

China Vehicle Fleet Model: Estimation of Vehicle Stocks, Usage, Emissions, and Energy Use

Model Description, Technical Documentation, and User Guide

Energy Systems Division

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China Vehicle Fleet Model: Estimation of Vehicle Stocks, Usage, Emissions, and Energy Use

Model Description, Technical Documentation, and User Guide

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ACRONYMS

AAGR	Annual average growth rate
BDS	BeiDou Navigation Satellite System
BEV	Battery electric vehicle
CAAM	China Association of Automobile Manufacturers
CAFC	Corporate Average Fuel Consumption
CAFE	Corporate Average Fuel Economy
CAPI	Cheshi Auto Price Index
CATARC	China Automotive Technology and Research Center
CD	Charge-depleting
CERC-CVC	U.S.-China Clean Energy Research Center
CH ₄	Methane
CKD	Completely knocked down
CNG	Compressed natural gas
CO ₂	Carbon dioxide
CPCA	China Passenger Car Association
CS	Charge-sustaining
DME	Dimethyl ether
DOE	U.S. Department of Energy
EERE	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EIU	Economist Intelligence Unit
EtOH	Ethanol
FCR	Fuel consumption
FCV	Fuel cell vehicle
FE	Fuel economy
FEEI	Fuel Economy and Environmental Impacts model
FTD	Fischer-Tropsch diesel
GDP	Gross domestic product
GHG	Greenhouse gas
GPS	Global Positioning System
GREET [®]	Greenhouse gases, Regulated Emissions, and Energy use in Transportation [®]
GVW	Gross vehicle weight
GWP	Global warming potentials
HDT	Heavy-duty truck
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicles
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund

IPCC	Intergovernmental Panel on Climate Change
LDPV	Light-duty passenger vehicle
LDT	Light-duty truck
LHV	Lower heating value
LNG	Liquefied natural gas
MDT	Medium-duty truck
MeOH	methanol
MIIT	Ministry of Industry and Information Technology of China
MiniT	Mini truck
MIT	Massachusetts Institute of Technology
MJ	Megajoule
MoT	Ministry of Transport of China
MPV	Multi-purpose vehicle
MY	Model year
N ₂ O	Nitrous oxide
NEDC	New European Driving Cycle
NEV	New energy vehicle
NG	Natural gas
NMSAC	National Manufacturing Strategy Advisory Committee
OECD	Organization for Economic Co-operation and Development
PHEV	Plug-in hybrid electric vehicle
PTW	Pump-to-wheels
RMB	Renminbi, the official currency of the People's Republic of China
SAE China	Chinese Society of Automotive Engineers
toe	Tonnes of oil equivalent
UF	Utility factor
US\$	U.S. dollar, the official currency of the United States
USEPA	United States Environmental Protection Agency
VCW	Vehicle curb weight
VKT	Vehicle kilometers traveled
VPI	Vehicle price index
VTO	U.S. Department of Energy, Vehicle Technologies Office
WTP	Well-to-pump
WTW	Well-to-wheels

1 INTRODUCTION

With fast economic growth, urbanization, and industrialization, China has experienced rapid expansion in the on-road transportation sector in the past three decades. The highway vehicle population in China increased from 1.65 million in 1980 to 208 million in 2017 with an annual average growth rate (AAGR) of about 14% [1]. Since 2009, China has surpassed the United States as the largest vehicle market in the world, and over 28.5 million highway vehicles were sold in 2017 [2]. With such rapid development in the on-road transportation sector, Chinese petroleum consumption, as well as related greenhouse gas (GHG) emissions, continue to increase and are of great interest to governments, industries, and researchers. To relieve foreign energy dependence and environment pollution from rising oil demand and GHG emissions in the transportation sector, the Chinese government has implemented a series of standards to lower the fuel consumption of highway vehicles since 2005, and has been actively promoting the development and the deployment of new energy vehicles (NEV, i.e., battery electric vehicles, plug-in hybrid electric vehicles, and fuel cell electric vehicles) and alternative transportation fuels to reduce petroleum fuel use. Under these circumstances, it is important to develop modeling capabilities for the Chinese vehicle fleet to examine vehicle fleet turnover pace, future energy use, and GHG emissions, especially the capability to assess the energy and environmental impacts from the deployment of different advanced vehicle technologies and alternative transportation fuels.

This report introduces the China Vehicle Fleet Model developed by Argonne National Laboratory (Argonne). The model includes different vehicle classes, their market shares, fleet turnover, and estimation of long-term energy use and GHG emissions associated with the vehicle fleet in China up to the year 2050. The model also aims to evaluate the impacts of alternative vehicle technologies, alternative fuels, future regulations, and potential policies on the energy use and GHG emissions of the Chinese highway transportation sector. It uses the well-to-pump (WTP) energy use and GHG emission intensities derived from a life-cycle transportation model named China-GREET, which is developed based on Argonne's U.S. GREET[®] (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model to reflect specific energy/fuel production pathways in China.

The China Vehicle Fleet Model is based on Argonne's VISION model [3], which is a vehicle fleet model for the United States, and earlier versions of the Chinese models developed by Argonne and Tsinghua University [4-8]. The structures, methodologies, and interfaces of these previous models were systematically reviewed, updated, modified, and/or redesigned in the new fleet model to reflect the vehicle classification and public data availability of the current Chinese vehicle fleet.

The China Vehicle Fleet Model is a user-friendly spreadsheet-type tool built with Microsoft Excel to maximize the transparency and the accessibility of the methodology, data, assumptions, and results. By default, Argonne has configured a *Base Case* in the model, deriving the historical inputs from publicly available data sources. For future projections of the Chinese vehicle market, the fuel consumption rates and market shares of individual vehicle technologies for model years up to 2030 are based on the *Technology Roadmap for Energy Saving and New Energy Vehicles* released by the Chinese Society of Automotive Engineers in October 2016 [9]. All other projections in the *Base Case* reflect Argonne's up-to-date research on future Chinese policies, regulations, and standards. Figure 1 shows some *Base Case*

results from the model. The model also allows a user to configure a *Scenario Case* in parallel with the *Base Case* for easy comparison.

