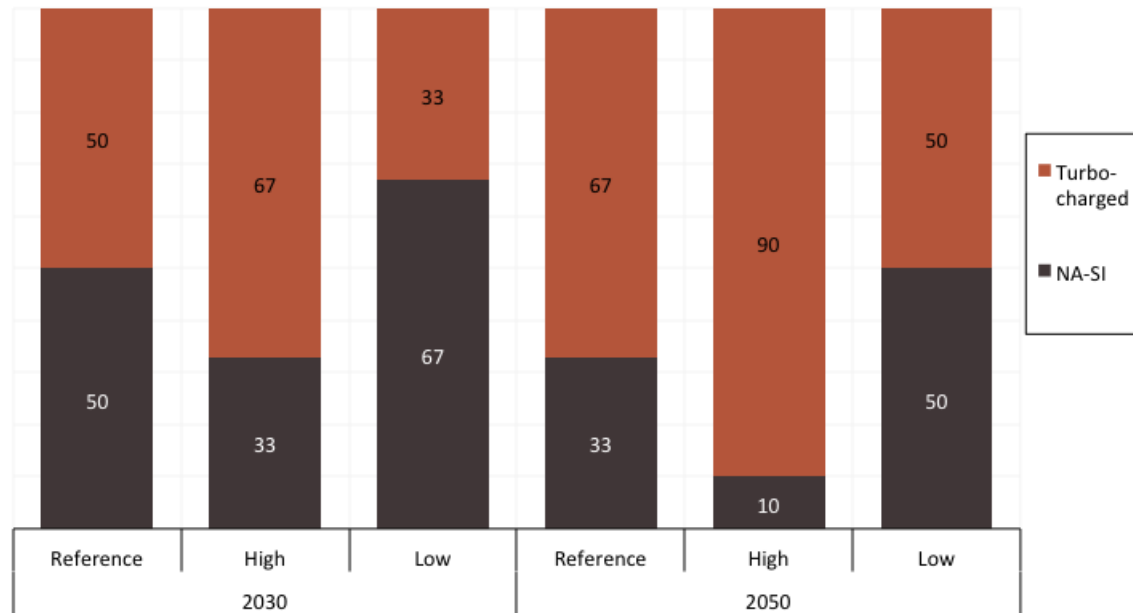


Figure 6-10: Future turbocharged car marketshares.

6.5.2 Powertrain technologies

To implement alternative powertrains, the model requires initial marketshare breakdowns in 2010 for cars, minitrucks and minibuses as well as growth curves until 2050 for these three categories. In base year 2010, I assume 7% and 1% of passenger cars sold have turbocharged gasoline engines and diesel engines, respectively. Electrified powertrains comprise ~0% of sales (I use 0.1% while true figures are close to 0.04% (Gong et al., 2012)), leaving 92% of sales relying on conventional gasoline engines. I assume 1% and ~0% of sales of light trucks are turbo charged and electrified, respectively. Diesel engines comprise 23% of sales, leaving conventional gasoline engines 77% of sales. I assume 1% of minibuses are diesel, 1% are turbocharged and ~0% are electric (see Appendix C, Powertrain mix).

Setting future sales marketshares for these various alternative powertrain technologies is one of the most difficult aspects of proper fleet modeling. Unproven technologies are difficult to model in an input-dependent bottom-up fleet model. The fleet model uses annual percentage point growth in sales to model future marketshares of alternative powertrains, but I peg future sales growth to expected future marketshare ratios among different powertrains (See Appendix B, Powertrain marketshare mix). As with other inputs, these ratios exist in reference, high and low alternatives. In the reference scenario, turbocharged powertrains take 50% of the ICE market in 2030 and 67% in 2050 (Figure 6-10). In the high scenario, turbo powertrains achieve 67% of marketshare in 2030 and 90% marketshare in 2050. Meanwhile, the low scenario sees 33% in 2030 and 50% in 2050. There are two electric powertrain sales ratios. One, the combined marketshare of the three electrified powertrains: HEV, PHEV and EV. Two, the portion of the electrified powertrain composed of HEVs. In the reference scenario, passenger car sales achieve 15% and 30% percent electrification in 2030 and 2050, respectively (Figure 6-11). Hybridization accounts for 67% and 50% of electrified sales in 2030 and 2050. For light trucks, electrification is 10% and 20% in 2030 and 2050, respectively. Hybridization accounts for 70% and 65% of sales. In the low scenario, electrification gains no traction, while in the high scenario electrification is more rapid and EV dependent. In the high scenario, 30% and 60% of cars and 25% and 50% of light trucks are electrified

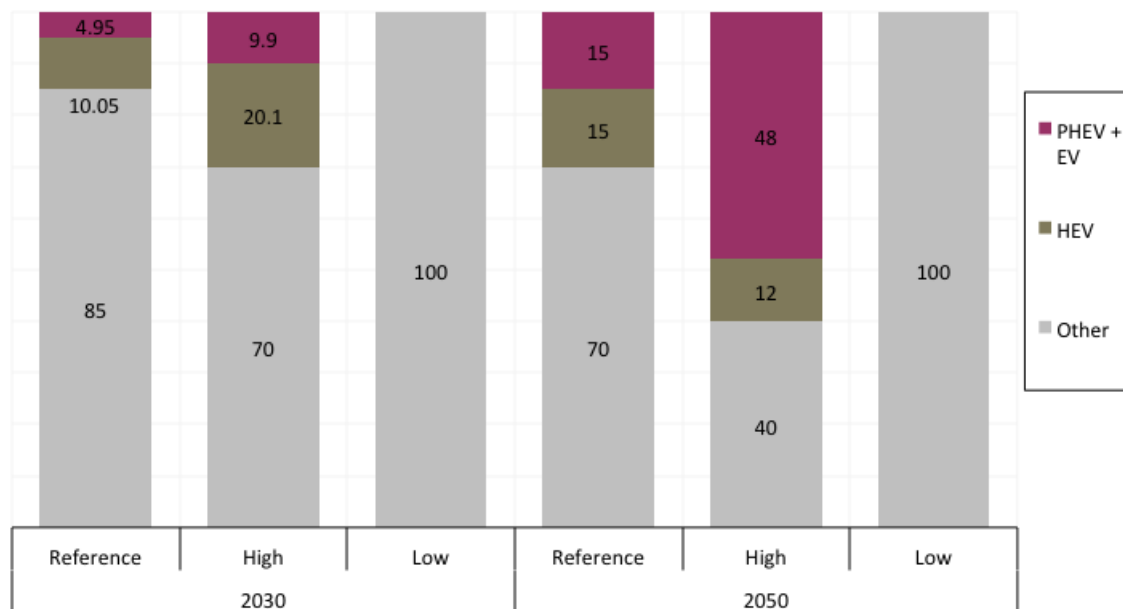


Figure 6-11: Future electrified car marketshares.

in 2030 and 2050, respectively. Hybrid vehicles account for just 33% and 20% of car sales and 40% and 25% of light truck sales in 2030 and 2050, respectively.

6.6 Comparison across models

6.6.1 Fuel consumption

In their reference or baseline scenario assumptions, some modelers assume fuel economy improvement while others do not. Yan and Crookes (2009) assume no fuel economy improvements in their base case assumptions relative to their base year average fuel economy 2005. However, a better case future assumes vehicles attain a 40% improvement in fuel economy from fuel economy regulations and a 20% improvement from fuel taxes by 2030. This overall 52% improvement in fuel economy translates to an average 2.1% annual improvement in fuel economy between 2005 and 2030. Hao et al. (2011a) also assume no fuel economy improvement in the base case scenario relative to 2010. In a fuel consumption reduction scenario, passenger cars reduce their fuel consumption 20% by 2015 and a further 15% by 2020, after which no further fuel consumption improvements occur. A 35% fuel consumption improvement in 10 years translates to an annual 4.4% reduction in fuel consumption over these ten years, but a 1.1% improvement over the forty year period to 2050.

Ou et al. (2010b) do assume fuel consumption reductions in their base case scenario from 2008 until 2030, and static fuel consumption from 2030 to 2050. Gasoline and CNG passenger cars achieve 1.3% annual fuel consumption reductions, while diesel passenger cars achieve 1.5% annual reductions. Spread over forty-two years and ignoring the effect of diesel vehicles that comprise a very small portion of the passenger vehicle fleet, this translates to a 0.68% annual reduction in fuel consumption.

Huo et al. (2012b) assume fuel consumption improvements in the reference scenario: conventional gasoline cars decrease fuel consumption from 8 L / 100 km in 2010 to 6.5 L / 100 km in 2030. This is a 0.5% annual improvement on the 2010 - 2050 timeframe. An alternative scenario is more aggressive:

conventional gasoline cars achieve an average fuel consumption of 3.5 L / 100 km in 2050, which is a 2.1% annual improvement for the 2010 to 2050 period.

My projected average annual fuel consumption improvements from 2010 to 2050 for the reference, mitigated and unbound scenario of 0.55%, 1.20% and 0.25% for conventional gasoline vehicles are thus within line with other studies. That said, including the effects of increased marketshares of turbo vehicles in my scenarios would increase these average annual fuel consumption improvements.

6.6.2 Powertrain technologies

Most other fleet models do not assume alternative vehicle adoption in base scenarios. Ou et al. (2010b) do assume vehicle electrification in the base scenario: 2.5%, 2.44%, 1.27% and 1.27% of vehicle sales in 2030 and 10%, 9%, 4.5% and 4.5% of light duty truck, passenger car and minivan sales in 2050 are electric vehicles, mild hybrid vehicles, full hybrid vehicles and plug-in hybrid vehicles, respectively. Diesel fuel shares will grow from 0% in 2008 to 20% in 2050, implying higher diesel engine vehicle car sales in 2050. In the model's electrified scenario, diesel fuel shares remain at base scenario assumptions, but the fleet electrifies significantly: 10%, 11.25%, 5.6% and 5.6% of vehicle sales in 2030 and 40%, 30%, 15% and 15% of light duty truck, passenger car and minivan sales in 2050 are electric vehicles, mild hybrid vehicles, full hybrid vehicles and plug-in hybrid vehicles, respectively.

Hao et al. (2011a) assume no electrification in the base scenario, but have a electrification scenario. 20% and 25% in 2030 70% and 80% in 2050 of private passenger vehicles and non-private passenger vehicles are assumed electrified. Vehicles are 40% and 0% HEV, 36% and 40% PHEV and 24% and 60% EV in 2030 and 2050, respectively. Because non-private vehicles are a minority of vehicles, one can approximate these results to slightly more than 8%, 4.8% and 7.2% of sales in 2030 being HEV, PHEV and EV, respectively, and 0%, 28% and 48% of sales in 2050 being HEV, PHEV and EV, respectively.

The base scenario in Yan and Crookes (2009) includes no alternative powertrains. Their overall better case scenario does not include electrification but does include aggressive diesel passenger car adoption. The authors expect diesel fuel to take up 40% of passenger vehicle fuel in 2030.

Huo et al. (2012b) include a diesel adoption, fuel diversification and electrification scenario, each of which projects different sales marketshares for different alternative powertrain technologies and different passenger car types (private, business and taxi). Reporting results only for private LDVs, 45% and 60% of powertrains are diesel driven in 2030 and 2050, respectively while in the electrification scenario, 43% and 58% percent of vehicles are electric in 2030 and 2050, respectively. Business LDVs adopt the same marketshares in 2030 under different scenarios in 2030 and more aggressive alternative powertrain marketshares in 2050. Taxis remain a small portion of the total vehicle fleet. This study considers all electrified powertrains to be EVs.

My reference scenario assumptions are not dissimilar from Ou et al. (2010b)'s but I assume higher hybrid and plug-in hybrid marketshares (See Appendix B, Powertrain marketshare mix, for exact figures) and gentler electrification adoption among minitrucks than passenger vehicles. However, my mitigated scenario electrification assumptions are less aggressive than all three other studies that include electrification scenarios. I also do not include any scenarios with passenger vehicle diesel adoption.

Chapter 7

Vehicle fuels

Transportation relies on gasoline and diesel for power because they are both energy dense and the engine technologies that use them are technologically mature. One top contender, electric vehicles, were examined in the previous chapter. Using electric power for transportation, however, has proven more difficult as the technology is immature. On the other hand, many alternative fuels such as methanol or ethanol are less energy dense than gasoline. Another key concern with alternative fuels is that merely displacing conventional fuel does not necessarily correspond with reducing greenhouse gases. Burning compressed natural gas (CNG) releases less CO₂ than does gasoline or diesel, but releases much methane. All coal-derived transportation fuels, however, release more CO₂ per unit energy than does gasoline. Unlike electric cars, however, which are more energy efficient than ICEs, cars that rely on methanol, dimethyl ether or synthetic gasoline or synthetic diesel are about as energy efficient as gasoline vehicles. Priorities diverge: is it more important to reduce conventional fuel demand or reduce CO₂ emissions?

7.1 Progress and policies to date

Research in China has endeavored to develop a wide portfolio of alternative fuels for transportation including CNG, liquid natural gas (LNG), ethanol, methanol, biodiesel, dimethyl ether (DME), synthetic fuels such as liquid petroleum gas (LPG) or coal to liquids (CTL), and hydrogen.

The national government created a natural gas transportation initiative in 1999 that funded research, development and policy planning. The program expanded to 18 demonstration cities and two provinces and methanol and set 127,000 CNG and 116,430 LPG vehicles on the road (Hu et al., 2010). The authors caution, however, that China's natural gas resources may not be large enough to support a full-scale expansion into transportation. Additionally, because gasoline and diesel have fixed prices while LPG does not, these fuels may become more expensive than gasoline. In this case, natural gas vehicles would not be able to proliferate without government subsidies.

Methanol is the cheapest of all the coal-derived transportation fuels, which also include DME and coal to liquids. Hu et al. (2010) explain that while policy interest at the national level and among auto manufacturers in China is low, the coal mining Shanxi province is still forging ahead. The whole province may mandate sales of M15. Ou et al. (2010a) also note that because methanol is miscible with gasoline, it is often illegally blended into existing gasoline fuel. 15.8 million barrels have been added this way.

Methanol is not only the cheapest coal-derived fuel, but also the most carbon intensive. DME and CTL technology provide alternatives. Hu et al. explain that dimethyl ether grew to supply 15% of

methanol demand in 2007. CTL technology is least commercializable among the coal derived fuels, but China has invested in research since the 1990s, seeing it as a way to use its abundant coal reserves. Several demonstration plants are under construction.

China has also experimented with plant based fuels. Hu et al. (2010) explain that the national government gradually encouraged ethanol fuel during the 2000s, refunding the value added tax and subsidizing the consumption tax. However, though five provinces and 27 cities now supply E10, the feedstocks are corn, wheat and cassava, which has raised concerns over loss of arable land and put a stop to all project approvals from food based sources (Yao et al., 2011). Biodiesel in China has thus far been made primarily from cooking oil, but government plans to expand production to 4.2 million tons in 2020 (Yao et al., 2011) may fall short as Hu et al. (2010) explain that waste oil will only be able to account for 1 million tons of fuel. The national government has therefore pushed for research into new feedstocks. These will be necessary as Ou et al. (2012) conclude from their life cycle analysis that only non-food feedstocks will reduce greenhouse gas emissions.

7.2 Fleet model implementation

7.2.1 Energy demand

The fleet model treats alternative fuels after calculating total fleet energy demand. The model then assumes alternative fuels supply a portion of the conventional energy demand and recalculates volumes of conventional and alternative fuels accordingly. CNG and methanol can replace gasoline. Two key assumptions follow: 1) an alternative fuel powertrain is as efficient as its conventional fuel alternative on a per joule energy basis and 2) contribution of alternative fuels is not relegated to a specific powertrain but could be spread among all powertrains that use a conventional fuel (NA-SI, turbo, hybrid electric and plug-in hybrid electric for gasoline).

I only implement scenarios for natural gas and methanol, excluding the ethanol and biodiesel bio-fuels. Coal is the most abundant primary energy source in China and pressure will remain to make it an important feedstock for alternative fuels. I do not consider coal to liquid technologies that produce synthetic diesel or gasoline. First, although China is developing numerous pilot plants, synthetic fuels are likely to remain niche products until 2030. Methanol is cheaper to produce. Second, CTL plants most commonly produce diesel, which primarily powers heavy duty vehicles in China. Third, all coal derived transportation fuels are more carbon intensive than conventional fuels. As such, adopting methanol as an alternative transportation fuel will show the same trends in reductions in conventional fuel demand and increases in total emissions as any coal-derived fuel would.

CNG is already gaining acceptance as an alternative fuel in China. 4.1% of non-private cars run on natural gas (see Appendix C, Fuel shares for the calculation) and the fuel is particularly popular among taxi fleets.

Although China has shown interest in biofuels, I choose not to implement them for two reasons. One, calculating life cycle emissions for biofuels is exceedingly complex. Second, China's national government is already concerned over issues of food security, and would be loathe to convert large swaths of agricultural land to produce fuel.

I thus create two separate sets of reference, high and low values for methanol and natural gas (see Figure 7-1). Methanol will grow slowly, replacing 3% and 5% of gasoline equivalent energy in 2030 and 2050. Natural gas will replace large amounts of non-private car conventional fuel demand - 20% and 30% in 2030 and 2050, respectively - and modest amounts of conventional fuel demand for other

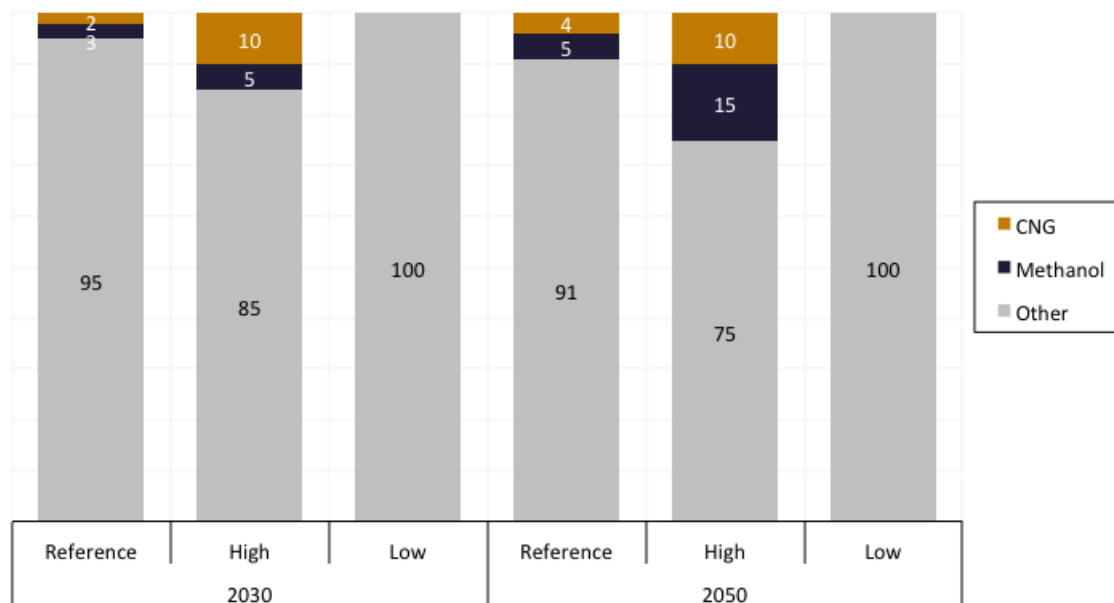


Figure 7-1: Future car alternative fuel volumes.

light duty vehicles - 2% and 4% in 2030 and 2050, respectively. Low values assume no alternative fuel adoption save non-private vehicles, while high values assume double to triple rates of alternative fuel adoption.