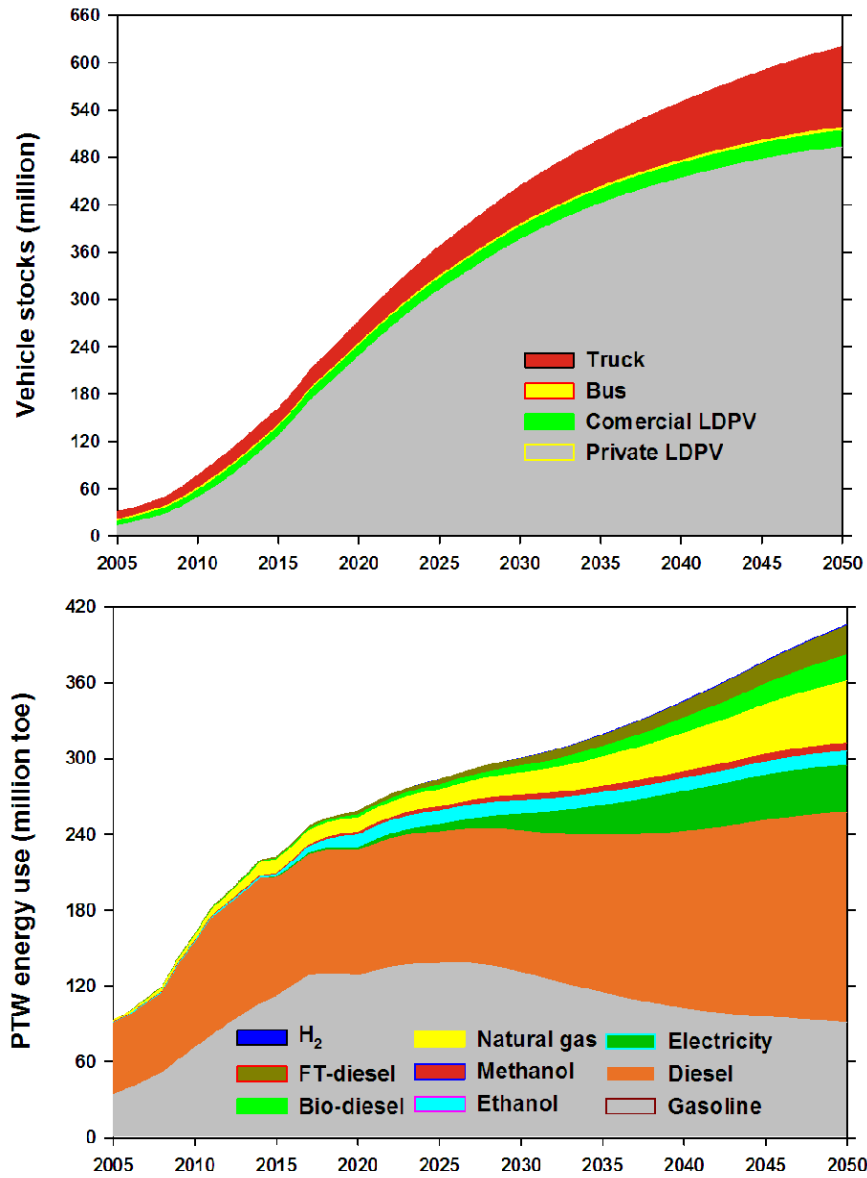


Figure 1. Sample results from the China Vehicle Fleet Model in the *Base Case*.

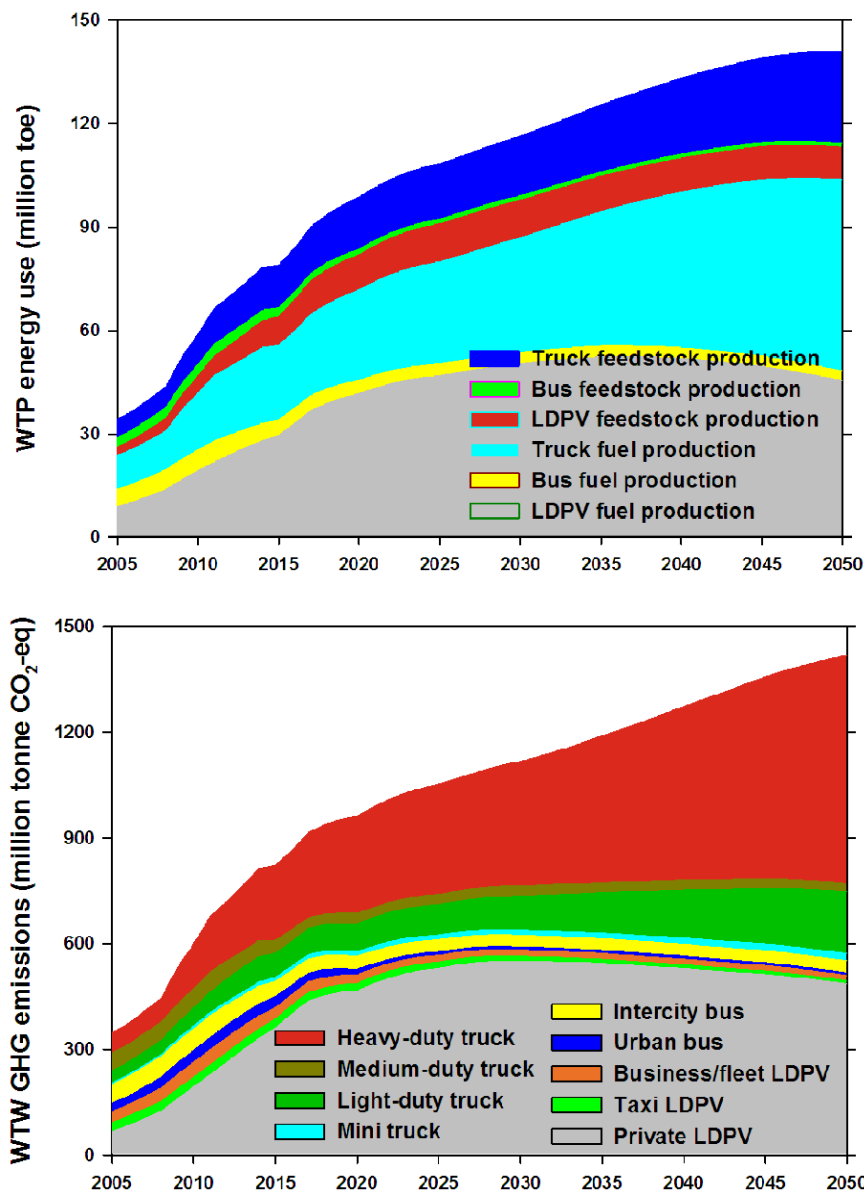


Figure 1. Continued. Sample results from the China Vehicle Fleet Model in the *Base Case*.

Argonne National Laboratory developed the technical documentation and user guide described in this report for the beta version of the China Vehicle Fleet Model released in October 2018. Revisions and updates to the current beta version will continue in the future. Section 2 provides a quick guide to start reviewing the model's structure, features, inputs, and results. Section 3 documents the methodology and data sources for the model. The user guide in Section 4 provides detailed instructions for interacting with individual worksheets and running the model.

2 QUICK REFERENCE GUIDE TO THE CHINA VEHICLE FLEET MODEL

This section provides a quick overview of the technical requirements, structure, and main features of the China Vehicle Fleet Model. A detailed user guide for the model is available in Section 4.

2.1 GETTING STARTED

The China Vehicle Fleet Model is a spreadsheet-type model developed using Microsoft Excel 2016. The model has been tested with Microsoft Excel 2010 and later versions in Windows operating systems. It has not been tested with earlier versions of Excel or in other operating systems. When opening the model file, if Excel asks whether you want to enable the macro functions built into the model, you should click the *Enable* button so that the macro functions embedded in the model can operate properly. By default, the *manual* calculation feature of Excel is enabled to improve the model performance. When the model file is closed, Excel's calculation mode (i.e., *manual* or *automatic* calculation) returns to its original status before the model was opened.

- [Overview](#) worksheet (white background) presents the China Vehicle Fleet Model's copyright statement, the model introduction, and a brief description of individual worksheets.
- [Index](#) worksheet (light red background) includes hyperlinks to all worksheets, all inputs and results sections of the model, and a color-coding legend section for cells.

2.2 MODEL INPUTS

The China Vehicle Fleet Model has five input worksheets (light yellow background) that present key control variables and key input parameters and assumptions:

- [Inputs VType](#) worksheet contains inputs at the vehicle type level, such as vehicle stocks, sales, etc. It also provides options for the calculation methods for vehicle sales and vehicle stocks.
- [Inputs VTechnology](#) worksheet contains inputs at the vehicle technology level, such as vehicle technology market shares, survival patterns, vehicle kilometers traveled (VKT), fuel consumption rates, etc.
- [Inputs Upstream](#) worksheet contains inputs related to end-use fuels/energies and their upstream information, such as alternative fuel blending levels, GHG emission intensities, energy use intensities, etc. These inputs are derived from China-GREET — a life-cycle model for vehicle/fuel systems in China based on Argonne's GREET[®] model.
- [Macro Data](#) worksheet contains macro-socioeconomic data.
- [Fuel Specification](#) worksheet contains specifications for individual fuels and unit conversion factors, which are shared with China-GREET.

The China Vehicle Fleet Model uses a consistent design for all time-series input parameters and assumptions to help users configure the model easily. Section 4.3.2 describes detailed steps for entering the time series data. In addition, the model allows users to configure a *Base Case* and a *Scenario Case* simultaneously to support comparison of simulation results for the two cases. Section 4.3.4 provides the steps for configuring the *Scenario Case*.

2.3 MODEL RESULTS

The China Vehicle Fleet Model will automatically perform calculations when you navigate to the Model Results worksheet (light green background) or any vehicle fleet turnover calculation worksheets (orange background). At this time, a message box showing the calculation status of the model will appear. You should wait until this message box disappears to review the simulation results (normally less than 30 seconds).

Model Results worksheet summarizes the aggregated modeling results by vehicle technology, by vehicle type, and by fuel/energy type for:

- Vehicle stocks
- New vehicle sales
- Vehicle travel (total VKT)
- Fleet average VKT per vehicle
- New vehicle fuel consumption rates
- Fleet average fuel consumption rates
- Vehicle fleet pump-to-wheels (PTW) energy use (both in the unit of tonnes of oil equivalent (toe) and physical units)
- Well-to-pump (WTP) fuel production stage energy use
- WTP fuel feedstock production stage energy use
- PTW GHG emissions
- Well-to-wheels (WTW) GHG emissions

The individual vehicle fleet turnover calculation worksheets provide detailed results for each vehicle technology. These results include:

- Vehicle fleet composition by age
- Scrapped vehicle stock
- Vehicle fleet total VKT, average VKT per vehicle, lifetime VKT per vehicle
- New vehicle and fleet average fuel consumption rates
- PTW fuel consumption by end-use fuel type
- PTW GHG emissions by end-use fuel type
- WTW GHG emissions by end-use fuel type
- WTP fuel production stage energy use by end-use fuel type
- WTP fuel feedstock production stage energy use by end-use fuel type