7.2.2 Emissions

Having developed a variety of fuels (gasoline, methanol, diesel, CNG and electricity) within the fleet model, the model can calculate the resulting carbon dioxide emissions. To do so, I set life cycle “well to wheels” emission values for the different fuels (See Appendix B, Fuel CO₂ intensity, for details). Gasoline, diesel and natural gas have fixed emission cycles over time. Coal to methanol conversion processes improve and the power grid becomes cleaner, reducing the relative emissions disadvantage of methanol and electric power to gasoline (see Figure 7-2). I use the 2012 World Energy Outlook’s grid power predictions(IEA, 2012a), a transmission loss factor and charging loss factor for electricity emissions. I also use life cycle analysis for methanol emissions from Ou et al. (2012).

7.3 Comparison across models

This study, as well as the Ou et al. (2010b) study, assume alternative fuel adoption in the reference scenarios. In 2050, Ou et al. (2010b) assume 20% of passenger vehicles are diesel-powered. CNG and LPG fractions will double by 2020 and thereafter stay constant; this equates to about 2% of passenger vehicles sales. Finally, it assumes a contribution of other alternative fuels with 37 Mt bioethanol, 20 Mt biodiesel, 22 Mt coal-derived methanol, and 5 Mt CTL in the base case scenario. I approximate this will replace 37 Mt gasoline and 25 Mt diesel, using methanol and ethanol volumetric energy conversions.

In this study, CNG will supply 5% of future gasoline equivalent energy, which is more aggressive. Methanol will supply 6% of energy, which is less aggressive because it is equivalent with 13.2 mtoe.

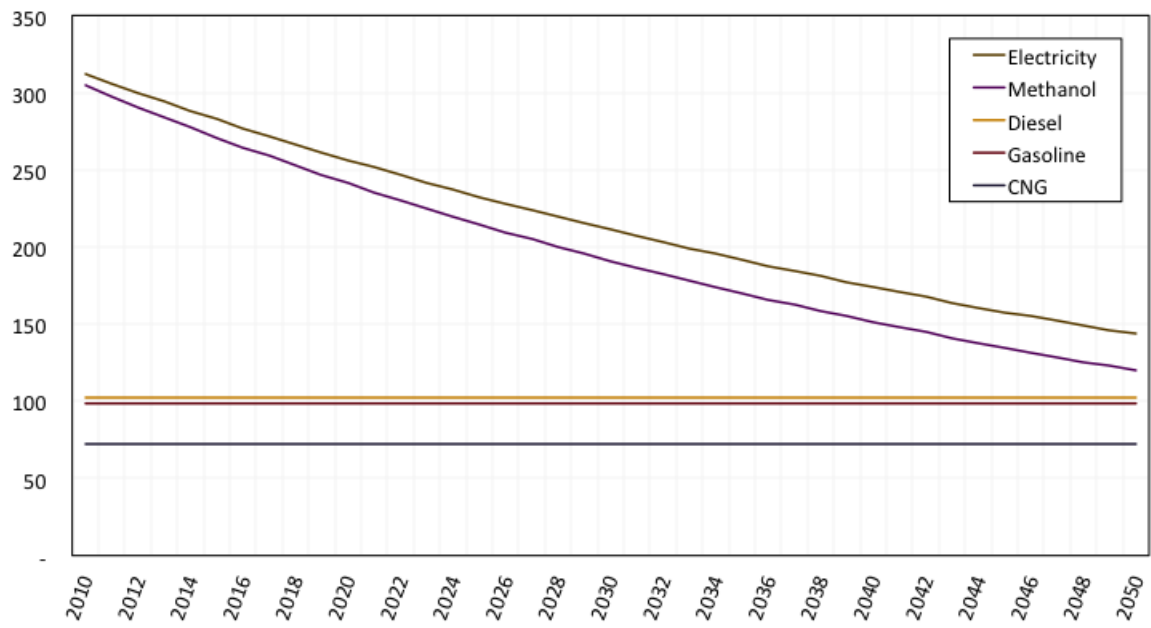


Figure 7-2: CO₂ emission intensities for different fuels in g CO₂ per MJ .

Part III

Results and policy implications

Chapter 8

Results

This chapter presents and reviews results in two sections. First, I present the results of a reference scenario and critically compare it against other fleet model results drawn from literature. Second, I create three sensitivity analyses, one for each output, to show which drivers are most significant in determining outcomes.

8.1 Reference case

Many different phrases are commonly used in scenario modeling to describe the initial case off which all others are compared. These include “business as usual,” “reference,” “baseline,” “no change” or more esoteric, alphabetical codes. In this study, I use “reference” to denote a scenario that is aggressive, yet possible to achieve without an explicit environmental target in mind. Instead, it takes into account the comparable evolution of international vehicle ownership and use, the government’s desire to develop an international competitive automotive industry, and anxiety over reliance on foreign oil. Perhaps the ability of policies to control automotive energy demand are overstated in the reference case; perhaps mitigating global environmental pollution will be a more legitimate concern: the work contains other scenarios as well. These predict both higher and lower future energy demand than does the reference scenario.

This differentiates the reference case against those of other China fleet models. First, other models tend to assume few implemented policy improvements. Second, other models pick reference cases as the upper bound scenario in order to allow comparison against an unrestricted, maximum energy baseline. This model sets the reference scenario as a median. By setting it as a median, this approach can judge the relative importance of different drivers.

8.1.1 Future energy demand, fossil fuel demand and CO₂ emissions

Key assumptions

The reference case builds up future energy demand with the reference values from all different variable input drivers: sales, VDT, turbocharged vehicles, electrified vehicles, fuel consumption, methanol and natural gas. The model implementation sections Part II discuss these assumptions in detail, and numerical descriptions of each are also recorded, explained and justified in Appendix B and C. I endeavored to be neither too pessimistic nor too optimistic as I set values for each input driver. To do so for the

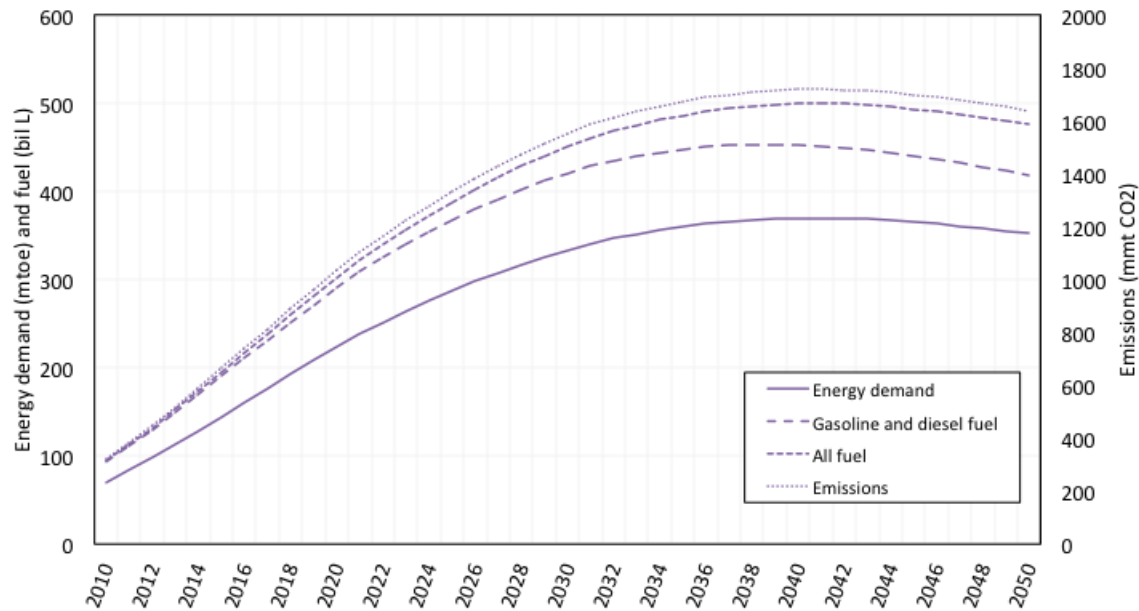


Figure 8-1: Reference scenario energy demand, fuel demand and CO₂ emissions. Energy demand is in mtoe, fuel volumes are in bil L gasoline equivalent terms, emissions are in mmt CO₂. All fuel combines all energy sources that power vehicles, including electricity.

reference scenario, I hedged future values against current numbers of other countries (for sales and VDT inputs), assumed future progress more modest than aggressive government targets but more optimistic than no progress (for fuel consumption and alternative powertrains), or assumed some but not significant adoption (for alternative fuel volumes).

Reference results

China's energy demand, total fuel demand and CO₂ emissions grow sharply until about 2030, after which growth levels off (Figure 8-1). Levels peak in 2041 at 369 mtoe consumed (equivalent to 7.4 million barrels of oil per day), 499 bil L of fuel consumed,¹ and 1693 mmt CO₂ emitted. They thereafter begin to decline slowly. Conventional fuel demand of gasoline and diesel also increases rapidly to about 2030, after which it peaks in 2038 at 453 bil L of gasoline and begins to decline. The difference between conventional fuels and new fuels surpasses 5% in 2024, but continuously increases to nearly 14% in 2050. Thus, the reference scenario assumes the combination of relatively small numbers of plug-in hybrid vehicles and electric vehicles and some amount of natural gas and methanol will be able to supply a modest amount of Chinese road transportation energy demand in the future. Even so, energy demand, fuel demand and CO₂ emissions in the Chinese light duty vehicle sector will increase more than fivefold in the reference case over the coming forty years, while conventional fuel demand will increase nearly fivefold. Moreover, because this scenario assumes certain efficiency gain, technology adoption and fuel diversification, actual energy and emissions could be higher or lower. Transformations in Chinese travel patterns will drive this and significantly impact China's future oil imports, even as changes in the Chinese automotive industry may mitigate some of the effects.

The results clearly show, however, that Chinese vehicle energy demand will not continue to increase

¹In gasoline equivalent terms, including electricity

at a frenetic pace. Rather, as the vehicle market matures and technologies advance, China will stabilize at a high, but given its population not unreasonably high, vehicle energy demand.

These results can also be disaggregated by fuel or powertrain (Figure 8-2). Gasoline's continued dominance remains unchallenged although other fuels begin to contribute over a tenth of energy demand and CO₂ emissions in the 2030s. Meanwhile, the dominance of the traditional naturally aspirated ICE vehicle begins declining before 2030 as turbocharged ICE vehicles proliferate. They eventually dominate, even as new, alternative powertrains account for larger fractions of total energy demand, fuel demand and CO₂ emissions. Diesel is an uncommon fuel in 2010 and continues to be uncommon in the future. Because diesel contributes more CO₂ emissions on an energy basis than gasoline, the yellow band on the bottom left is proportionally wider than that on the top left. Among the electrified powertrains, hybrids contribute the most to energy demand, fuel demand and CO₂ emissions. This is both because I predict hybrid vehicles to be more numerous than their plug-in and wholly electric counterparts and because they are less energy efficient than these counterparts. The proportionally wider PHEV and EV bands on the bottom left than the top left stem from the fact that the electricity grid in China is predicted to remain more CO₂ intensive than gasoline through 2050. Concerning fuels, the width of the band on the top right and bottom right indicate electricity, methanol and natural gas are, respectively, more, more and less CO₂ intensive than gasoline. These alternative power sources for cars comprise replace over 10% of energy demand by 2050 and nearly 20% of emissions by 2050.

Because the model uses both alternative powertrains and alternative fuels, comparing all these alternatives collectively based on a common metric clearly the differences in energy efficiency and CO₂ emissions among them more clearly (Figure 8-3). Cleaner fuel production drastically lowers methanol emissions while a gradually cleaner electricity grid means plug in hybrid and electric vehicle emissions improve faster than those of conventional gasoline vehicles. Thus, while emissions for natural gas and all electrified options are quite similar now, plug-in hybrid and electric vehicles will provide clear CO₂ emissions benefits over hybrids and natural gas vehicles in 2050. PHEVs in particular show the greatest energy efficiency gains, aided not only by improvements in ICE technology, but also increasing electric power utilization rates and electric motor energy efficiency. It was surprising to note, however, that electrified powertrains are already cleaner than gasoline powertrains. The difference is due to an electric engine efficiency advantage over gasoline engines.

8.1.2 Comparison across models

Figure 8-4 compares future reference scenario energy projections across a number of different studies. Most studies cluster energy demand predictions after 2030 between 400 and 600 mtoe. In addition to this study, Ou et al. (2010b) and Huo et al. (2012b) also predict energy demand growth will significantly slow or flatten after 2030 while others studies predict continually rising energy demand. Projections from Kishimoto et al. (2012), while in line with other projections until 2030, thereafter continue rising to 900 mtoe as the clear upper outlier prediction. The IEA (2012a) and EIA (2011) model energy demand for the entire transportation sector, but only until 2035. Because their projections also include rail and aviation, their predictions are expectedly among the highest. This study predicts the lowest future energy demand of 352 mtoe, 15% - 61% below the other four predictions clustered between 400 and 600 mtoe. Figure 8-5 compares future reference scenario CO₂ emissions projections across a similar set of studies. There is a wide range of future emissions projections throughout the time range that narrows as 2050 approaches. Surprisingly, although this study projected the lowest future energy demand, it does not project the lowest emissions. I explore the probable explanations and causes of

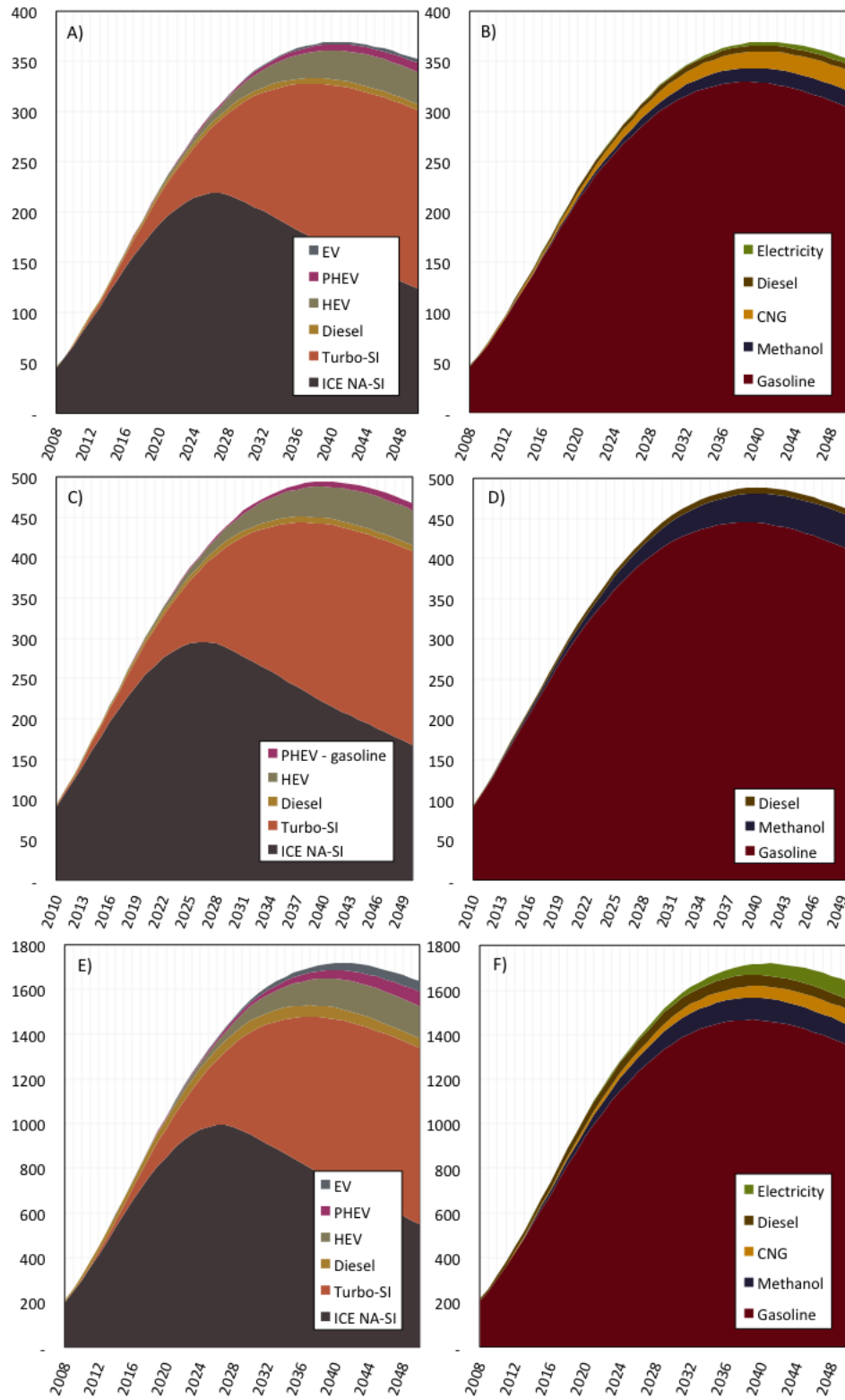


Figure 8-2: Reference scenario disaggregated by powertrain (left) and fuel (right). A) and B): energy demand in mtoe; C) and D): fuel demand in bil L, without energy content volume equivalency conversions; E) and F): CO₂ emissions in mmt CO₂.