3 TECHNICAL DOCUMENTATION: METHODS AND DATA SOURCES

3.1 GENERAL METHODOLOGY

Figure 2 illustrates the general methodology adopted in the China Vehicle Fleet Model. The model estimates vehicle stock by category, type, and technology, and calculates the well-to-wheels (WTW) energy use and GHG emissions of the highway vehicle fleet in China. The terms “vehicle category,” “vehicle type,” and “vehicle technology” are defined explicitly and used consistently throughout this document and the China Vehicle Fleet Model. We classify highway vehicles in China into three vehicle categories (i.e., light-duty passenger vehicles [LDPVs], buses, and trucks), nine vehicle types (i.e., private, taxi, and business/fleet LDPVs, urban and intercity buses, and heavy-duty trucks [HDTs], medium-duty trucks [MDTs], light-duty trucks [LDTs], and mini trucks [MiniTs]), and 49 detailed vehicle technologies. Section 3.2 provides vehicle classification details.

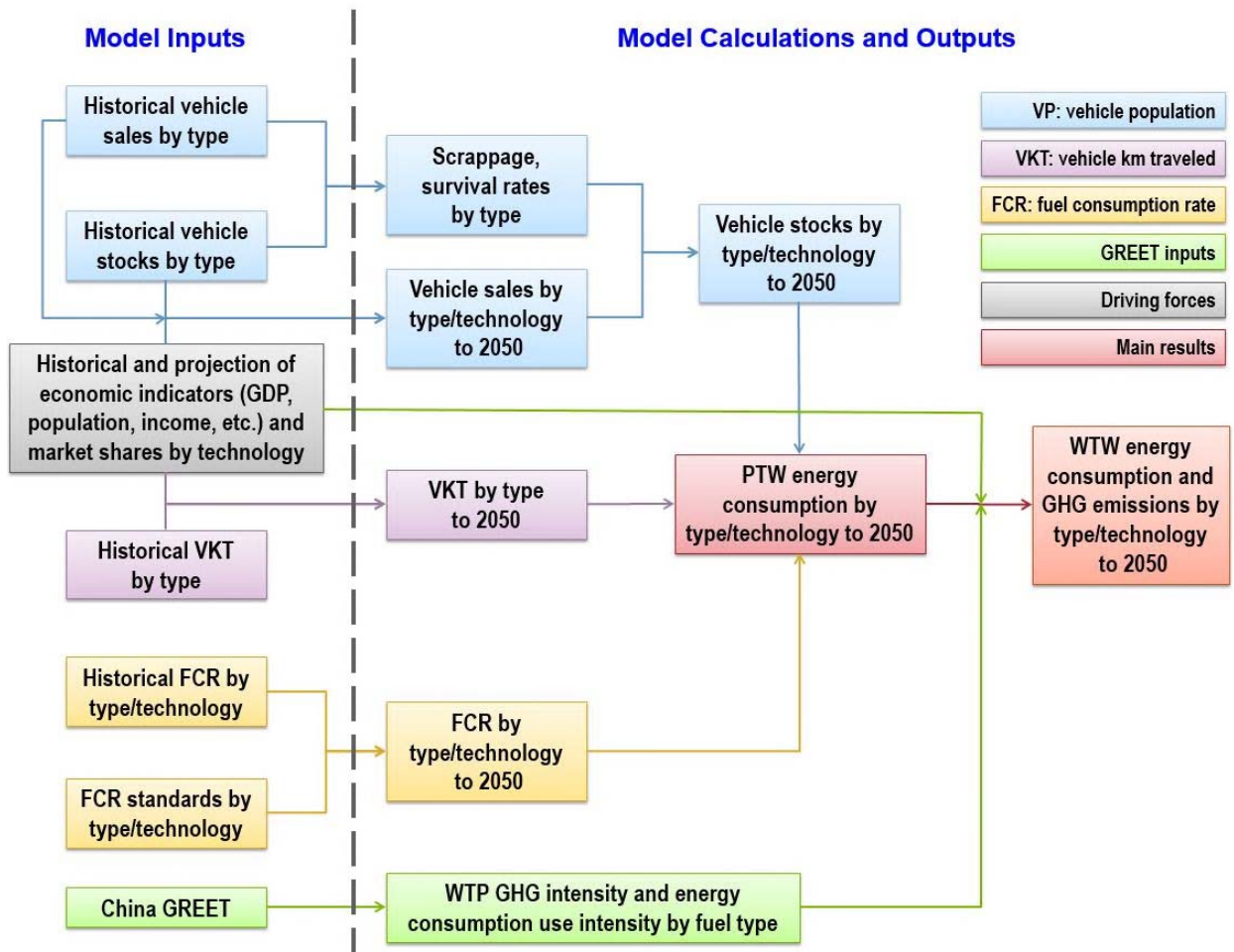


Figure 2. Methodology framework of the China Vehicle Fleet Model.

The energy consumption of the PTW stage by vintage is calculated as the product of the corresponding vehicle stock (i.e., vehicle population), vehicle-use intensity (i.e., vehicle kilometers traveled [VKT]), and fuel consumption rate per 100 km traveled (FCR). These parameters are based on available historical data, driven by macro socioeconomic indicators (e.g., gross domestic product [GDP], population, income, etc.), and will be affected by future vehicle fuel consumption standards and regulations. The PTW energy consumption is further combined with the well-to-pump (WTP) GHG intensities and energy use intensities generated from China GREET to derive the WTW energy use and GHG emissions of the Chinese highway vehicle fleet by vehicle type and technology.

3.2 CHINESE HIGHWAY VEHICLE CLASSIFICATION

The statistical standard for highway vehicles in China was not internally consistent over time and has been updated several times in the past three decades. Before 2002, the official statistics on highway vehicle stocks (e.g., *China Statistical Yearbook* [1] and *Year Book of China Transportation and Communications* [10]) only classified Chinese vehicles into passenger vehicles (i.e., cars and buses) and freight vehicles (i.e., trucks). After 2002, this type of classification was further divided into large-size buses, medium-size buses, small-size passenger vehicles, and mini passenger vehicles according to the sizes/lengths of passenger vehicles and heavy-duty, medium-duty, light-duty, and mini trucks according to the gross vehicle weights (GVW) of trucks. In this classification system, passenger cars can be treated as small-size or mini passenger vehicles.

From the vehicle manufacturing and sales point of view, the automotive industrial statistics in China (e.g., *China Automotive Industry Yearbook* [2]) adopted similar length- and GVW-based classifications as official stock statistics until the year 2004 (i.e., vehicle classification standard GB/T3730.1-88). The only exception separated passenger cars from small-size and mini passenger vehicles. Starting in 2005, the automotive industrial statistics began to use new standards (i.e., GB/T3730.1-2001 and GB/T15089-2001) that classify highway vehicles into passenger vehicles (passenger vehicles with no more than nine seats including passenger cars, minivans, sport-utility vehicles, and crossovers) and commercial vehicles (large-size buses, medium-size buses, and small-size passenger vehicles with more than nine seats and HDTs, MDTs, LDTs, and MiniTs). However, to our knowledge, there are no official vehicle stock statistics corresponding to this new highway vehicle classification.

In the China Vehicle Fleet Model, to increase the data availability and consistency among various vehicle statistics, we classify highway vehicles in China into three categories and nine types: light-duty passenger vehicles (LDPVs, including private, taxi, and other LDPVs owned by companies and government bodies), buses (urban and intercity buses), and trucks (HDTs, MDTs, LDTs, and MiniTs on the basis of GVW). As shown in Table 1 and summarized in Figure 3, the nine highway vehicle types are further divided into 49 detailed vehicle technologies consuming ten types of fuels/energies according to the historical and potential future applications (e.g., the ones emphasized in the *Technology Roadmap for Energy Saving and New Energy Vehicles* released by Chinese Society of Automotive Engineers [SAE China] [9]) of conventional and advanced vehicle fuel/technologies in China.

Table 1. Chinese highway vehicle classification

Vehicle categories	Vehicle types	Vehicle fuel/technologies ^a
Light-duty passenger vehicles (LDPVs)	Private LDPVs	ICEV-Gasoline, ICEV-Diesel, ICEV-NG, ICEV-Methanol, HEV-Gasoline, PHEV-Gasoline, BEV, FCV
	Taxi LDPVs	ICEV-Gasoline, ICEV-Diesel, ICEV-NG, ICEV-Methanol, HEV-Gasoline, PHEV-Gasoline, BEV, FCV
	Business/fleet LDPVs	ICEV-Gasoline, ICEV-Diesel, ICEV-NG, ICEV-Methanol, HEV-Gasoline, PHEV-Gasoline, BEV, FCV
Buses	Urban buses (i.e., transit buses)	ICEV-Diesel, ICEV-NG, ICEV-DME, BEV, FCV, HEV-Diesel, HEV-NG, PHEV-Diesel, PHEV-NG
	Intercity buses	ICEV-Diesel, ICEV-NG
Trucks	MiniTs (GVW≤1.8 tonnes)	ICEV-Gasoline, ICEV-Diesel, ICEV-NG, HEV-Gasoline, BEV, FCV
	LDTs (1.8 tonnes< GVW≤6 tonnes)	ICEV-Gasoline, ICEV-Diesel, ICEV-NG, BEV
	MDTs (6 tonnes< GVW≤14 tonnes)	ICEV-Diesel, ICEV-NG
	HDTs (GVW>14 tonnes)	ICEV-Diesel, ICEV-NG

^a Compressed natural gas (CNG) and liquefied natural gas (LNG) vehicles are combined as natural gas (NG) vehicles in the model due to the lack of detailed sales/stocks data. For LDPVs, urban buses, and trucks other than HDTs, nearly all ICEV-NG vehicles apply CNG technology. ICEV-LNG technology has some applications in HDTs and intercity buses, although CNG is still the dominant technology for NG vehicles now. ICEV = internal combustion engine vehicle; DME = dimethyl ether; BEV = battery electric vehicle; FCV = fuel cell vehicle; HEV = hybrid electric vehicle; and PHEV = plug-in hybrid electric vehicle.

Technology		ICE					HEV			PHEV			EV	FCV	Total No.
Fuel/Energy		Gasoline	Diesel	Natural Gas	MeOH	DME	Gasoline	Diesel	Natural Gas	Gasoline	Diesel	Natural Gas	Electricity	H2	
LDPVs	Private	✓	✓	✓	✓		✓			✓			✓	✓	8
	Taxi	✓	✓	✓	✓		✓			✓			✓	✓	8
	Business/Fleet	✓	✓	✓	✓		✓			✓			✓	✓	8
Buses	Urban		✓	✓		✓		✓	✓		✓	✓	✓	✓	9
	Intercity		✓	✓											2
Trucks	Mini <1.8t	✓	✓	✓			✓						✓	✓	6
	LD 1.8-6t	✓	✓	✓									✓		4
	MD 6-14t		✓	✓											2
	HD >14t		✓	✓											2
Total No.		5	9	9	3	1	4	1	1	3	1	1	6	5	49

Figure 3. Summary of vehicle type/technology/fuel combinations in the China Vehicle Fleet Model.