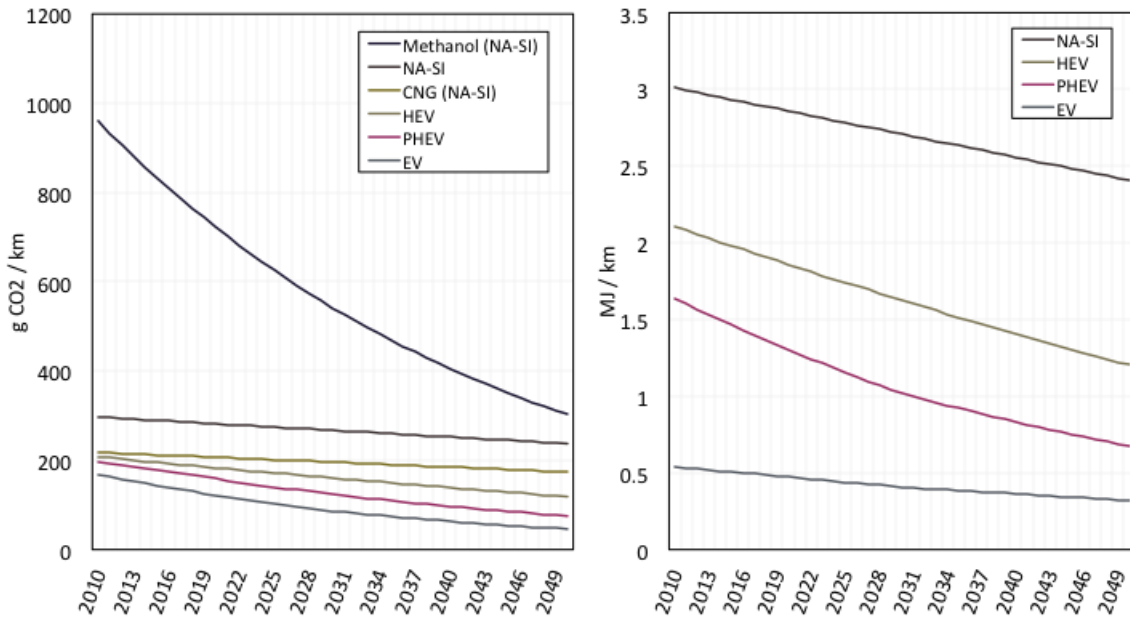


Figure 8-3: CO₂ emissions and energy per kilometer for cars for different powertrain technologies. Natural gas and methanol vehicles use NA-SI engines.

variation among the various studies in the following section.

Reference, BAU, Current Policies: Significant of Scenario Labels

Different studies label reference case scenarios differently (Table 8-1). Yan and Crookes (2009), Ou et al. (2010b), Huo et al. (2012b), Kishimoto et al. (2012) use the phrase “business as usual” to what Yan and Crookes call not a scenario, but “a reference vision for how energy demand and GHG emissions in China’s road transport sector would evolve if the Chinese government does nothing to influence long-term trends.” Hao et al. (2011a) and the EIA (2011) label their base case scenario “reference,” the IEA (2012a) labels it “current policies,” and the ICCT (Cristiano Facanha et al., 2012) does not label their base case scenario at all, even though all three also function as “business as usual” scenarios because they assume no mechanisms will alter the current trajectory of energy demand in China’s automotive sector. Thereafter, results compare the “business as usual” case with stringent policies in three different ways. First, a subtractive wedge style (Yan and Crookes, 2009; Cristiano Facanha et al., 2012) can show the maximum extent to which China’s future automotive energy demand could be mitigated and the contribution of individual policies to this. Second, results can compare the effects of one policy to another in altering the reference scenario (Huo et al., 2012b; Hao et al., 2011a). Third, the effect of a combined suite of policies (Ou et al., 2010b; EIA, 2011; IEA, 2012a; Kishimoto et al., 2012) creates one alternative to the baseline. As stated earlier, because the “reference” scenario in this study is a median projection that includes some efficiency improvements and technology adoption, it is unsurprisingly more optimistic in potential to curb Chinese automotive energy demand growth.

Alternative model methodologies

Most of the models use the same bottom-up fleet model methodology (Table 8-1) as this study does. Certain exceptions include Kishimoto et al. (2012), IEA (2012a) and EIA (2011). Kishimoto et al.

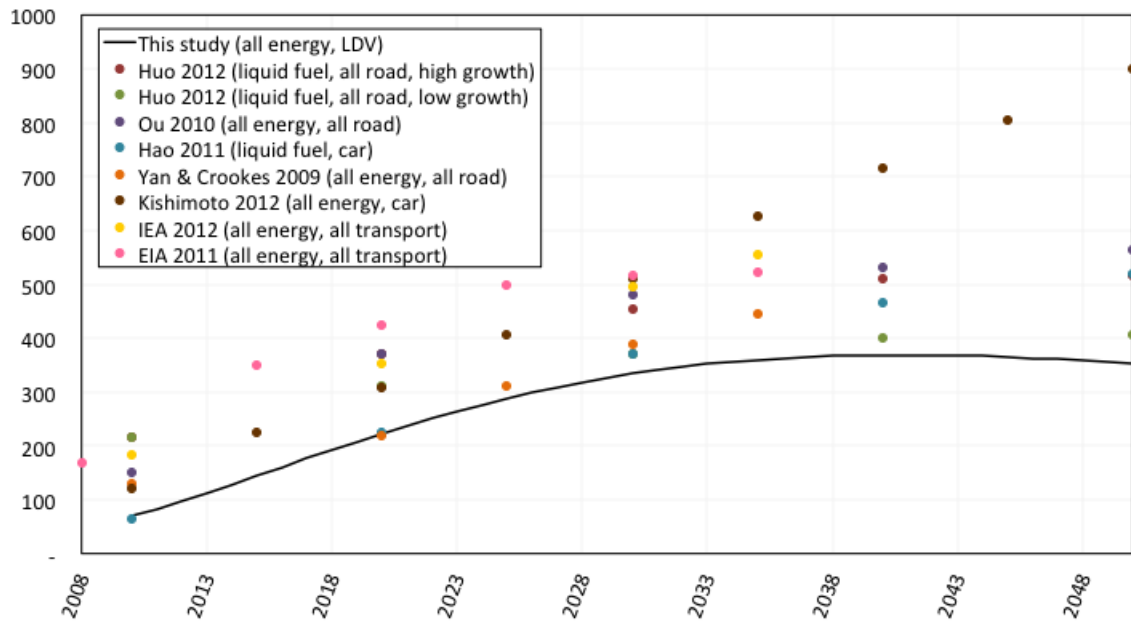


Figure 8-4: Energy demand comparison across models in mtoe.

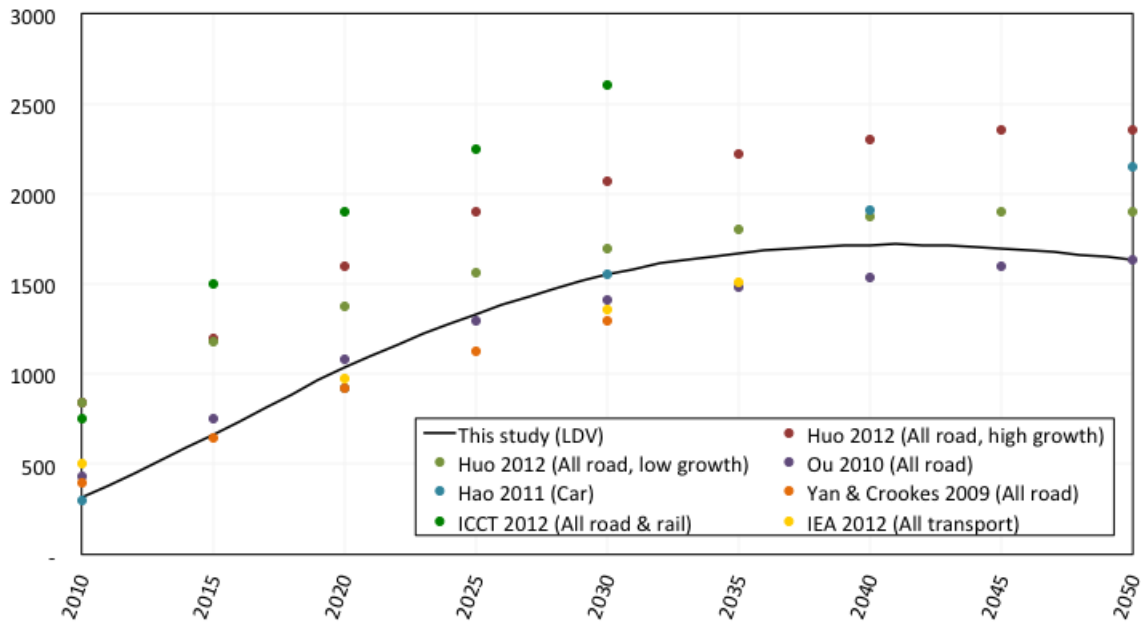


Figure 8-5: CO₂ emissions comparison across models in mmt CO₂.

Study	Model type	Base year	Fraction of road transport
This work	Fleet model	2010	Light duty vehicles
Huo et al.	Fleet model	2010	All vehicles
Hao et al.	Fleet model	2010	Passenger vehicles
Ou et al.	Fleet model	2007	All vehicles
Yan and Crookes	Fleet model	2005	All vehicles
Kishimoto et al.	CGE model	2005	Cars
IEA	Modified fleet model	2010	All vehicles
EIA	Modified fleet model	2008	All vehicles
ICCT	Fleet model	2005	All vehicles

Study	Fraction of energy	Label
This work	All energy	Reference
Huo et al.	Liquid fuel	BAU
Hao et al.	Liquid fuel	Reference
Ou et al.	Liquid fuel	BAU
Yan and Crookes	All energy	BAU
Kishimoto et al.	All energy	BAU
IEA	All energy	Current Policies
EIA	All energy	Reference
ICCT	Emissions	no label

Table 8-1: Characteristics comparisons across China road energy models.

(2012) use a recursive-dynamic general equilibrium model that simulates the world economy. With the transport sector modeled in great detail, it can effectively model automotive energy demand within the context of the larger economy. It shows that unrestricted economic growth without policy interventions will not induce fuel efficient vehicles or alternative energy technologies. This leads to an outlier energy demand projection. The IEA (2012a) and EIA (2011) models use modified fleet model approaches that use passenger distance travel demand instead of counting vehicles and vehicle use.

Types of vehicles

Only three of the studies: this thesis, Hao et al. (2011a) and Kishimoto et al. (2012) model exclusively model the light duty vehicle fleet. While passenger cars account for a large and growing portion of total energy demand in China, heavy duty vehicles may be fewer in number but with their high annual VDT and fuel consumption contribute to a significant portion of China’s energy demand. This should depress these three studies’ reference case energy projections below that of the other studies. This is not the case (see Figure 8-4) and model methodologies and other assumptions must play a larger role.

Built-in assumptions differ across studies

Comparing the assumptions that underlie the base case scenarios in different fleet models reveals inherent differences in input assumptions. The “Comparison across models” sections from Chapters 4, 5, 6 and 7 discuss these in details, and Figure 8-6 summarizes the differences among this model and four other bottom-up fleet models. Ou et al. (2010b) have the most aggressive assumptions. This study is second. All input assumptions do not have equivalent effects on determining future energy demand, but it is striking that this study’s reference scenario are not the most aggressive and yet results are the lowest. However, Ou et al. (2010b) model the entire vehicle energy fleet and heavy duty vehicles could

Study	Stock	VDT (km/vehicle/ y)	Fuel consumption (% decline/y)	Powertrain sales mix	Alternative fuels
This work	2050: middle scenario of three	2050: ~12000	0.7%	2050: 30% electrified, mostly HEV	Mild growth
Huo et al (2012)	2050: high & low scenario	2050: 13000 or 9000	0.5%	No change	No growth
Hao et al (2011)	2050: high forecast (of two)	2050: 12000	No decline	No change	No growth
Ou et al (2010)	2050: one forecast	2050: 15000	0.65%	2050%: 20% electrified, mostly EV	Mild growth
Yan & Crookes (2009)	2030: one forecast	2030: 14400	No decline	No change	No growth

Figure 8-6: Comparison of key assumptions across models. The darker the violet, the more aggressive the assumption, which would lead to lower energy demand. Note the table considers just light duty vehicle assumptions although Huo et al. (2012b), Ou et al. (2010b) and Yan and Crookes (2009) consider the entire vehicle fleet in their respective studies.

account for a large portion of energy demand.

Conclusions

This study's reference scenario differs from the "business as usual" scenarios from other studies because it is a median and not highest possible energy demand projection. Second, this study does not consider heavy duty vehicles. Third, I do assume technology adoption and efficiency improvements will occur. As a consequence, this reference scenario projects lower energy demand than other studies, especially in the long term.

8.2 Sensitivity analysis

The sensitivity analysis answers the central technical question of the thesis: what are the key drivers that determine future fuel demand? It does so by assigning each driver a more aggressive and less aggressive future trajectory than in the reference case. In addition to each pair of scenarios, I create two bounding extreme high and extreme low future alternatives by assuming all drivers evolve along their high (or low) trajectories. These are bounding because it is extremely unlikely future energy demand would be

higher or lower.

The goal of this sensitivity analysis is not to reveal how important one variable is to another in comparable percentage points because it is unlikely equal percentage point variations in two different variables would be equally likely to occur. Instead, the analysis groups drivers by small, modest or large impact on future energy demand. The values that underlie the sensitivity analysis are all contained and explained in Appendix B. A minority of key model assumptions are assumed static through all the scenarios: this includes scrappage, mileage degradation, relative fuel consumption among powertrains, and carbon intensity for different fuel sources over time (see Appendix B). The majority of drivers, eight in all, do vary:

- Stock: automotive ownership is currently very low in China and will increase to unknown future higher levels of ownership.
- VDT: the average annual distance traveled per vehicle in China is currently high compared with most developed countries, but could stay relatively constant or drop dramatically.
- Turbocharged: turbocharged vehicles already make up a small fraction of Chinese vehicle sales, but the technology may gain quick or slow acceptance.
- Electrification: will Chinese adopt hybrids, plug-in hybrids and electric vehicles?
- EV or HEV electrification: will electrification focus on hybrid electric vehicles or on true electric vehicles?
- Fuel consumption: vehicle efficiency may improve quickly or slowly.
- Natural gas: will natural gas become a popular alternative fuel?
- Methanol: will methanol become a popular alternative fuel?

8.2.1 Energy demand sensitivity

Figure 8-7 shows sensitivity analysis results for all scenarios in mtoe. Natural gas and methanol drivers are not represented here because implementing these scenarios would generate identical energy demand. Because I assumed engine efficiency for CNG and methanol vehicles to be identical with their gasoline powered alternatives, identical amounts of energy would be necessary to power the vehicle the same distance. Stock (violet) is the most sensitive driver in both raising and reducing energy demand. Greater or lesser presence of turbocharged vehicles (orange) has a small effect, as does the relative fraction of hybrids to electric vehicles in the modest reference electrification scenario (pink). Fuel consumption is a more significant driver in lowering energy demand than in raising it (green). This is logical: future fuel consumption in 2050 is 60% of current fuel consumption in the low scenario, 80% in the reference and 90% in the high scenario. Significant vehicle electrification proves itself to be a significant driver especially after 2040 (blue). Surprisingly, significant electrification dominated by HEVs is a fairly promising means to lower future energy demand (turquoise), indicating that it may be worthwhile to focus on getting highly fuel efficient vehicles on the road instead of converting an infrastructure system to wholly electric vehicles. Targeting VDT is also a fairly promising means to lower future automotive energy demand. Nevertheless, an individual driver cannot shift future energy 100 mtoe as results cluster tightly around the reference.

In addition, the “high-all” and “low-all” scenarios show resulting energy demand if all inputs evolve along their high or low predicted values. Future energy demand then varies between about 150 mtoe to nearly 700 mtoe. These results can also be calculated by multiplying the effects of individual drivers. Thus, this wide range underscores the need to focus attention on policy interventions that address significant drivers and also focus on multiple drivers.

8.2.2 Gasoline and diesel demand sensitivity

Figure 8-8 shows future conventional fuel demand for all scenarios. The two “high-all” trajectories, one without any alternative fuel adoption and one with significant alternative fuel adoption shows potential fuel demand savings could approach nearly 250 bil L of gasoline if all other drivers evolve per extreme values. The actual impacts of adopting methanol (olive) or natural gas (brown) are likely more modest and on the order of 50 bil L each. This differentiates this approach from the wedge approach other studies use: the absolute impacts of any one driver are smaller in a median reference scenario as compared with an extreme reference scenario. They are subject to marginal diminishing returns as society employs more methods to control automotive energy demand.

CNG (brown) has a large impact as a single driver early in the model, though its significance diminishes over time. Again, greater or lesser presence of turbocharged vehicles (orange) has a small effect, as does the relative fraction of hybrids to electric vehicles in the modest reference electrification scenario (pink). Methanol has a modest impact lowering energy demand, but a small one raising it (olive). Significant electrification and HEV dominated significant electrification are even more sensitive for fuel demand (blue and turquoise). Nevertheless, stock (violet) and vehicle fuel consumption (green) are again also important drivers in reducing conventional fuel demand, while VDT has a fairly large impact (red).

8.2.3 CO₂ emissions sensitivity

Alternative fuel adoption (olive and brown), composition of reference scenario electrification (pink) and turbocharged vehicle adoption (orange) have a very small impact on future CO₂ emissions (Figure 8-9). It is also noteworthy that increasing amounts of methanol, while it decreases conventional fuel demand, increases emissions. This is because methanol is more CO₂ intensive than gasoline. Vehicle stock is once again the most significant driver in terms of both increasing or decreasing reference scenario emissions, even if significantly decreasing fuel consumption has a similar effect to decreasing vehicle stock growth. In contrast with energy demand and conventional fuel demand, reductions or increases in VDT is the next most significant driver, ahead of electrification. However, because electrified vehicles are more efficient than their internal combustion engine counterparts, even though China’s electric grid will remain more CO₂ intensive than gasoline, there is still a CO₂ emissions benefit from significant electrification. The same benefit of circa 100 mmt CO₂ can be achieved, however, with mostly hybrid electric vehicles rather than mostly plug-in hybrid and electric vehicles.