3.3 VEHICLE STOCKS

The historical highway vehicle stocks in China are collected from a variety of governmental and industrial statistics including the *China Statistical Yearbook* [1], *Year Book of China Transportation & Communication* [10], *Statistical Bulletin of the Motor Vehicles and Drivers* [11], *Statistical Bulletin of the National Economic and Social Development* [12], *China City Statistical Yearbook* [13], *China Urban Construction Statistical Yearbook* [14], *Statistical Bulletin of the Transportation and Communication Development* [15], etc. With minor adjustments, the historical vehicle stocks by type were derived and used as constraints to the total number of vehicles for each type in the fleet.

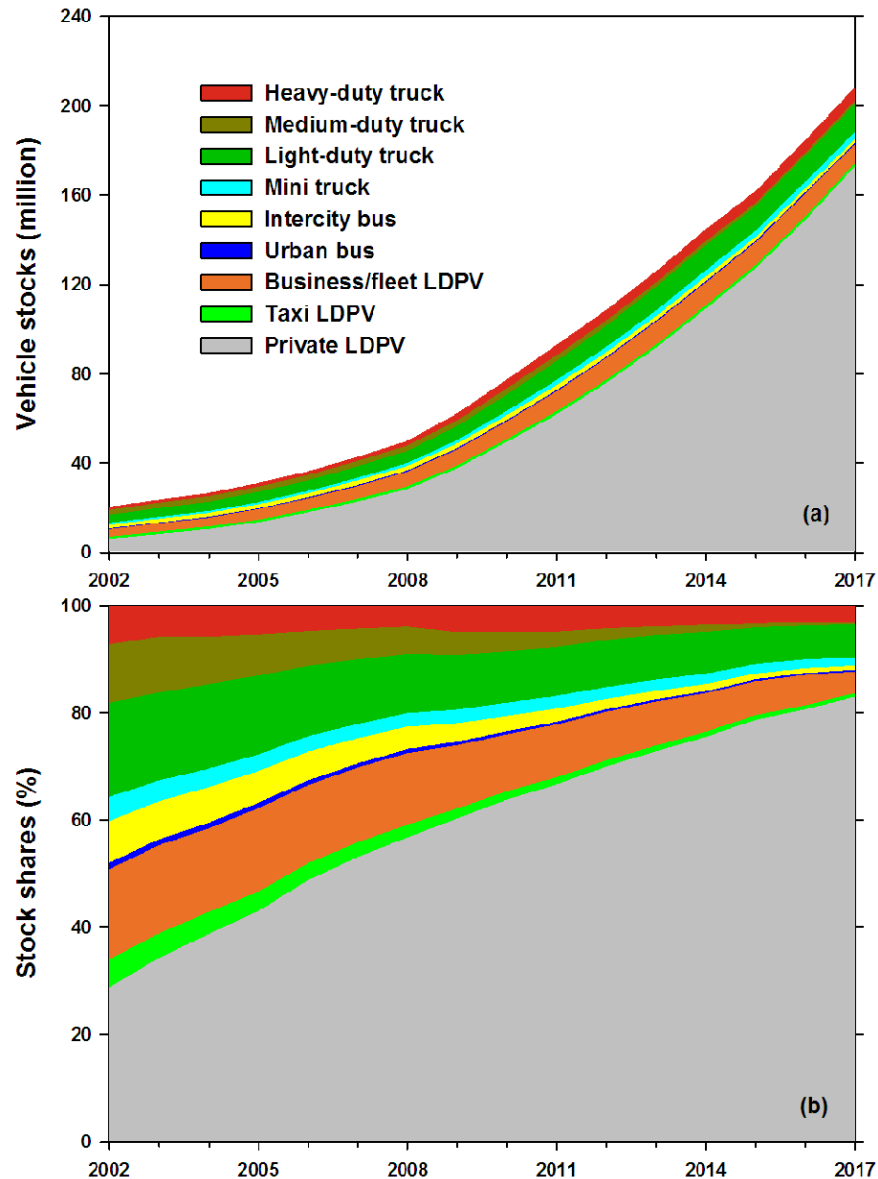


Figure 4. Highway vehicle stocks (a) and stock shares (b) by type in China from 2002 to 2017.

Figure 4 shows the historical highway vehicle stocks by type in China from 2002 to 2017. In the past 16 years, highway vehicle population in China has increased from 20.1 million to 208 million with an annual AAGR of 16.8%. Clearly, private LDPV was the single largest contributor to the fast growth, accounting for ~89% of the total highway vehicle stock increase. Compared to developed countries (e.g., the United States, European countries, Japan, etc.), which have a vehicle ownership per 1000 people in the range of 400–900 during 2010s [16-18], the Chinese automobile market (~150 vehicles per 1000 people in 2017) has large potential for continuous growth.

3.3.1 Stock Projection of Private LDPVs

Compared to developed countries that have long-term vehicle fleet data, China has relatively poor data availability, a short-term data accumulation period, and inconsistent vehicle classifications over time. Therefore, an “aggregate time series” car ownership model [19] is more appropriate for projecting vehicle stock levels in China, because it has the lowest data requirement in comparison with the other car ownership model types applied in developed countries [19]. In the “aggregate time series” model framework, the development of vehicle ownership over time is usually related to a number of economic parameters (e.g., GDP, per-capita GDP or per-capita income, etc.) by using a sigmoid-shape function that increases slowly in the beginning when economic levels are low, subsequently rises steeply, and gradually approaches a saturation level (the so-called S-curve growth pattern). Such framework and its simplified variants were widely applied in previous studies [20-22], particularly in a number of Argonne’s earlier attempts to project vehicle stock levels in China. For example, Wang and He [7] projected the growth of vehicle population in China from 2000 to 2030 by examining historical trends of developed countries; based on the historical data on per-capita vehicle ownership and per-capita GDP. He et al. [4] used a simple economic elasticity method to project the vehicle stock trend in China up to 2030; Wang et al. [8] and Huo et al. [5] related per-capita vehicle ownership in China to per-capita GDP with a sigmoid-shape growth curve (i.e., Gompertz curve) and projected the vehicle stock in China to the year 2050. In particular, Huo and Wang [23] recently upgraded the previous methodology so that it can simulate the private car ownership on an income-level basis by taking into account the car purchase price. Based on Huo and Wang’s work, Hsieh et al. [24] used a Monte Carlo method and discussed the uncertainties of the method. The method was also applied at the province level to project the trends of vehicle stocks and GHG emissions of Chinese motor vehicles for the period of 2010–2030 [25]. In this work, we adopt a similar approach developed by Huo and Wang [23] and further update and improve it with new data collected to project the private LDPVs through 2050.

In general, the total private LDPV stock in year m ($Stock_{Private_LDPV,m}$) is calculated as

$$Stock_{Private_LDPV,m} = TP_m \cdot \int_{x=0}^{\infty} [s(x)_m \cdot t(x)_m] dx \quad (1)$$

where TP_m represents the total population in year m ; $s(x)$ and $t(x)$ are the private LDPV ownership per 1000 people and income distribution, respectively, as the functions of disposable income x . In the following sections, we will present the methods and data of these two key functions.

3.3.1.1 Function of the Private LDPV Ownership

It has been widely recognized that income (household income, per-capita income, per-capita disposable income, etc.) is the most important parameter that determines the vehicle ownership rate [19, 22, 26-28]. Huo and Wang [23] compared the private LDPV ownership per 1000 people and per-capita disposable income for the period of 2004–2009 in China. Taking into account the “vehicle price index” (VPI), which is a ratio of the prices of LDPVs in a given year to those of LDPVs with same models in 2004 (i.e., VPI of 2004 is one), they found that the quotient of per-capita disposable income and VPI (representing the vehicle purchasing power) correlated much better than per-capita disposable income alone. In this work, we conduct a similar analysis and extend the period of study to 1997–2017.

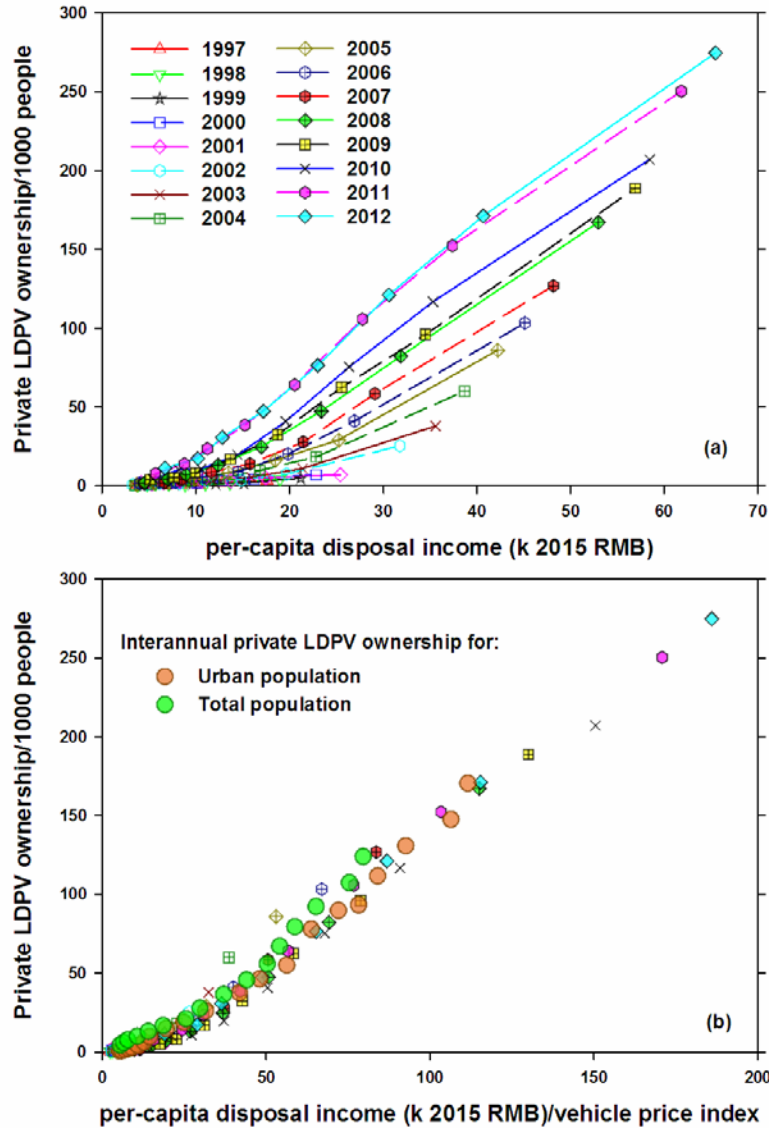


Figure 5. Historical private LDPV ownership per 1000 people versus (a) per-capita disposable income (constant 2015 RMB) and (b) the ratio of per-capita disposable income (constant 2015 RMB) to vehicle price index of LDPV.