8.2.4 Discussion

Taking future energy demand, conventional fuel demand and CO₂ emissions into account, vehicle stock has the greatest impact in both increasing or decreasing demand or emissions. If significant gains can be made in lowering fuel consumption, it too can be an important tool in limiting future energy demand and CO₂ emissions. Significant electrification holds great potential for lowering energy demand and

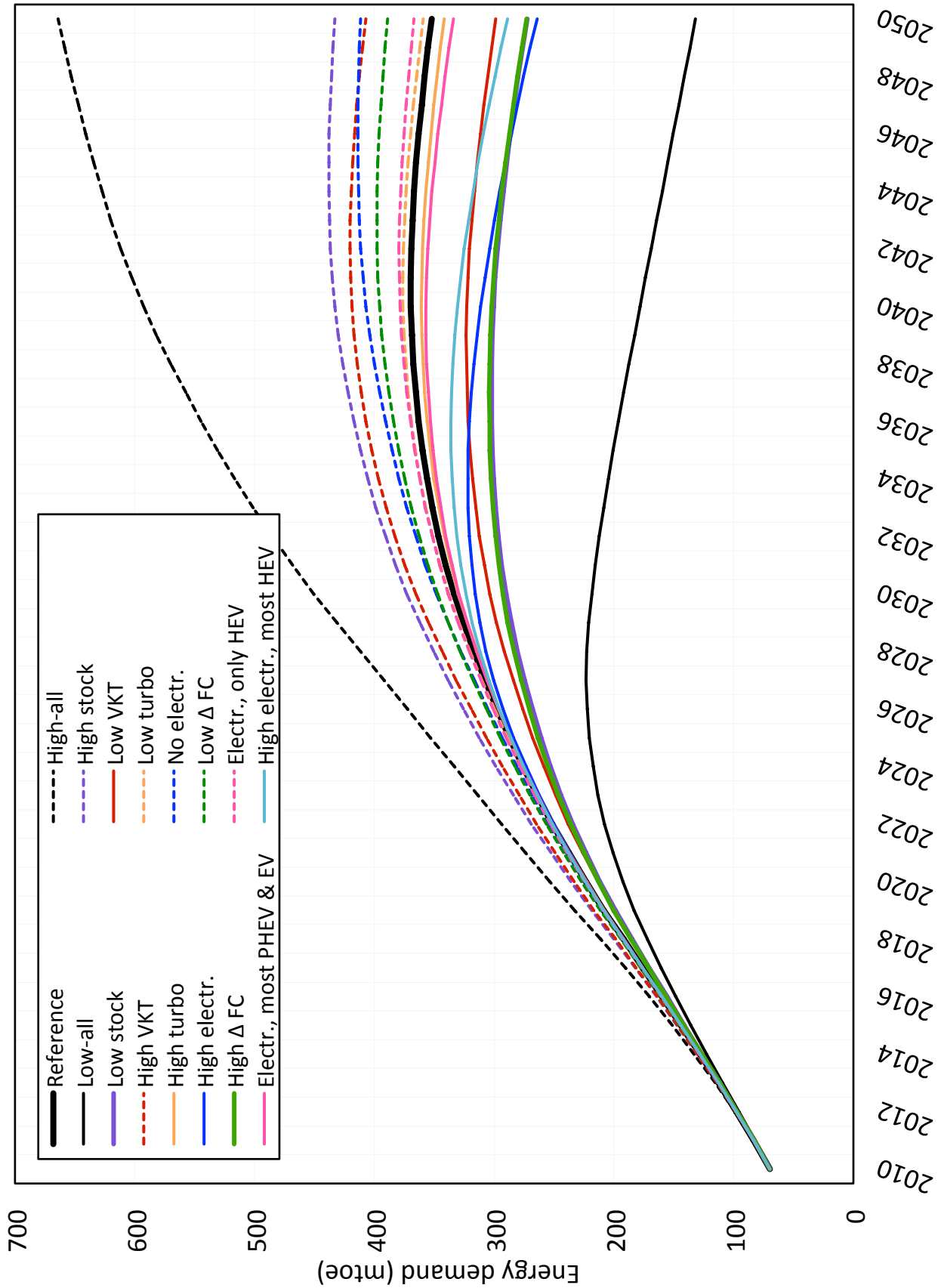


Figure 8-7: Future energy demand sensitivity analysis. The black lines define the reference and extreme scenarios while each individual driver is represented as a pair of colored lines. "alt." is alternative, "Δ FC" is change in fuel consumption, "electr." is electrification.

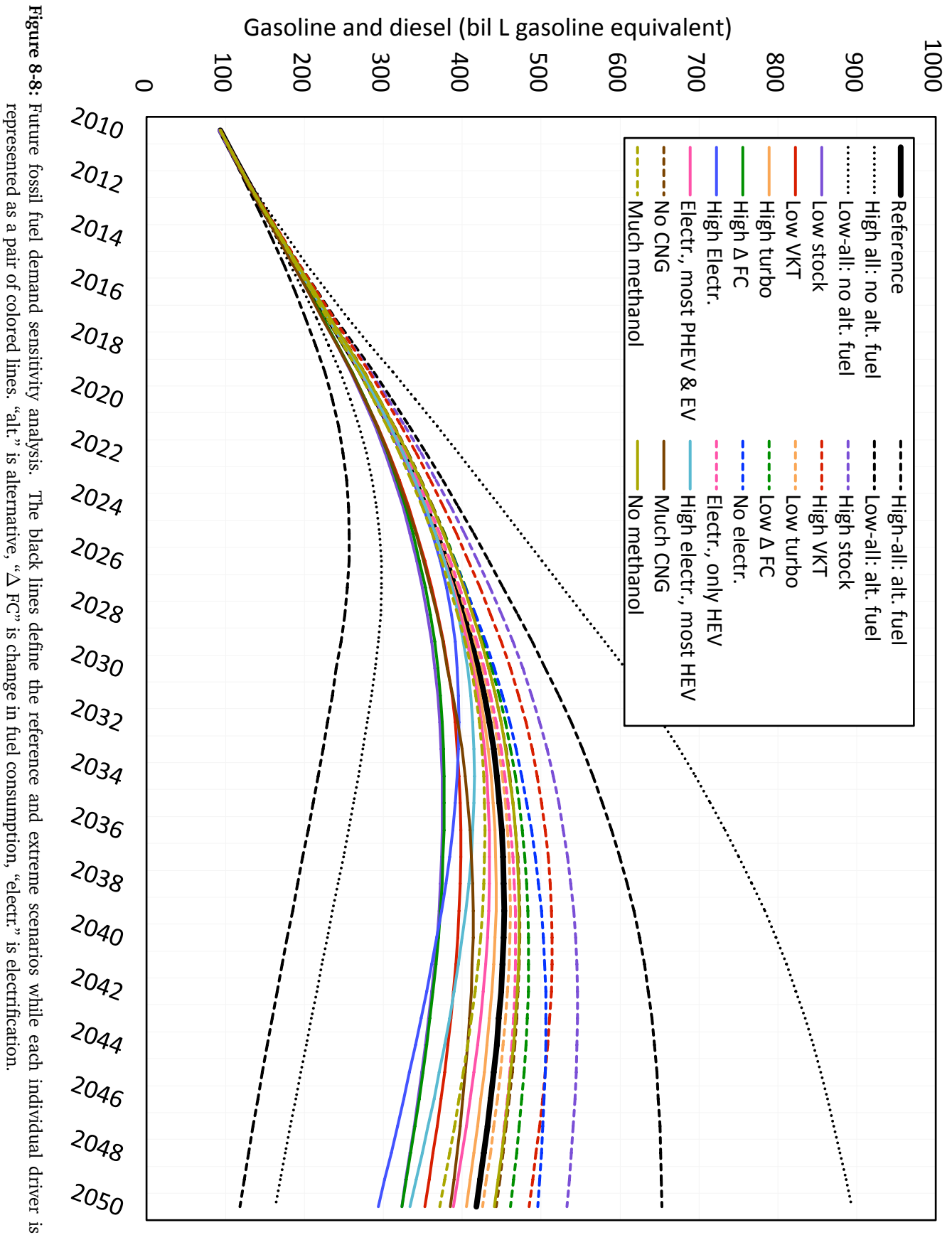


Figure 8-8: Future fossil fuel demand sensitivity analysis. The black lines define the reference and extreme scenarios while each individual driver is represented as a pair of colored lines. "alt." is alternative, "Δ FC" is change in fuel consumption, "electr." is electrification.

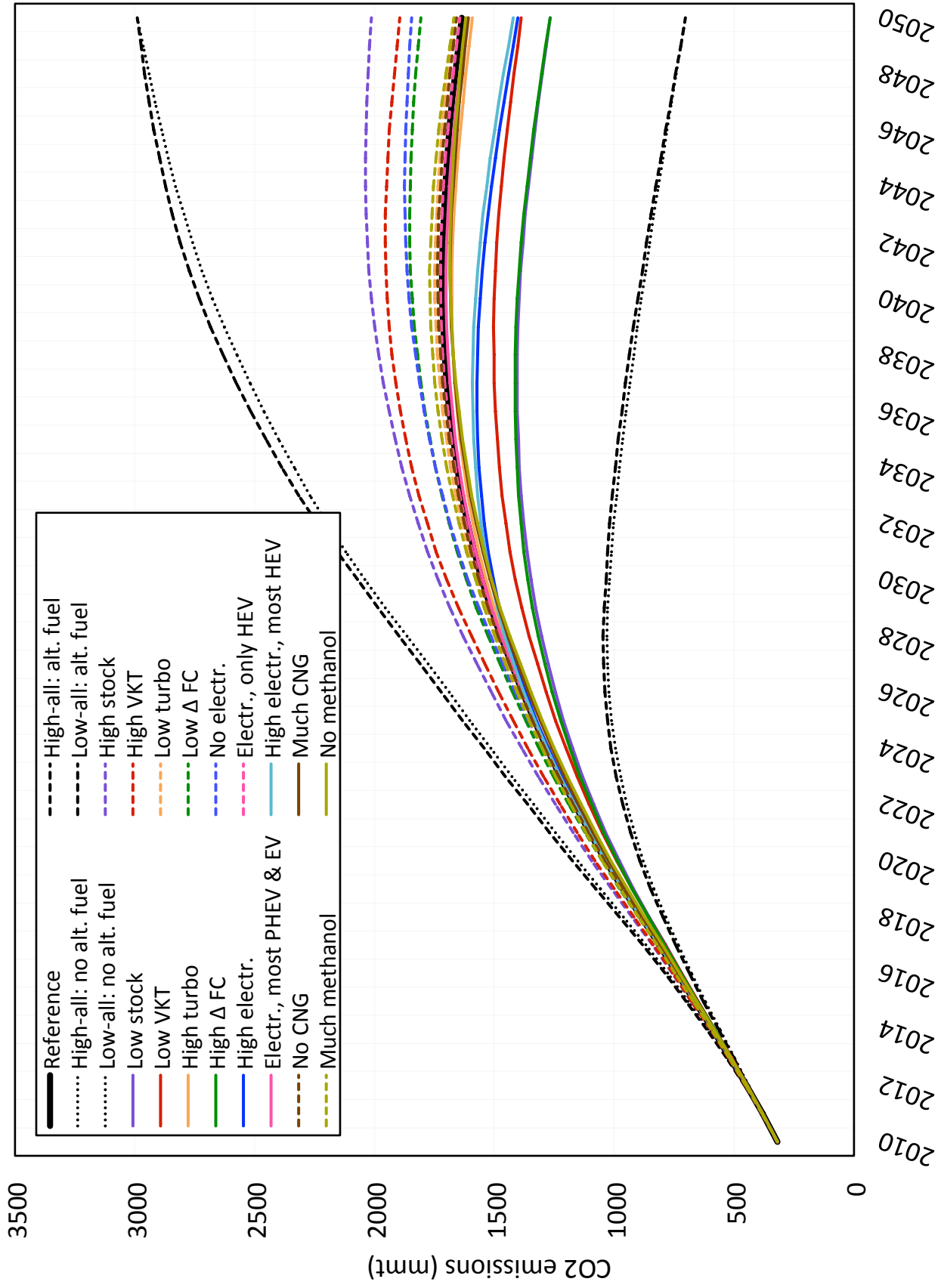


Figure 8-9: Future CO₂ emissions sensitivity analysis. The black lines define the reference and extreme scenarios while each individual driver is represented as a pair of colored lines. “alt.” is alternative, “Δ FC” is change in fuel consumption, “electr.” is electrification.

displacing conventional fuel. Moreover, this electrified fleet need not be wholly electric - significant HEV adoption can achieve the same benefits as EVs in reducing CO₂ emissions, while achieving ~75% of reductions in energy demand and conventional fuel demand. Although alternative fuels contribute to modest increases or decreases in conventional fuel demand, they impact future CO₂ emissions very little. VDT is a fairly significant driver, but many strategies that target ownership can also influence VDT and vice versa. Thus, managing vehicle demand remains the most important tool in determining future energy use, fuel demand and CO₂ emissions in China, along with significantly reducing fuel consumption. Pursuing significant hybrid electric vehicle adoption will deliver similar benefits to significant electric vehicle adoption.

Chapter 9

Implications

Chapter 8 that vehicle ownership, vehicle fuel consumption and hybrid electric and electric vehicles are the most significant drivers to control light duty vehicle energy demand, light duty vehicle fuel demand, and light duty vehicle CO₂ emissions. This chapter analyzes how well current Chinese policy initiatives address these four factors. It also evaluates the policy interventions discussed in Part II by how likely institutional barriers from key stakeholders would prevent policy efficacy. Finally, it also discusses the work's implications for the international community and for research.

9.1 Research implications

The results from the Chapter 8 reveal that China's future light duty vehicle energy demand, conventional fuel demand and CO₂ emissions are likely to level off in the 2030s and 2040s. It is possible for energy demand to remain stable given lower fuel consumption, modest fleet electrification, and some alternative fuel adoption, coupled with falling VDT and average OECD vehicle ownership. Even if one or a few of the input variables are off, energy demand is still likely to remain roughly around the median. The next area of inquiry, then, is to investigate what policy steps will achieve that future.

However, although China's future light duty vehicle energy demand will level off, at what precise amount it will do so is uncertain. The extreme scenarios reveal a large variation in possible future energy demand, fuel demand and CO₂ emissions. Acknowledging this, the solution I developed did set a reference scenario, but use a modified sensitivity analysis to determine which drivers are the most significant and establish how much China's future light duty vehicle energy demand, fuel demand and CO₂ emissions might vary. The extreme scenarios do show that the possible variation in China's future energy demand is remarkably large - a possible fivefold spread in future energy demand, an eightfold spread in future conventional fuel demand and over a fourfold spread in future emissions. Although the extremes are unlikely, they bound the range of possible future outcomes.

Having identified how future Chinese energy demand, fuel demand and CO₂ will evolve and which drivers are significant in determining the precise future outcome, further work calls for understanding these drivers in depth.

9.2 Policy implications for China

Throughout Chapters 4 through 7, I reviewed and critically evaluated several policies that contribute to controlling Chinese automotive energy demand, conventional fuel demand and CO₂ emissions.

- Vehicle ownership and vehicle use: land use policy, transportation system policy, automobile friendly policies
- Vehicle ownership: vehicle sales quotas
- Vehicle use: vehicle use bans, vehicle fuel taxes
- Vehicle efficiency and technology: fuel consumption targets, vehicle sales tax, electric vehicle policies
- Vehicle fuels: alternative fuel research, development and subsidies

By combining the results of Chapter 8 with the policy analysis from Chapters 4 through 7, this section can evaluate how well current Chinese policy aligns with the most significant drivers to reduce automotive energy demand. Taking this, political feasibility and other barriers into consideration, I can recommend which policies will be more effective in control future automotive energy demand growth.

Automotive ownership rises in step with increasing per capita income, and so China's automotive population will continue to rise. However, once a society becomes dependent on automobile travel, force of habit makes it difficult to break that dependency. Especially because cities contain the majority of light duty vehicles in China, exploring options now to reduce automotive reliance in urban areas is imperative. I examined four strategies and policies: maintaining city density through land-use policy, building public transportation, adopting or eschewing automobile friendly policies, and vehicle sales quotas. I found that the central government favors maintaining tight city borders and high city densities, but local governments often extend the limits of their city masterplans. Political incentives, pressures to generate revenue, inter-city competition, and increasingly affluent city residents all contribute to city sprawl. Even as city development goals espouse sustainable development, implementing this development is more difficult. Poorly integrated transportation planning and automotive friendly design policies contribute. In response, some cities, faced with intolerable congestion and air pollution, have resorted to vehicle sales quotas. These curtail vehicle sales in order to maintain vehicle population near current levels.

Vehicle driving bans and vehicle fuel taxes are two methods of lowering automotive travel demand. Vehicle driving bans restrict a portion of the vehicle population from driving at certain times of day or days of the week, and a handful of cities across China have experimented with them. High vehicle fuel taxes increase the cost of driving to make it more expensive and less desirable. Local governments previously lobbied against such a policy, but fuel prices have risen in recent years to surpass US prices.

Through fuel consumption targets, vehicle sales taxes, and electric vehicle policies, the national Chinese government has ambitious plans to improve and transform its automotive fleet. Electric vehicle policies have poured money into research and development, provided pilot project purchase incentives to private citizens and local governments to acquire electric vehicles, and set ambitious sales targets in 2020. China has also adopted internationally rigorous fuel consumption policies, seeking to lower average passenger car fuel consumption by 54% from 2010 to 2020. Finally, in a further bid to reduce vehicle fuel consumption and promote small vehicles, China taxes vehicles by engine size. The electric vehicle program has not come close to meeting targets, but the other two policies may yet succeed.

Finally, research and development into alternative fuels has sought solutions to conventional fuel demand imports. The government has funded research and subsidized various products including coal-derived fuels, natural gas and biofuels.

Policies that best control energy demand The sensitivity analysis in Chapter 8 suggested that the three most important drivers to control future automotive energy demand, conventional fuel demand and CO₂ emissions are automotive ownership, vehicle fuel consumption, and vehicle electrification. HEVs can provide a majority of the electric vehicle benefits, and thus the composition of the electrified fleet matters less. Mapping these results on to the aforementioned ten policy strategies suggests seven levers that are more attractive from an impact view. Reducing vehicle ownership by 100 vehicles per 1000 capita off reference in 2050 may not be exactly equivalent to reducing fuel consumption from reference by 33% in 2050, or raising electrified powertrains from 30% to 60% of sales in 2050. Moreover, it is not clear how these seven policies should be formulated or which in each category will be the most effective. However, these three drivers are collectively more significant than all the other examined drivers, and thus these seven policy strategies are worth investigating further.

Policies that face fewer political barriers All ten policies face significant political barriers to implementation. As the analysis in Chapter 4 and 6 showed, Chinese government policy is not homogeneous. Rather, the national government and local governments have different powers, interests and objectives. The result means that sincere intentions to control automotive energy use or implement other policies that could have this effect at the national level of government may not succeed. Frequently, the local governments will ignore or delay implementing national government policy: they will change urban land-use plans and extend development outward, or ignore calls for automotive industry consolidation and build up their own automotive industries. Furthermore, national policy is often vaguely worded. Additionally, when local governments receive national pilot project funds, they use this to support their local industries. In the process, this may hinder national government policy success. For example, the national policy initiative Tens of Cities, Thousands of Vehicles project gave money to local governments who then purchased electric vehicles from their local manufacturers. Because each manufacturer made few individual vehicles, few were able to benefit from the economies of scale and learning more concentrated manufacturing may have created.

A strict focus on raising short term revenues through means other than taxes and pressures to achieve GDP growth targets has created a situation where many national government initiatives are unable to succeed if the level of implementation is local. This imperils many of the aforementioned policies: land use, transportation systems, and electric vehicle incentives are implemented at the local level. In addition, policies implemented at the national level may negatively impact certain localities, in which case policy success is uncertain. For example, my analysis showed that domestic brand vehicle technology lags JV vehicles technology. Reducing automotive fuel consumption, a central government target, will drive up vehicle costs. Unfortunately, domestic brands already target and do well in the microcar market segment. Downsizing vehicles to achieve better fuel consumption at a low vehicle cost may not be an option, but neither is increasing vehicle cost and losing a customer base. Thus, this policy may be incompatible with a central government goals to raise the fraction of domestic brand sales marketshares. Some domestic firms will fail. But, potential failure will meet strong resistance from local governments, who own the companies and are heavily invested in their success.

Other barriers to implementation Some policies may be more difficult to achieve for different reasons. In general, policies can be broken down into regulations, expenditures, incentives and advocacy efforts.

- Regulations: Either the central government or local government will mandate or prohibit certain actions.
- Expenditures: Related to the provision of public services, the local governments carry these out.
- Incentives: Intended for citizens, companies or local governments these promise complete or partial financial compensation in return for an action
- Advocacy: By informing citizens or companies, governments can encourage desired behaviors.

The ten policies enumerated in this chapter tend to be regulations, expenditures and incentives. In comparison with expenditures and incentives, regulations are far less costly to a government and can often bring revenues. Vehicle sales quotas are a regulation. They cost little to implement and can even generate government revenue if set up as an auction. Developing public transportation is a large expenditure that lacks direct monetary gains, although potential long term gains exist. Moreover, many Chinese cities subsidize transit fares. Maintaining strict land-use is a regulation the central government imposes on local governments. However, when land-use policy is coupled with foregone land rights sale incomes, it acts more as a foregone incentive to local governments. Vehicle sales quotas are thus the cheapest policy for local governments to implement, and unsurprisingly this is the policy a few local governments have adopted.

Vehicle driving bans and fuel taxes are regulations; government revenue accompanies fuel taxes. However, this may unduly impact commercial and industrial transportation, which is important to economic development. Vehicle fuel consumption targets are also a regulation, but a target that does not generate government revenue. The vehicle sales tax is an incentive. Plans for electrification necessitate both government expenditures and government incentives. Unfortunately, policy success presumes people will purchase electric vehicles. Unless the technology becomes cost effective, this is unlikely to be the case. This strategy could yet succeed, but is far more risky and potentially more expensive than other strategies. Similarly, alternative fuel research and development is also a large, risky government expenditure.

Recommendation Considering this, vehicle fuel consumption targets emerge as the policy likeliest to significantly reduce future automotive energy demand growth. It is a simple policy, relatively free from political barriers, and costs little to implement. Vehicle sales quotas are also inexpensive and potentially effective, but constrain the central government goal of growing an automotive industry. While an electric vehicle revolution remains elusive, hybrid electric vehicles could achieve a majority of the benefits of electric vehicles. They hold promise, although they will require further government research and development incentives.

9.3 Policy implications for the international community

Historically, China's transportation energy demand as a fraction of world energy demand has been small (Figure 9-1). Europe and the US have accounted for roughly a quarter each of all transportation energy in 2010, they accounted for nearly a third of all road transportation energy in 1970. Meanwhile,

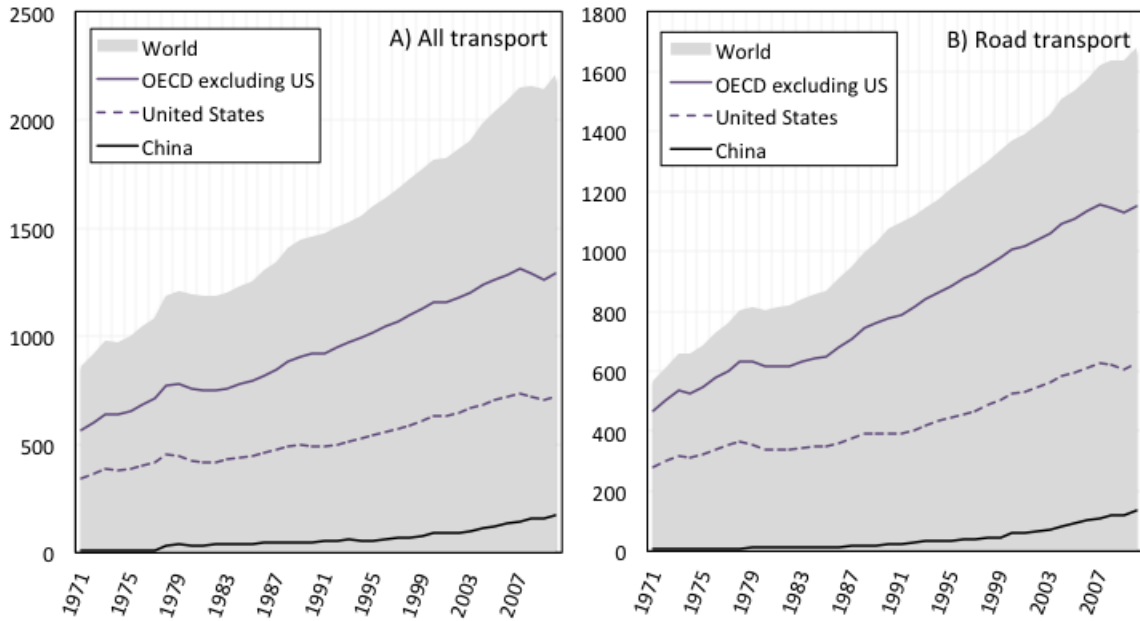


Figure 9-1: International road transport energy demand in million tons. The lines are stacked while the shaded portion is separate.

China accounted for almost no share of international energy demand in the early 1970s, but is quickly approaching 10% of international energy demand. As China's conventional fuel demand continues to grow, this will change the dynamics of the international oil trade market.

Surprisingly, the China reference scenario peak light duty vehicle fuel demand of ~500 bil L around 2040 closely matches US light duty vehicle fuel demand in 2008 of ~525 bil L (Figure 9-2). This coincidence is striking considering that the US has fewer cars than China will have. Differences in VDT, fuel consumption and energy technologies account for the difference. Before US fuel demand declines, however, the two countries will together demand ~900 bil L of fuel in 2030. These comparisons are valid because the fleet models for this study and Bastani et al. (2012) originate from the same precursor and certain key assumptions (on future relative fuel consumption among powertrains, for example) remain constant across both.

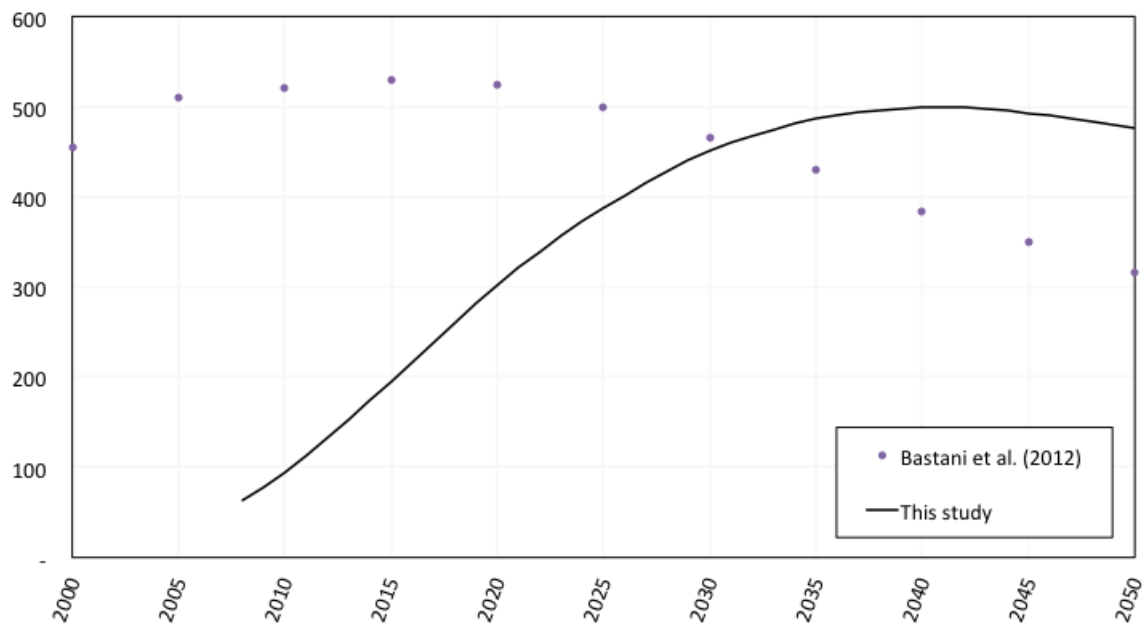


Figure 9-2: Future China and USA road transportation energy demand in bil L. Source: this study and Bastani et al. (2012).

Chapter 10

Conclusions

This analysis built a light duty vehicle fleet model to project future vehicle stock, energy demand, fuel demand and CO₂ emissions. The reference scenario strove to present a moderately aggressive but feasible future. Comparing these results with the reference results of other studies' revealed this study projects higher future automotive ownership but lower future automotive energy demand. While those base cases are maximum energy demand scenarios, this study's reference scenario presents a median outcome. Thereafter, a sensitivity analysis constructed from the median scenario used the fleet model tool to craft scenarios. The three sensitivity analyses identified three key drivers - vehicle ownership, vehicle fuel consumption and vehicle electrification - that should be aligned with policy priorities in order to achieve maximum effect in controlling automotive energy demand growth.

A concurrent policy analysis examined a plethora of Chinese policies that can reduce automotive energy demand. These included land use policies, transportation system policies, urban design policies, vehicle sales quotas, vehicle use bans, vehicle fuel taxes, vehicle sales taxes graded by engine size, fuel consumption targets, electric vehicle policies, and alternative fuel policies. Throughout the text it became clear that all promulgated policies can face significant institutional barriers that stymie implementation. For example, if a policy is proposed at the national level, it might not be implemented as intended or at all at the local level.

Vehicle ownership is the most significant driver, and it correlates with per capita income. As the Chinese population grows more affluent, vehicle ownership will rise. During the past ten years, growth in China's light duty vehicle transportation sector has been concentrated to urban centers. Although rural Chinese incomes may pass the threshold for automotive ownership and cars at some point in the future, the urban centers will continue to account for the large majority of vehicles. Moreover, these cities will grow. Keeping vehicle stock in check without sacrificing human development is difficult. A handful of Chinese cities have already passed strict policies to limit vehicle sales. Reducing underlying demand, however, is more complex. Many cities have decided to extend public transportation systems, but this alone is insufficient. In order to reduce the sprawl that favors automobiles, research indicates that land use policy must be rethought. Local government finances, incentives, and evaluations must be rethought. This may slow urban de-densification. Cities must also rethink urban design. Unfortunately, the institutional changes that will be necessary in order to implement policies that may retard vehicle ownership and reduce VDT appear nearly insurmountable.

Vehicle fuel consumption was identified as another significant driver. China's future passenger car fuel consumption targets are aggressive. If the country succeeds in meeting them, it will significantly reduced future potential automotive energy demand. Second, fuel consumption policy enforcement

may crack from provincial pressure. Those local governments with weak automotive manufacturers have strong incentives to see their companies survive. The national government, meanwhile, seeks both to expand domestic brand marketshares and achieve dramatically lower fleet fuel consumption. Based on my analysis comparing JV and domestic brand technology, JV technology still exceeds domestic technology. The Chinese government may thus have to sacrifice one of its two goals.

Finally, electrified powertrains - hybrid electric, plug-in hybrid electric, and electric vehicles - are a significant driver. China's electric vehicle targets are among the most ambitious in the world. However, many barriers lie in the way of success, and the existing electric vehicle strategy - leapfrogging past hybrid vehicles to electric vehicles - has not worked. Instead, because China could receive a majority of the fuel saving and CO₂ emissions saving benefits from hybrid vehicles, shifting the strategy to hybrid vehicle development may prove fruitful.

Future research must therefore further explore these significant drivers of automotive energy demand growth. Regarding automotive ownership, researching the relationship between urban and rural automotive ownership and their respective drivers may offer clues to how ownership in cities will evolve. It may be possible to split the fleet model into two sections to do this. Better understanding how urban development and form relate to automotive energy demand growth may enable incorporating these pressure into the model. On the vehicle technology side, the existing vehicle characteristics data can be further analyzed to elucidate the differences between joint venture and domestic brand technology.

This work's central findings:

- **It is a plausible expectation that China can offset unrelenting rapid automotive energy demand growth with reductions in fuel consumption and introduction of new vehicle technologies.**

The developed world expects reductions in fuel consumption and adoption of new vehicle technologies to pave a path towards reducing transportation sector energy demand. In China, future income growth will inevitably raise current rates of vehicle ownership. However, similar reductions in fuel consumption and adoption of new vehicle technologies can retard and eventually reverse future automotive demand growth. If China can stabilize and eventually begin to reduce its automotive energy demand, it will do so with a population four times that of the US. Moreover, its energy demand will peak at US peak energy demand. In 2010, Chinese light duty vehicle energy demand was 94 bil L and in 2050 it will be 476 bil L gasoline equivalent fuel, but only 418 bil L gasoline equivalent conventional fuel. What can derail China from achieving these targets is not resolve, but follow through.

- **The best policies to reduce both conventional fuel demand and CO₂ emissions will focus on maintaining moderate levels of vehicle stock, reducing vehicle fuel consumption, and introducing hybrid electric or electric powertrains into the fleet.**

As a whole, China's policies are relatively well aligned with the model-identified priority strategies. Targets for reducing fuel consumption and raising electric vehicle sales exceed model expectations. However, the analysis also found reasons to doubt China's ability to achieve these strategies. While urban centers ostensibly embrace development that does not depend on motorized transportation, local government incentives are misaligned with implementing such development. The central government seeks to lower automotive fuel consumption, raise domestic manufacturer sales marketshares for cars, and promote the automotive industry. These goals may be difficult to achieve simultaneously. Electrification is a laudable goal, but Chinese incomes and electric batteries expensive.

- **Central government policies that could control automotive energy demand growth are not implemented as intended at the local level.**

The list is long. Local governments frequently flout central government land use policy by acquiring rural agricultural land and expanding their city borders. The central government has set standards for low carbon cities and supported eco-city development together with select pilot cities, but several developments have failed. The central government has continually attempted to consolidate the automotive industry, but the companies and local governments resist these plans. The central government decided a list of automotive champions, but enterprising local governments founded their own car manufacturing companies. The central government has created a pilot program across a few dozen cities for electric vehicles, but ambitious targets were not met.

- **Current domestic brand vehicles lag joint venture vehicles in technology and are ill-equipped to meet future stringent fuel consumption standards without compromising low prices, larger cars or marketshares.**

Although domestic and JV brand vehicles weigh both conform to fuel consumption standards for their weight class, the JV vehicles have more powerful and larger engines for a given weight class. This gap in technology might be intentional as Chinese brand manufacturers target the low end market, but it might be attributed to technological capability. Regardless, Chinese manufacturers may find it difficult to achieve the new fuel consumption targets.

China's motivations to control automotive energy demand, conventional fuel demand and CO₂ emissions are numerous. To effectively control growth, it can conserve energy demand by promoting policies that lower travel demand and vehicle ownership demand. It can improve existing ICE technology to lower fuel consumption. It can improve political structures and incentive systems to ensure more successful policy implementation. Finally, it can potentially transform current technologies with alternative powertrains. Focusing on any one portion of solutions is insufficient. Instead, controlling future vehicle ownership, reducing future vehicle fuel consumption and introducing electrified powertrains will involve conserving energy demand, improving current institutions and technologies, and transforming the current automotive system. China is not yet locked into a physical and societal system dependent on the automobile as is the developed world. It is changing fast. Regardless of the specific path it chooses, China should act now and capitalize on this change.

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Appendix A

Abbreviations

- BAIC: Beijing Automotive Industry Corporation
- CAAM: China Association of Automotive Manufacturers
- CAIY: China Automotive Industry Yearbook
- CATARC: China Automotive Technology and Research Center
- CNG: Compressed natural gas
- CTL: Coal-to-liquid technology
- DME: Dimethyl ether
- E10: Gasoline with 10% ethanol by volume
- EV: Electric vehicle
- FAW: First Automotive Works
- FC: Fuel consumption
- FCV: Fuel cell vehicle
- GAC: Guangzhou Automotive Company
- HEV: Hybrid electric vehicle
- ICET: Innovation Center for Energy and Transportation
- ICCT: International Council for Clean Transportation
- ICE: Internal combustion engine
- LDV: Light duty vehicle
- LDT: Light duty truck
- LNG: Liquid natural gas
- LPG: Liquid petroleum gas

- JV: Joint venture, a jointly (often 50-50) owned domestic Chinese and foreign owned company
- M15: Gasoline with 15% methanol by volume
- MB: Minibus
- MIIT: Ministry of Industry and Information Technology
- MT: Minitruck
- NA-SI: Naturally aspirated stroke injector, the current default internal combustion engine
- NDRC: National Development and Reform Commission
- NEV: New energy vehicle, encompasses EV, FCV, HEV and PHEV vehicles
- NP-Car: Non-private car
- PHEV: Plug-in hybrid electric vehicle
- RMB: China's currency, the renminbi. Also referred to as yuan.
- SAIC: Shanghai Automotive Industry Corporation, one of China's largest automotive companies
- SOE: State-owned enterprise, a firm where the Chinese government holds a majority share
- TC: Turbocharged
- VDT: Vehicle distance traveled, the distance traveled per vehicle per year
- VKT: Vehicle kilometers traveled, the kilometers traveled per vehicle per year
- VMT: Vehicle miles traveled, the miles traveled per vehicle per year
- VW: Volkswagen

Appendix B

Model assumptions

This appendix describes in detail all of the fleet model inputs for projecting demand, energy, fuel and emissions. When pertinent, all the tables in this appendix will refer to the three variants for future values as reference, high and low.

Vehicle sales

The model predicts vehicles sales using percent annual growth rates in sales (Table B-1). Sales growth rates are the same across all four modeled vehicle types, though private car and non-private car sales are predicted jointly. Increases in sales are generally more drastic between 2010 and 2020, after which they decelerate.

To ensure predicted sales and stock numbers are reasonable, I check final vehicle ownership levels against those of developed countries: vehicles owned per capita in China in 2050 are likely between the lowest and highest current OECD ownership levels. Chapter 4, Vehicle ownership, discusses how the model treats ownership extensively. As a reference for these discussions, Table B-2 lists the numbers that underlie this analysis: future LDV sales, stock and ownership for key years.

Private and non-private cars

In order to separate private car and non-private car stock, I predict a ratio of private car sales to total car sales (Table B-3). I verify these numbers by comparing the ratio with that of another country, the US. In the US, taxi fleets and company fleets are owned by private, but do overlap reasonably well in function

Annual growth in sales (%)	Reference	Low	High
2010-2014	10	9	11
2015-2019	7	6	8
2020-2029	4	3	4.5
2030-2039	1.5	1	2
2040-2050	0.5	0	1

Table B-1: Vehicles sales growth assumptions by scenario.

Sales (million) and ownership (vehicles/1000 people)	Reference	Low	High
LDV sales, 2030	39	32	45
LDV sales, 2050	47	35	59
LDV stock, 2030	396	346	441
LDV stock, 2050	578	449	708
Vehicle ownership, 2030	325	290	358
Vehicle ownership, 2050	498	398	598
LDV ownership, 2030	284	249	317
LDV ownership, 2050	446	347	546

Table B-2: Future vehicle sales, stock and ownership predictions.

Model year	2010	2011	2012	2013	2014	2015	2016	2017	
% private cars sold of all cars	89.0	89.5	90.0	90.5	91.0	91.25	91.5	91.75	
	2018	2019	2020	2021	2022	2023	2024	2025	2026+
	92.0	92.25	92.5	92.75	93.0	93.25	93.5	93.75	94.0

Table B-3: Ratio of private car sales to all cars.

with non-private cars in China. 4.26 million cars in the US belonged to fleets¹ in 2010, out of 130.9 million automobiles (National Transportation Energy Databook, 2012). This 3.26% of all automobiles can be company cars, taxi fleets, rental cars or government vehicles. China's legacy of also giving state-owned enterprise executives and government officials the perk of having an official vehicle likely means China's non-private vehicle to private vehicle ratios will be higher than the US but still within range. I assume 94% of cars will be private by and after 2026.

Vehicle scrappage

This model calculates vehicle scrappage using a logistic regression expression:

$$\exp^{-\left(\frac{x}{T}\right)^B} \quad (\text{B.1})$$

B expresses the rate at which vehicles disappear from the vehicle stock. T is the vehicle half-life, or the age at which half of vehicles from model year remain in use. Parameters vary between vehicle types because of regulations, intensity of use, and type of use. China has no official statistics available on vehicle scrappage. Field studies or fitting an equation to historical stock and sales are possible methods to set the two variables. For private cars and non-private cars, the model uses values from a Beijing field study (Hao et al., 2011c) (Table B-4). While specific to one urban environment, because the majority of vehicles in China are urban, the values are a reasonable approximation of reality. For minitrucks and minibuses, I analyze the values Yan and Crookes (2009) deduced from historical data sales and stock and thereafter fit appropriate values of T and B.

The model assumes rates of vehicle aging are constant both before base year 2010 and until 2050. There are two reasons not to vary scrappage in the future. First, because there is no time series data on scrappage in China, it is difficult to predict future trends. Second, the impact of varying scrappage is modest. While in the short term changing scrappage rates will alter the number of vehicles on the road, variable scrappage rates do not change underlying vehicle demand. Vehicle stock should remain

¹A fleet vehicle is either one of 15 or more vehicles, or is purchased in annual groups of at least five vehicles

Scrappage values	B	T (years)
Private car	4.7	14.46
Non-private car	5.33	13.11
Minitruck	5.58	7.8
Minibus	4.5	16.5

Table B-4: Vehicle scrappage assumptions.

constant over the long term. Nevertheless, recycling vehicles faster or slower could accelerate or retard introduction of cleaner technologies into the fleet. I altered scrappage parameters while adjusting sales to keep total number of vehicles on the road constant. However, varying both T and B under these conditions produced very little difference in overall energy demand. Therefore, I fixed scrappage as an input for the sensitivity analysis.

Vehicle distance traveled

Similar to vehicle sales, vehicle distanced traveled (VDT)² values are set by percentage point annual growth rates (Table B-5). The model treats VDT with an exponential decay function, and the growth rates in VDT change how far a vehicle drives in the first year it rolls on the roads. Average annual VDT for the whole fleet is sensitive to rapid change in vehicle stock. If sales remain rapid, the VDT of new vehicles will comprise a very large portion of fleetwide average annual VDT. Conversely, as future sales slow in China and older vehicles make up a larger fraction of the vehicles on the road, VDT will naturally retard. Thus, all three scenarios see VDT decline for all four vehicle types. Indeed, the high scenario keeps average annual VDT levels just constant, while the reference scenario and low scenario decline average annual VDT by a little and a lot (Table B-6). In addition, I assume that for different scenarios, the low scenario and high scenario average annual VDT values will vary more for private cars than non-private cars and minitrucks. Non-private cars and minitrucks are not discretionary, and are thus more robust against pressures to decrease VDT. I assume minibuses will tend closer to private car VDT.

As explained in Section 5.2, projecting minibus and minitruck VDT is straightforward. However, I benchmark future private car and non-private car values against average car values. To separate private and non-private, I first determine a saturation level for the fraction of non-private cars that are taxis. I set this at 5%, following the analysis in Appendix C, Stock. Next, I assume taxi VDT will saturate at 110 000 km per year - although taxi VDT growth fit a linear relationship between 2000 and 2010, this growth will not continue uncontrollably (see Appendix C, VDT). In other words, average annual taxi VDT will add 5500 km to 95% of average annual non-taxi, non-private car VDT to give non-private car VDT in 2050. I set values for all three scenarios for target private car VDT and non-private car VDT such that the two sets of weighted averages - for taxis and non-taxi, non-private cars, as well as non-private cars and private cars - accord with the three overall target car VDT values in 2050 of 10000, 13000 and 16000 km/vehicle/year. I also assume the majority of change in VDT occurs before 2030 as sales slow more rapidly during this period and VDT will retard more (Figure B-1).

²VDT refers to annual distance traveled per vehicle, not the annual distance traveled for the whole fleet

Annual Change in VDT (%)	Reference	Low	High
Private car, 2010-2014	-0.1	-1.2	0.9
Private car, 2015-2019	-0.1	-1.15	0.8
Private car, 2020-2029	-0.1	-1	0.75
Private car, 2030-2050	-0.15	-0.7	0.15
Non-private car, 2010-2014	-0.4	-0.75	-0.1
Non-private car, 2015-2019	-0.35	-0.6	0
Non-private car, 2020-2029	-0.2	-0.5	0
Non-private car, 2030-2050	-0.2	-0.4	0
Minitruck 2010-2014	-0.5	-0.65	0
Minitruck, 2015-2019	-0.4	-0.65	0
Minitruck, 2020-2029	-0.3	-0.6	0
Minitruck, 2030-2050	-0.25	-0.55	0
Minibus 2010-2014	-0.75	-1.3	0
Minibus, 2015-2019	-0.75	-1.3	0
Minibus, 2020-2029	-0.7	-1.3	0
Minibus, 2030-2050	-0.6	-1.3	0.1

Table B-5: Annual change in VDT assumptions .

Average Annual VDT (km/vehicle)	Reference	Low	High
Private Car, 2010	15852		
Private Car, 2030	13165	11266	15148
Private Car, 2050	12414	9387	15523
Non-private Car, 2010	30310		
Non-private Car, 2030	24136	23046	25200
Non-private Car, 2050	22997	21005	24986
Minitruck, 2010	24282		
Minitruck, 2030	21741	20778	23325
Minitruck, 2050	20519	18472	23578
Minibus, 2010	19592		
Minibus, 2030	15291	13981	16731
Minibus, 2050	13022	10441	16073

Table B-6: Future VDT predictions.

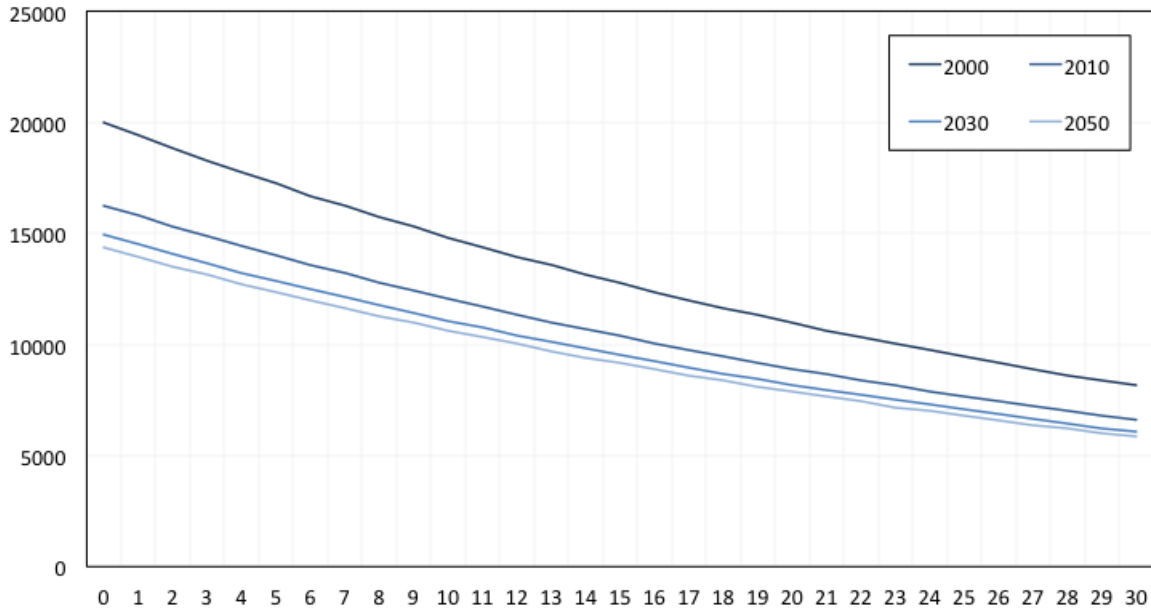


Figure B-1: Future private car VDT over vehicle age by km/vehicle/year.

Mileage degradation rate

The model treats VDT with an exponential decay function, and the mileage degradation rate represents the rate of decay. In other words, mileage degradation rate is the distance by which a vehicle is driven less and less as it ages. The set value, 5%, indicates vehicle use declines 5% annually for all types of vehicles. The model holds the degradation rate constant over time both before and after base year 2010. I assume this because very little information on the degradation rate in China is available and the available sources conflict (Figure B-2). Converted into an average annual exponential decay, the vehicle emissions control data indicates mileage decreases 28% per year while Chinese field studies indicate more modest average annual declines of 4% and 8%, which are more in line with the US data of 8% per year (Huo et al., 2012c).

Powertrain marketshare mix

Powertrain marketshare model inputs are expressed as annual percentage point increases in sales marketshares by powertrain. These inputs, however, are two levels removed from sales marketshare ratios among powertrains and lack interpretability. I devise such powertrain sales marketshare ratios and then stepwise translate them to model inputs. These three sales marketshare ratios among powertrains include the ratio of turbo engines to NA-SI engines, the size of the electrified portion of the fleet, and the composition of the electrified portion of the fleet (Table B-7). While the reference, extreme high and extreme low scenarios in the sensitivity analysis in 8.2 combine all assumptions, the sensitivity analysis also breaks apart these assumptions and considers them separately.

I assume the same growth in turbocharged vehicles for all four vehicle types (Figure B-7). The low scenario assumes turbo growth will eventually break through to comprise 50% of NA-SI and turbocharged sales by 2050. However, a 50% sales ratio is achieved in 2030 in the reference scenario and even earlier in the high scenario.

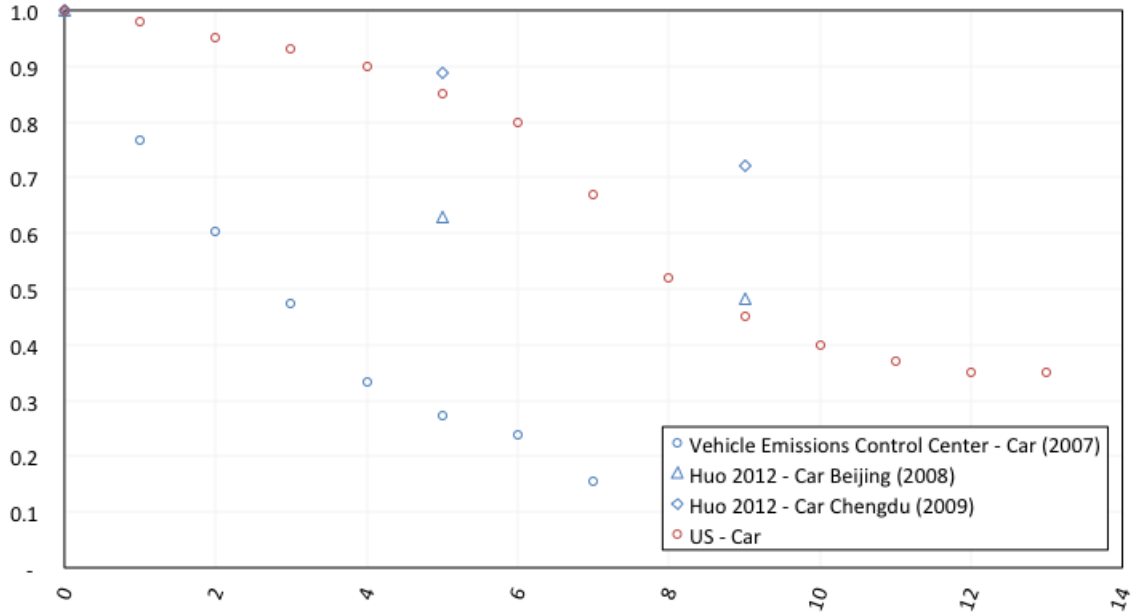


Figure B-2: Car mileage degradation over vehicle age by fraction of surviving vehicles.

While turbo powertrain growth can be projected using existing trends, powertrain electrification is more difficult to predict as there has been no fleet electrification to date. I consistently assume electrification is adopted earlier in the car and minibus fleet than the minitruck fleet. The reference scenario assumes a majority of EVs are HEVs. The high scenario is more radical: EVs dominate the electrified fleet and electrified powertrains dominate sales in 2050. A low scenario assumes no electrification at all, save the initial 2010 inputs. China's cars have not depended on diesel and there is no reason to believe they will. I assume they will remain at a 1% marketshare.

Diesel engines have a modest marketshare among minitrucks. When predicting future turbocharged engine growth, I have ensured that the ratio of diesel engines is constant in relation to the NA-SI and turbocharged vehicles.

I set annual percentage point increases in sales marketshares for different powertrains that meet the ratios among powertrains explained above (Table B-8 and B-9). Note that powertrain sales mixes are the same across both private cars and non-private cars. This may not be entirely correct: it is easy to imagine that the government purchases electric vehicles to stimulate private vehicle sales growth. However, it is a useful simplification.

These percentage point increases in sales also correspond with actual sales mixes that reveal interesting trends (Table B-10). First, the high electrification scenario assumes EVs dominate electrification among cars, but PHEVs dominate electrification among minitrucks. In addition, I reiterate here that the 0.1% of sales in 2010 that are hybrid electric, plug-in hybrid electric and electric vehicles are not based in data. Rather, 0.1% of sales effects miniscule differences in total energy demand predictions but creates a starting point from which to grow sales marketshares.

Powertrain Marketshares (%)	Reference	High	Low
Ratio of TC / (TC + NA-SI): all, 2030	50	67	33
Ratio of TC / (TC + NA-SI): all, 2050	67	90	50
% electrified: car & MB, 2030	15	30	~0
% electrified: car & MB, 2050	30	60	~0
% electrified: MT, 2030	10	25	~0
% electrified: MT, 2050	20	50	~0
HEV % of electrification: car & MB, 2030	67	33	n/a
HEV % of electrification: car & MB, 2050	50	20	n/a
HEV % of electrification: MT, 2030	70	40	n/a
HEV % of electrification: MT, 2050	65	25	n/a
% Diesel: Car, 2030	1	1	1
% Diesel: Car, 2050	1	1	1
% diesel: MB, 2030	0	0	0
% diesel: MB, 2050	0	0	0

Table B-7: Powertrain sales marketshare target ratios. Note that “electrified” refers to the sum of HEV, PHEV and EV. n/a refers to “not applicable” as there is no electrification.

Relative powertrain fuel consumption

Alternative powertrains are more energy efficient than the dominant NA-SI powertrain (Bandivadekar et al., 2008). Even in the future, as engine technology improves, alternative powertrains will remain more efficient than their NA-SI counterpart. Although the model varies future fuel consumption values, it keeps the relative fuel consumption among powertrains fixed (Table B-11). Note that the “1” for NA-SI is a placeholder: fuel consumption is expected to vary, but this is treated in the next section.

Future fuel consumption

The model interprets improved fuel consumption by the ratio for which future fuel consumption is lower than base year on-road fuel consumption (Table B-12). Base year NA-SI fuel consumption is 9.01 L / 100 km (on-road). As the reference scenario assumes fuel consumption will improve 10% by 2030 and 20% by 2050, relative to 2010, future fuel consumption will be 8.11 L / 100 km and 7.21 L / 100 km in 2030 and 2050, respectively. I also contextualize these results in annual percentage point reductions in fuel consumption.

My analysis shows fuel consumption decreased .77% per year between 2002 and 2010 (see Appendix C, Fuel consumption), and my reference scenario assumption is slightly more modest, while low and high scenarios are more and less aggressive, respectively. The derivation of 9.01 L / 100 km as a base-year on-road fuel consumption and 15.5% as an appropriate label to on-road adjustment factor are discussed in Chapter 6. I assume the 15.5% adjustment factor to be constant over time before and after base year 2010.

Table B-12 also shows that I assume private vehicles, non-private vehicles and minibuses have identical fuel consumption rates. This is likely incorrect. However, rather than using an arbitrary assumption (because I have no specific data), the model collapses together these vehicle categories. The model also assumes that vehicle fuel consumption stays constant as a given vehicle ages: hardware degradation does not increase fuel consumption.

These future fuel consumption scenarios concern cars and light duty buses. For minitrucks, I de-

Cars					Minitruck				
Annual growth in sales (%)	Reference	High	Low		Annual growth in sales (%)	Reference	High	Low	
Turbo, 2010-2014	18	18	16		Turbo, 2010-2014	30	30	25	
Turbo, 2015-2019	12.5	12.5	9		Turbo, 2015-2019	20.5	20.5	18	
Turbo, 2020-2029	5.5	6,6	5		Turbo, 2020-2029	17	18.25	16	
Turbo, 2030-2039	0.5	0	3		Turbo, 2030-2039	2	0	3.5	
Turbo, 2040-2050	0.5	-2,4	1.25		Turbo, 2040-2050	0.2	-1.1	0.9	
Diesel, 2010-2014	0	0	0		Diesel, 2010-2014	-1	-1.25	0	
Diesel, 2015-2019	0	0	0		Diesel, 2015-2019	-1	-1.25	0	
Diesel, 2020-2029	0	0	0		Diesel, 2020-2029	-1	-1.5	0	
Diesel, 2030-2039	0	0	0		Diesel, 2030-2039	-1	-1.75	0	
Diesel, 2040-2050	0	0	0		Diesel, 2040-2050	-1	-2	0	
HEV, 2010-2014	60	60	0		HEV, 2010-2014	60	60	0	
HEV, 2015-2019	30	30	0		HEV, 2015-2019	30	30	0	
HEV, 2020-2029	15	15	0		HEV, 2020-2029	11	15	0	
HEV, 2030-2039	3	1	0		HEV, 2030-2039	4	1.25	0	
HEV, 2040-2050	1	1	0		HEV, 2040-2050	2	1	0	
PHEV, 2010-2014	30	35	0		PHEV, 2010-2014	25	35	0	
PHEV, 2015-2019	25	25	0		PHEV, 2015-2019	20	25	0	
PHEV, 2020-2029	12	22	0		PHEV, 2020-2029	11	21	0	
PHEV, 2030-2039	7	6	0		PHEV, 2030-2039	6	7	0	
PHEV, 2040-2050	4	3	0		PHEV, 2040-2050	2.5	5.75	0	
EY, 2010-2014	30	35	0		EY, 2010-2014	25	35	0	
EY, 2015-2019	20	30	0		EY, 2015-2019	15	30	0	
EY, 2020-2029	11	25	0		EY, 2020-2029	9	20	0	
EY, 2030-2039	8	6	0		EY, 2030-2039	6	3	0	
EY, 2040-2050	4	3.25	0		EY, 2040-2050	2.5	2	0	

Table B-8: Powertrain sales marketshare assumptions.

Mimibus				
Annual growth in sales (%)	Reference	High	Low	
Turbo, 2010-2014	30	30	27	
Turbo, 2015-2019	20	21.5	19	
Turbo, 2020-2029	19.5	20	17.75	
Turbo, 2030-2039	1	0	3.5	
Turbo, 2040-2050	0.1	-2.3	1	
Diesel, 2010-2014	0	0	0	
Diesel, 2015-2019	0	0	0	
Diesel, 2020-2029	0	0	0	
Diesel, 2030-2039	0	0	0	
Diesel, 2040-2050	0	0	0	
HEV, 2010-2014	60	60	0	
HEV, 2015-2019	30	30	0	
HEV, 2020-2029	15	15	0	
HEV, 2030-2039	3	1	0	
HEV, 2040-2050	1	1	0	
PHEV, 2010-2014	30	35	0	
PHEV, 2015-2019	25	25	0	
PHEV, 2020-2029	12	22	0	
PHEV, 2030-2039	7	6	0	
PHEV, 2040-2050	4	3	0	
EV, 2010-2014	30	35	0	
EV, 2015-2019	20	30	0	
EV, 2020-2029	11	25	0	
EV, 2030-2039	8	6	0	
EV, 2040-2050	4	3.25	0	

Table B-9: Powertrain sales marketshare assumptions, continued.

	Car			Minitruck			Minibus		
	Reference	Low	High	Reference	Low	High	Reference	Low	High
NA-SI, 2020	68.6	67.4	78.2	66.8	65.7	70.2	86.9	85.3	92.4
NA-SI, 2030	41.8	22.7	66.0	35.4	18.7	41.6	42.2	23.2	66.8
NA-SI, 2050	22.9	3.8	49.8	21.7	3.8	38.3	23.2	4.0	49.6
Turbo, 2020	25.8	26.1	20.5	8.5	8.6	6.5	8.5	9.1	7.3
Turbo, 2030	42	46.3	43.2	35.6	38.8	35.1	42.6	46.8	32.9
Turbo, 2050	46.4	35.5	48.9	43.5	34.3	38.4	47.1	36.2	50.1
Diesel, 2020	1	1	1	20.8	20.2	23	0	0	0
Diesel, 2030	1	1	1	18.8	17.3	23	0	0	0
Diesel, 2050	1	1	1	15.4	11.9	23	0	0	0
HEV, 2020	2.80	2.8	0.1	2.70	2.8	0.1	2.80	2.8	0.1
HEV, 2030	10.14	9.94	0.1	7.19	9.97	0.1	10.14	9.94	0.1
HEV, 2050	14.76	12.13	0.1	12.72	12.44	0.1	14.76	12.13	0.1
PHEV, 2020	0.98	1.24	0.1	0.67	1.23	0.1	0.98	1.24	0.1
PHEV, 2030	2.90	7.85	0.1	1.83	7.30	0.1	2.90	7.85	0.1
PHEV, 2050	8.20	18.35	0.1	4.05	24.81	0.1	8.20	18.35	0.1
EV, 2020	0.79	1.54	0.1	0.54	1.48	0.1	0.79	1.54	0.1
EV, 2030	2.18	12.17	0.1	1.23	7.87	0.1	2.18	12.17	0.1
EV, 2050	6.71	29.24	0.1	2.73	12.76	0.1	6.71	29.24	0.1

Table B-10: Powertrain sales predictions.

FC relative to NA-SI	2010	2030	2050
NA-SI	1	1	1
Turbo	0.9	0.88	0.86
Diesel	0.84	0.84	0.84
HEV	0.7	0.7	0.7
PHEV	0.7	0.7	0.7

Table B-11: Relative future powertrain fuel consumption values, Bandivadekar et al. (2008).

Key NA-SI fuel consumption statistics	Reference	High	Low
Car & MB, 2030/2010 FC ratio	.9	.75	.95
Car & MB, 2050/2010 FC ratio	.8	.6	.9
MT, 2030/2010 FC ratio	.9	.75	.95
MT, 2050/2010 FC ratio	.8	.6	.9
Car & MB, annual change in FC (%), 2010-2029	-0.53	-1.43	-0.26
Car & MB, annual change in FC (%), 2030-2050	-0.59	-1.11	-0.27
MT, annual change in FC (%), 2010-2029	-0.53	-1.43	-0.26
MT, annual change in FC (%), 2030-2050	-0.59	-1.11	-0.27
Car & MB, on road FC (L/100 km), 2030	8.11	6.76	8.56
Car & MB, on road FC (L/100 km), 2050	7.21	5.41	8.11
MT, on road FC (L/100 km), 2030	10.18	8.49	10.75
MT, on road FC (L/100 km), 2050	9.05	6.79	10.18

Table B-12: Future NA-SI fuel consumption assumptions.

Electric Motor Efficiency (kWh/km)	Reference	Low	High
Car and minibus, 2010	0.150		
Car and minibus, 2030	0.113	0.095	0.120
Car and minibus, 2050	0.089	0.067	0.099
Minitruck, 2010	0.203		
Minitruck, 2030	0.162	0.135	0.171
Minitruck, 2050	0.128	0.096	0.135

Table B-13: Electric motor engine efficiency.

rive an 8.02% difference in fuel consumption rates in Appendix C, Fuel consumption, apply it to all powertrains, and assume this value constant before and after base year 2010.

Electric motor efficiency and use

Electric powertrains have different fuel consumption and efficiency metrics than their combustion engine alternatives. I assume that relative efficiency across scenarios varies in proportion to ICE efficiency. However, I set 2010 electric motor efficiency and expected efficiency increases for the reference scenario independently of other fuel consumption improvements (Table B-13). I derive these values from a recent National Academies of Science report (2013). The high and low electric motor scenarios are equally stringent or lax as different NA-SI fuel consumption scenarios are to each other - .095 kWh/km is .75/.9 of .113, for instance.

For electric engine utilization rates, I fix rates for plug-in hybrids across scenarios, but assume utilization rates improve over time. Today, electricity powers plug-in hybrids at most 30% of the time, and often less (Zoepf et al., 2013). I assume 30% as a starting value but assume technology improves and utilization rates rise to 50% in 2030 and 60% in 2050. The model linearly extrapolates the values for the years in between.

Fleetwide FC, car & MB	Model year 2010	Model year 2030	Model year 2050
	On-road fuel consumption (L / 100 km)		
Reference	8.92	6.14	4.69
Low		4.25	2.10
High		7.06	6.51
High turbo		6.02	4.55
Low turbo		6.26	4.79
High electrification		5.37	3.22
No electrification		6.58	5.64
Electrification, only HEV		6.23	5.28
Electrification, most EV + PHEV		5.96	4.37
High electrification, most HEV		5.66	3.61
Large change in FC		5.11	3.52
Small change in FC		6.48	5.28

Table B-14: Fleetwide fuel consumption for sensitivity analysis.

Fleetwide fuel consumption

Measuring fleetwide fuel consumption is another way to compare the inputs of the different alternative scenarios in the sensitivity analysis (Table B-14). This measures the average fuel consumption of all vehicles sold in a given year, thus combining the effects of technology improvements in fuel consumption for different powertrains with changes in the sales mix towards powertrains with lower fuel consumption. Base year 2010 fleetwide fuel consumption is 7.72 L / 100 km (label) and 8.92 L / 100km. Note that fuel consumption is not listed for all pathways: individual scenarios that affect neither powertrain sales marketshares nor the rate of fuel consumption change share the reference case's fleetwide fuel consumption projections.

Fuels

I implement two alternative fuels in the fleet model: methanol and natural gas. The model input quantifies how many vehicles compatible with an alternative fuel do run on an alternative fuel (Table B-15). A value of 10% indicates that 10% (in any combination) of NA-SI, Turbo, HEV and PHEV powertrains rely on alternative fuel and thus alternative fuels replace 10% of gasoline equivalent energy demand. Total fleet wide energy demand remains constant because I assume equivalent energy efficiency for engines powered on gasoline, methanol or natural gas. I derive base year fuel share values for different powertrains in Appendix C, Fuel shares. Finally, this model does not implement Diesel-HEV or Diesel-PHEV vehicles: all electric powertrains use electricity or gasoline as fuel.

I also set energy density values for the various fuels used in the study (Table B-16). I calculated values for gasoline, methanol and diesel with specific gravity and lower heating values from (Heywood, 1988, pg 914). This means the energy content 1 L of gasoline is equivalent to 1.43 L of ethanol and 1.86 L of methanol.

Fuel CO₂ intensity

Although fuel carbon intensity values can vary significantly from one means of extraction to another, I assume a fixed carbon intensity value for a given fuel and calendar year (Table B-17). Lifecycle CO₂

Contribution: gasoline equivalent fuel demand (%)	Reference	High	Low
Methanol, 2010	0		
Methanol, 2030	3	5	0
Methanol, 2050	5	15	0
CNG, private car, 2010	0		
CNG, private car, 2030	2	10	0
CNG, private car, 2050	4	10	0
CNG, non-private car, 2010	4.1		
CNG, non-private car, 2030	20	40	5
CNG, non-private car, 2050	30	50	6
CNG, minitruck and minibus, 2010	0		
CNG, minitruck and minibus, 2030	2	10	0
CNG, minitruck and minibus, 2050	4	10	0

Table B-15: Alternative fuel assumptions.

Fuel	Gasoline	Methanol	CNG	Diesel	Electric power
Energy content	33.4 MJ/L	18 MJ/L	38 MJ/m ³	35 MJ/L	3.6 MJ / kWh

Table B-16: Fuel energy content values.

g CO ₂ / MJ	2010	2030	2050
Gasoline	98.6	98.6	98.6
Diesel	102.4	102.4	102.4
Methanol	304.4	191.1	119.9
Natural Gas	72.7	72.7	72.7
Electricity	264.9	179.3	121.9

Table B-17: Fuel CO₂ intensity predictions.

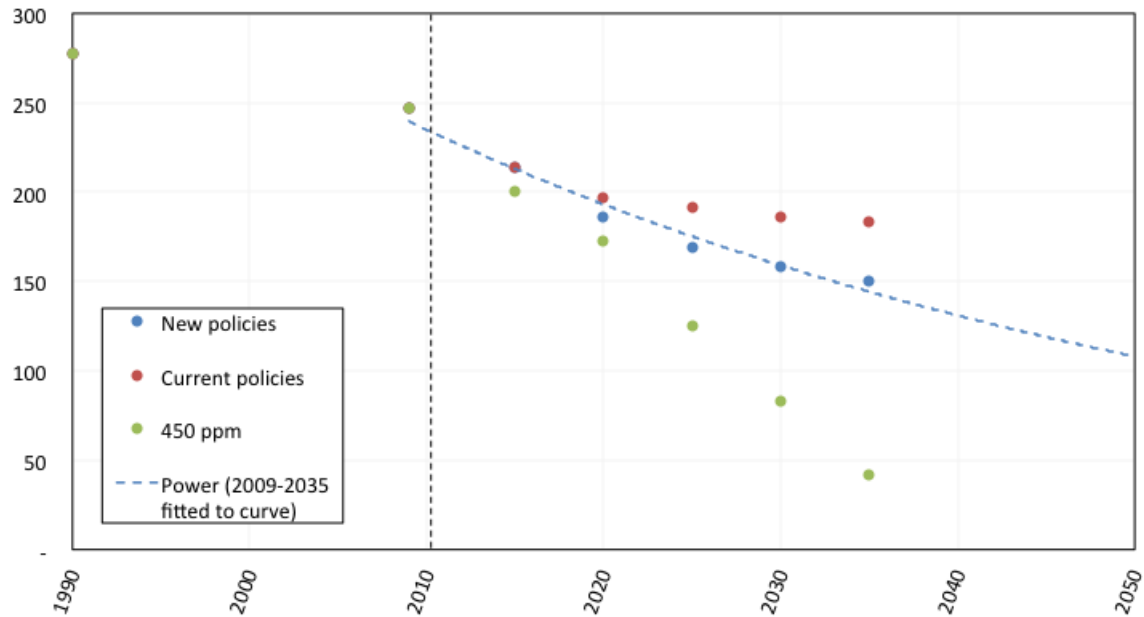


Figure B-3: Electric grid CO₂ intensity. Source: author analysis base on IEA, 2012a.

emission intensity for gasoline, diesel and natural gas values are constant over time. However, coal to methanol conversion will improve over the coming decades. I derive a predicted annual decrease in coal-derived methanol lifecycle CO₂ emissions intensity from the historical 2008 and predicted 2020 values in Ou et al. (2012). I extrapolate this improvement factor to 2050 to generate yearly methanol lifecycle CO₂ intensity values. For electricity, I use the IEA's World Energy Outlook predictions to project CO₂ intensity values for China's electric power generation (See Figure B-3, IEA (2012a)). I converted the statistics from tons CO₂/ MWh to g CO₂/ MJ and fitted a power regression to the "new policy" scenario with base year 2009 and projections to 2030.³ Extending the projection to 2050, applying a 7% transmission loss (Yan and Crookes, 2009), and a 10% charging loss (Bandivadekar et al., 2008) generated yearly CO₂ emissions intensity projections for electric powertrains.

³ fitted relationship is $CO_2 \text{ intensity} = (4E + 132)x^{-39.41}$

Appendix C

Historical model inputs

Model inputs include both long term historical values and single base year values. Sources include both direct historical statistics, field studies in literature, and values extrapolated from one or a few years of data.

Sales

I source historical sales data from the 2011 CAIY from car, minitruck and minibus columns (Table C-1).

Stock

I use historical stock data from the 2011 China Statistical Yearbook to calculate the historical percentage of car stock private (C-2). The China Statistical Yearbook and CAIY statistics on sales do not accord for minitruck and minibus categories. Because of these differences, I do not calibrate model predicted stock with China Statistical Yearbook stock.

For VDT and fuel share inputs, I need to take taxi stock into account. The 2008 China City Statistical Yearbook reports taxi stock for all prefecture level cities (Table C-3), and I calculate taxi stock as a fraction of the model's historical non-private vehicle stock. Fitting an exponential curve to taxi stock as a fraction of non-private vehicle stock allows for near term forecasts, relevant for VDT calculations (Figure C-1).

Private and non-private cars

Having derived private car and non-private car stock in Table C-2, I set historical ratios for private and non-private car sales in the model to generate appropriate ratios for non-private and private car stock (Table C-4 and C-5). Because small and mini passenger vehicles from the China Statistical Yearbook correspond roughly with the passenger car category from the CAIY, this comparison is valid.¹ The stock ratios track within 1 percentage point of each other (Figure C-2).

¹Although minibuses are included among small and mini passenger vehicles and a higher fraction are likely private than among cars because cars includes government sedans and taxis, because I have no specific information, I exclude them. Therefore, the % of car sales that are private used in the model may be somewhat lower than in reality.

Year	Car	Minitruck	Minibus
1996	.386	0.142	0.169
1997	.480	0.150	0.210
1998	.507	0.146	0.257
1999	.570	0.137	0.293
2000	.613	0.132	0.410
2001	.721	0.140	0.489
2002	1.13	0.147	0.631
2003	1.97	0.137	0.696
2004	2.33	0.171	0.742
2005	2.79	0.233	0.831
2006	3.83	0.291	0.918
2007	4.73	0.315	0.988
2008	5.05	0.361	1.06
2009	7.47	0.505	1.95
2010	9.49	0.612	2.49

Table C-1: Historical light duty vehicle sales. Source: China Automotive Industry Yearbook (2011b).

Year	Small & mini	Private small & mini	% private vehicles
2002	10.22	5.78	56.6
2003	12.87	7.96	61.8
2004	15.33	10.15	66.2
2005	19.19	13.25	69.1
2006	23.95	17.56	73.3
2007	29.62	22.53	76.1
2008	35.95	28.13	78.3
2009	45.61	37.40	81.5
2010	58.62	49.19	83.9

Table C-2: Historical vehicle stock. Source: author analysis and China Statistical Yearbook (2011a).

Year	Non-private vehicle	Taxi
1997	1.070	.614
1998	1.310	.502
1999	1.546	.654
2000	1.762	
2001	1.972	.712
2002	2.252	.757
2003	2.668	.779
2004	3.148	.792
2005	3.635	.783
2006	4.171	
2007	4.701	.804
2008	5.253	.819

Table C-3: Taxi and non-private vehicle stock. Source: China City Statistical Yearbook (1997-1999, 2001-2005, 2007-2008).

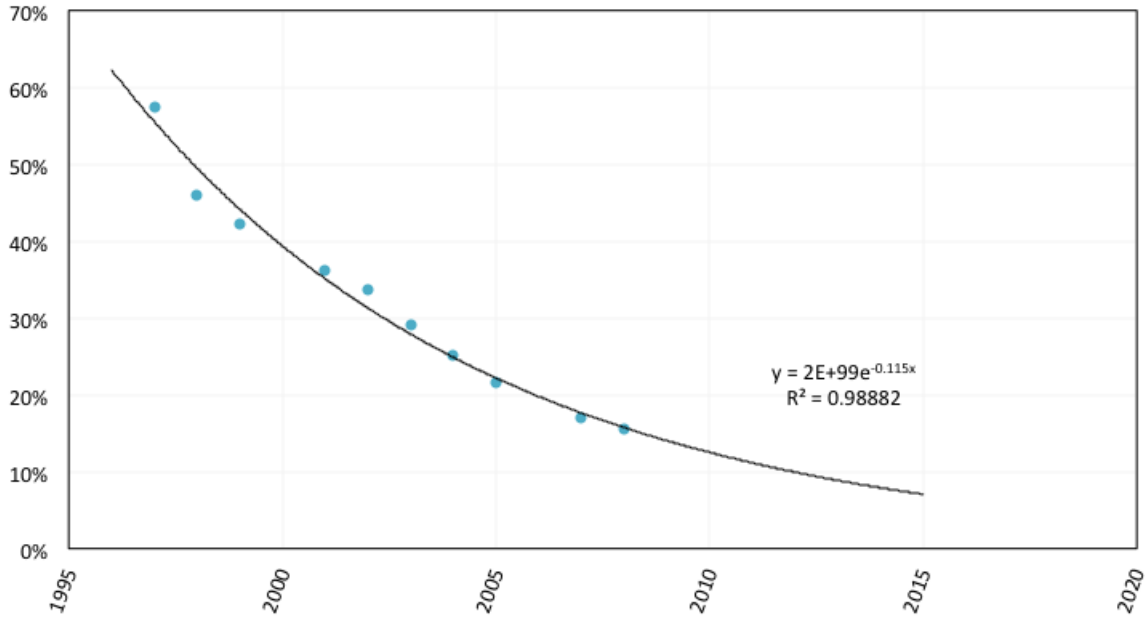


Figure C-1: Taxis as fraction of non-private vehicles.

% Private cars of cars	2002	2003	2004	2005	2006	2007	2008	2009	2010
Model	57.4	62.6	66.1	69.3	72.9	76.3	78.5	81.4	83.5
Data	56.6	61.8	66.2	69.1	73.3	76.1	78.3	81.5	83.9

Table C-4: Ratio of private cars to cars in vehicle stock.

Year	1995 -	1996	1997	1998	1999	2000	2001	2002	2003
% private of all cars	45	50	50	50	55	60	65	70	75
	2004	2005	2006	2007	2008	2009			
	75	78	82	85	85	89			

Table C-5: Ratio of private cars to cars in sales.

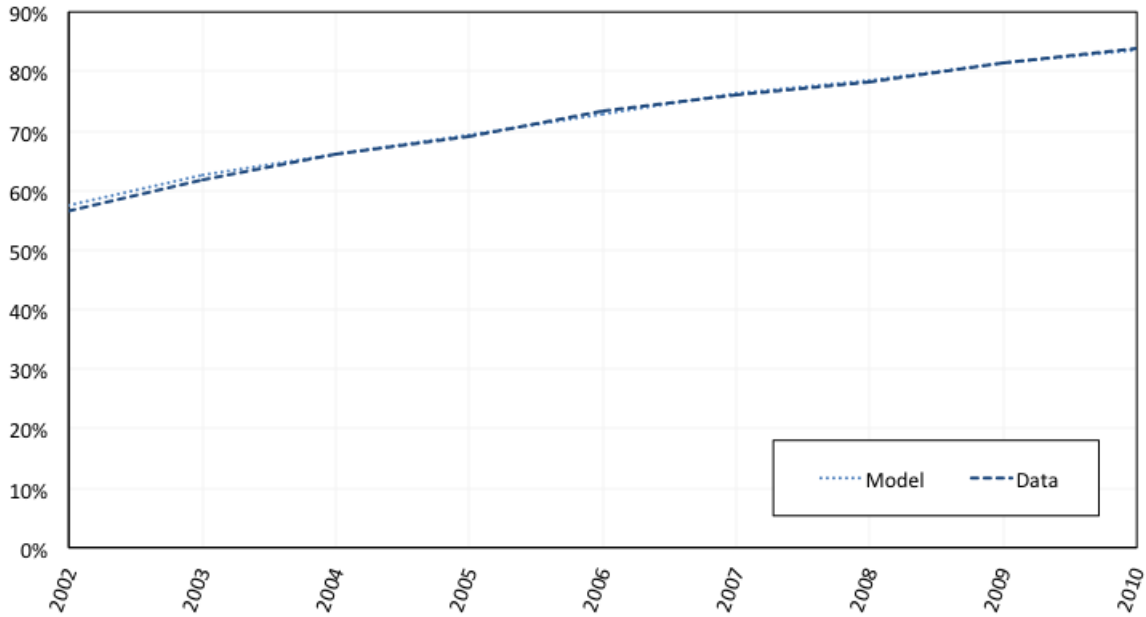


Figure C-2: Ratio of private cars to cars in stock.

	Private car	Non-private car	Minitruck	Minibus
2000 new car VDT	20250	45000	29000	25000
1991-1999 (%)	-2.3%	-2.3%	-1.8%	-2.3%
2000-2004 (%)	-1.75%	-3.5%	-1.2%	-1.0%
2005-2009 (%)	-1.5%	-3%	-0.65%	-1.0%

Table C-6: Historical VDT input values.

VDT

Field studies conducted since 2000 give clues to annual vehicle distance traveled per vehicle type over the past ten years. Both Huo et al. (2012c) and Hao et al. (2011a) provide their estimates for annual VDT for both private light duty vehicles and business light duty vehicles based upon several field studies, many of which the authors conducted themselves. Huo et al. (2012c) also report taxi VDT values over time. Although taxis accounted for just 16% of the non-private car population in 2008 (see Table C-3), because their average annual VDT per vehicle was nearly 100 000 km, the non-private car category VDT is sensitive to taxi VDT.

Available data on small truck VDT is scarce. Two studies assume 30 km/year/vehicle and 20 km/year/vehicle, respectively (Huo et al., 2012c; Ou et al., 2010b). Minibus VDT is not available.

The model inputs include base year new vehicle VDT, mileage degradation rate and percent annual change in VDT (Table C-6). These were set to generate annual average VDT values per vehicle from 2000 to 2010 that corresponded with available sources (Figure C-4). For private cars, I assumed VDT was in between the values of two available sources (Huo et al., 2012c; Hao et al., 2011a). For non-private cars, I used a weighted average of taxi VDT and business car VDT. I derived business VDT by taking a rough average of two available sources (Huo et al., 2012c; Hao et al., 2011a). For taxi VDT, I took a linear trendline fit of the available source that incorporated changes over time (Huo et al. (2012c)). I then used values from the exponential relationship used to describe taxi stock as a fraction of the non-private

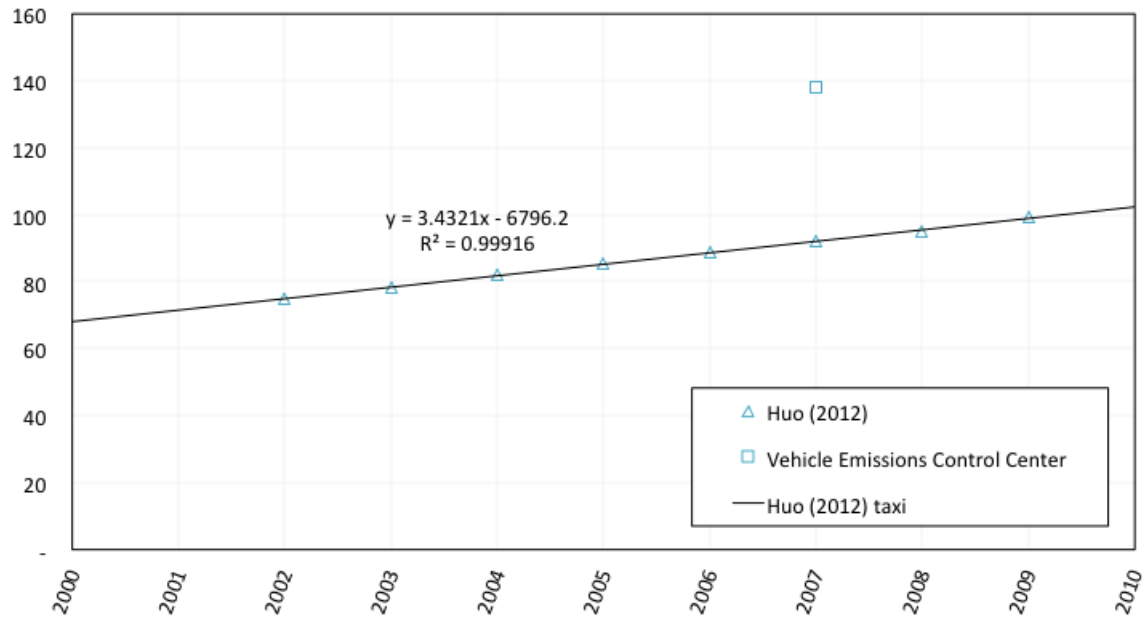


Figure C-3: Taxi VDT in thousand km per vehicle per year.

Year	Private car	Non-private car	Minitruck	Minibus
2000	18683	41037	26396	22370
2001	18236	39702	25392	21999
2002	17948	38501	25530	21705
2003	17808	37451	25149	21350
2004	17519	36387	24887	21004
2005	17205	35302	24802	20667
2006	16939	34244	24761	20333
2007	16654	33179	24632	19994
2008	16302	32132	24469	19657
2009	16053	31111	24395	19626
2010	15896	30326	24282	19604

Table C-7: Historical model VDT.

vehicle stock (Figure C-1) to derive a weighted average of the business cars and taxis. This became the model's non-private car category VDT.

I assume minitruck VDT shows the same declining trend over time, and also assume it is in between the two available datapoints from other sources. Without available data on minibus VDT, I assume it was similar to business car VDT. See Table C-7 and Figure 5-1 for an overview of all model vehicle types.

For all vehicle types, I assumed average historical VDT values had been declining through the 1990s. Regardless, the fraction of 1990s model year vehicles remaining in 2010 have low annual VDT values compared with new vehicles and are also few in number. They have essentially no impact on model energy demand results, irrespective of VDT.

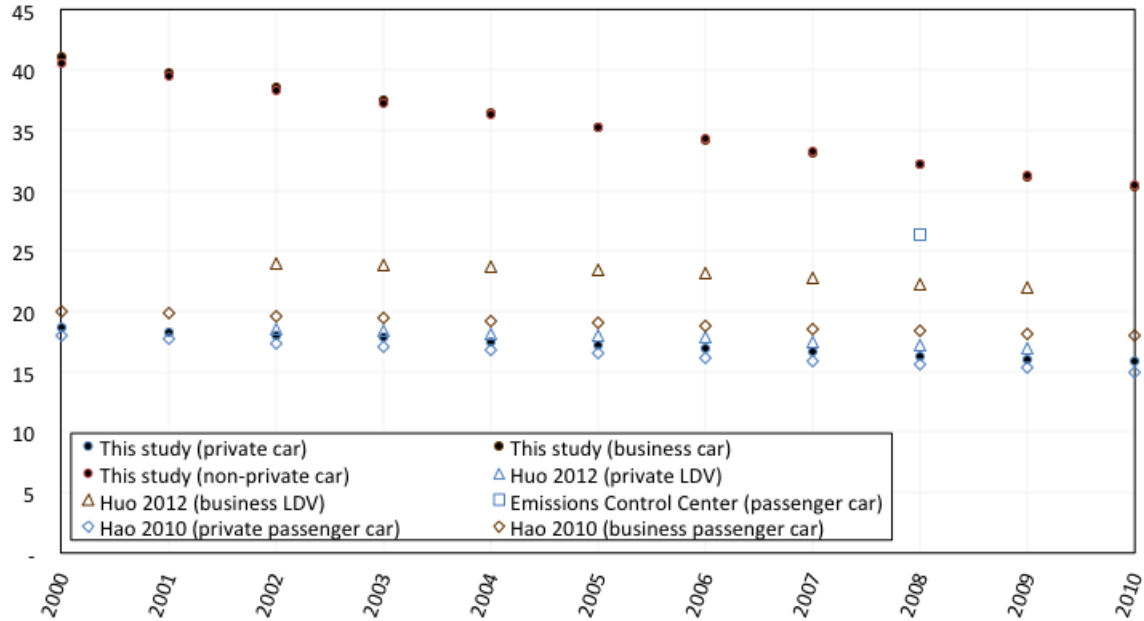


Figure C-4: VDT comparison across models in thousand km per vehicle per year.

Vehicle type	NA-SI	Turbo	Diesel	HEV	PHEV	EV
Private car	91.7	7	1	0.1	0.1	0.1
Non-private car	91.7	7	1	0.1	0.1	0.1
Minitruck	75.7	1	23	0.1	0.1	0.1
Minibus	98.7	1	0	0.1	0.1	0.1

Table C-8: Base year powertrain sales marketshares.

Powertrain mix

He and Tu (2012) report 7% of Chinese passenger cars are turbocharged in 2010, Ou et al. (2010b) and Huo et al. (2012b) explain 1% of passenger cars in 2006, 2007 and 2008 and private passenger cars in 2010 use diesel engines, respectively. I use this to generate base year powertrain sales mixes for cars (Table C-8). I approximate HEV, PHEV and EV as 0%, but allocate 0.1% each to provide a base value off which to grow sales. Huo et al. (2012a) provides information on gasoline and diesel engine shares for trucks under 1800 kg (see Table 6-2), and Ou et al. (2010b) report all minibuses use gasoline. I assume turbocharged vehicles are less common among these vehicle types because JV manufacturers, who employ more advanced technology, do not hold high marketshares among these categories. The model only incorporates NA-SI and diesel powertrains prior to base year 2010, and I allocate historical powertrain sales marketshares accordingly (Table C-9).

Fuel consumption

Using available literature data on Chinese average passenger car fleet fuel consumption, I regress a linear fit of the datapoints that span the years 2002 to 2010:

$$\text{Fuel consumption} = -0.0766 \times \text{year} + 161.79 \quad (\text{C.1})$$

Vehicle type	NA-SI	Turbo	Diesel	HEV	PHEV	EV
Private car	99	0	1	0	0	0
Non-private car	99	0	1	0	0	0
Minitruck	77	0	23	0	0	0
Minibus	100	0	0	0	0	0

Table C-9: Historical powertrain marketshares before 2010.

Car and minibus FC	Fuel consumption (L/100km)
Fleetwide (label)	7.72
Fleetwide (on-road)	8.92
NA-SI	9.01
Turbo	8.11
Diesel	7.57
HEV	6.31
PHEV	6.31

Table C-10: Base year car fuel consumption.

This generates the base value 7.72 L / 100 km (TableC-10). This is label fuel consumption and I use a 15.5% adjustment factor (Huo et al., 2011) to derive on-road fuel consumption of 8.92 L / 100 km for model year 2010 vehicles. Using 2010 sales marketshares and predetermined relative fuel consumption values among powertrains, I thereafter calculate fuel consumption for each powertrain to generate base year model inputs. I assume identical fuel consumption for private cars, non-private cars and minibuses.

Gasoline and diesel powered minitruck label fuel consumption was 7.96 L / 100 km and 7.84 L / 100 km in 2009, respectively (Huo et al. (2012a)). This is an average sales-weighted fuel consumption of 7.93 L / 100 km. I recalculated the average efficiency for each of the two powertrains based upon my 0.84 relative fuel consumption ratio of diesel engines to gasoline engines. This gives 8.24 L / 100 km and 7.08 L / 100 km for gasoline and diesel engines, respectively. This recalculation ensures minitruck diesel and gasoline engines are equally distributed across all minitruck weights. I calculate an adjustment factor of 8.02% between diesel cars and minitrucks using diesel label fuel consumption values (7.08 L / 100 km and 6.56 L / 100 km)². I use this adjustment factor to generate on-road base year minitruck fuel consumption values for all powertrains from corresponding car on-road fuel consumption values (Table C-11)

The model only includes gasoline and diesel powertrains prior to 2010. I assume fuel consumption

²I calculate label diesel car fuel consumption by assuming on-road car diesel fuel consumption of 7.57 L / 100 km is 15.5% higher than label fuel consumption. 6.56 L / 100 km is from Table C-10

Minitruck	Fuel consumption (L/100km)
Gasoline (label)	8.24
Diesel (label)	7.08
NA-SI (on-road)	9.73
Turbo (on-road)	8.76
Diesel (on-road)	8.18
HEV (on-road)	6.82
PHEV (on-road)	6.82

Table C-11: Minitruck base year fuel consumption.

Fuel	Private car	Non-private car	Minitruck	Minibus
Gasoline	100%	95.9%	100%	100%
CNG	0%	4.1%	0%	0%
Methanol	0%	0%	0%	0%

Table C-12: Base year fuel shares.

increases linearly prior to 2010 according to the regressed linear equation I use the regressed linear equation (EquationC.1) relating fuel consumption and year to calculate label fuel consumption for gasoline vehicles prior to 2010. I use the derived scaling factors of 15.5%, 8.02% and 0.84 to convert to on-road fuel demand, minitrucks and diesel engines, respectively.

Fuel shares

Huo et al. (2012b) reports that CNG vehicles powers 26% of taxis in China, but no private light duty vehicles or business light duty vehicles. The 820 000 taxis in China in 2008 (China City Statistical Yearbook, 1997-1999, 2001-2005, 2007-2008) accounted for 15.6% of the non-private car fleet. I thus assume that among the NA-SI, turbo, HEV, and PHEV fleet, gasoline powered 100% of private cars, minitrucks and minibuses in 2010, but only 95.9% of non-private cars (Table C-12).

Appendix D

China Daily articles

Links to the articles collected to create Figure 4-6 are listed below together with the forecast source, if available.

- From VW: www.chinadaily.com.cn/en/doc/2002-04/24/content_117012.htm
- From Autopolis: www.chinadaily.com.cn/en/doc/2002-10/15/content_139540.htm
- No source for forecast: www.chinadaily.com.cn/en/doc/2003-07/07/content_243364.htm
- From government: www.chinadaily.com.cn/en/doc/2004-01/02/content_295146.htm
- From Machine Industry Federation: www.chinadaily.com.cn/english/doc/2004-06/08/content_337404.htm
- No source for forecast: www.chinadaily.com.cn/english/doc/2004-09/09/content_372882.htm
- No source for forecast: www.chinadaily.com.cn/english/doc/2004-11/10/content_389993.htm
- From Toyota: www.chinadaily.com.cn/english/doc/2004-11/26/content_394945.htm
- No source for forecast: www.chinadaily.com.cn/english/doc/2005-10/21/content_486648.htm
- From government: www.chinadaily.com.cn/english/doc/2005-11/16/content_494969.htm
- From government: www.chinadaily.com.cn/english/doc/2005-12/28/content_507183.htm
- No source for forecast: www.chinadaily.com.cn/cndy/2006-08/24/content_672639.htm
- From CSM Worldwide: www.chinadaily.com.cn/cndy/2007-07/18/content_5438181.htm
- From General Motors: www.chinadaily.com.cn/cndy/2009-10/30/content_8870908.htm
- From JD Power: www.chinadaily.com.cn/cndy/2009-11/25/content_9041441.htm