Figure 5a shows the relationship between national-averaged private LDPV ownership per 1000 people and per-capita disposable income by level of household income in China for different years. These data were derived from surveys of Chinese urban households at eight income levels conducted by the National Bureau of Statistics of China [1]. Obviously, people with higher income possess more vehicles, confirming that rising income is the primary driving force behind the growth of the vehicle ownership [26, 27]. Additionally, LDPV ownership rates increased over the years because vehicle price decreased after China entered the World Trade Organization [23]. Here, we continue to use the concept of VPI to reflect the differences in LDPV prices over the years. The VPI values during 2004–2009 are from Huo and Wang [23] directly, which were based on an investigation of the price of hundreds of LDPV models. For years following 2009, VPI values are estimated based on the trends of the Cheshi Auto Price Index (CAPI) for Chinese passenger cars developed by Auto Market Online (www.cheshi.com), and the GAIN price index for Chinese passenger cars developed by I.S. Engine (www.isengine.com.cn). According to our estimates, 2017 model year (MY) LDPVs were 69% lower than 2004 MY LDPVs. We estimate that the VPI in 1997 was 70% higher than that in 2004 [29], and the VPI values for years between 1997 and 2004 are then interpolated.

The scatter plot of private LDPV ownership against the quotient of per-capita disposable income and VPI for all income levels in all years is shown in Figure 5b. Taking into account the impact of vehicle price, we observe a clear and consistent relationship between private LDPV ownership and vehicle purchasing power, in good agreement with the finding by Huo and Wang [23]. Figure 5b also shows the interannual growth pace of private LDPV ownership for urban populations (from 1997 to 2017) and total population (from 2002 to 2017). These follow the same growth pattern as the other income-specific data points, implying the reasonability of using the relationship in Figure 5b to extrapolate the private LDPV ownership in the future.

As introduced at the beginning of Section 3.3.1, the response of vehicle ownership to economic parameters can be expressed as a sigmoid-shape function. Following our previous studies [5, 8, 23], we use Gompertz function [27, 30] to describe the relationship between private LDPV ownership per 1000 people and the ratio of disposable income to VPI shown in Figure 5b.

$$s(x | a, b, c, VPI_m)_m = a \cdot \exp[-b \cdot \exp(-c \cdot \frac{x}{VPI_m})] \quad (2)$$

where $s(x)_m$ is the function of private LDPV ownership per 1000 people; variable x represents the corresponding disposable income at constant 2015 renminbi (RMB); VPI_m represents VPI in year m ; a represents the ultimate saturation level of private LDPV ownership per 1000 people; and b and c are parameters determining the shape of the sigmoid-curve. With a known private LDPV ownership saturation level (a), parameters b and c can be estimated by fitting the historical data of private LDPV ownership (s), per-capita disposable income (x), and VPI with Equation (2) (i.e., fitting data points in Figure 5b).

The ultimate saturation level of vehicle ownership a is a key parameter in determining the level of Chinese private LDPV stock in the future. Unlike in most developed countries, the private LDPV ownership in China is still growing rapidly (Figure 5b) and is far from saturation. Ownership saturation level a can be affected by factors such as population density, urban development patterns, government

decisions to control vehicle stock, etc. In previous studies, a in the range of 300–600 passenger cars per 1000 people was commonly used for China [4-6, 8, 21, 23, 25, 27, 31-34]. For the *Base Case* of the China Vehicle Fleet Model, we assume that a is 450. For reference, Beijing, Chengdu, Chongqing, Shanghai, Suzhou, and Shenzhen — the top six Chinese cities with the most vehicles — had private LDPVs ownership per 1000 people levels of 187 [35], 150 [36], 81 [37], 112 [38], 236 [39], and 309 [40], respectively, in 2016. It should be noted that the uncertainty of a could be large and could affect the private LDPV stock projection significantly [24]. In the China Vehicle Fleet Model, we provide pre-calculated stock projections with a in the range of 300 to 600 LDPVs per 1000 people. Users may choose different ultimate saturation levels of vehicle ownership for their simulations. Please refer to Section 4.5.1 for details.

The VPI of LDPV is difficult to project. According to the four-stage development theory of the automobile industry by Hamilton et al. [41], car price decreases during the market expansion stage and stabilizes in the mature market stage with competition in design and salesmanship. In *Base Case* of the China Vehicle Fleet Model, we chose to estimate the LDPV price trend in China during 2000–2050 based on car price trend in the early motorization stage in the United States (i.e., around 1900–1950) [16]. Similar treatments in the China LDPV price projection have been used in Huo and Wang [23] and Hsieh et al. [24]. As mentioned earlier, the price of LDPV has decreased dramatically (~80%) since 1997. The trend of dropping vehicle prices in China is similar to that seen in United States between 1900 and 2017, and this is consistent with the observation by David et al. [16] for the early motorization stage of developed countries. We therefore assume that LDPV VPI in China between 2020 and 2050 would follow a similar LDPV price trend as seen in the United States between 1920 and 1950. LDPV VPI would continue dropping till 2030 (i.e., corresponding to the decreasing VPI period of 1920–1930 in United States) and then increase slightly till 2050 (i.e., corresponding to the increasing VPI period of 1930–1950 in the United States; see Table 2).

Table 2. Historical and projected total/urban/rural population, per-capita GDP, per-capita disposable income, LDPV VPI, and Gini index in China

	Total population (million)	Urban population (million)	Per-capita GDP (2015 RMB)	Per-capita disposable income (2015 RMB)	LDPV VPI	Gini index
2005	1,308	562	21,118	8,482	0.796	0.485
2010	1,341	670	35,191	14,379	0.389	0.481
2015	1,375	771	50,127	22,563	0.337	0.462
2020	1,405	866	67,443	35,583	0.294	0.450
2025	1,419	938	87,540	50,982	0.276	0.425
2030	1,421	987	111,887	65,162	0.269	0.400
2035	1,414	1,016	140,043	81,559	0.274	0.390
2040	1,398	1,028	172,030	100,188	0.287	0.380
2045	1,375	1,033	208,128	121,211	0.304	0.365
2050	1,346	1,031	245,661	143,070	0.320	0.350

3.3.1.2 Function of Disposable Income Distribution

It has been widely tested that disposable income follows a lognormal distribution [42-44], especially in emerging economics such as China [45]. The probability density function can be described as

$$t(x | \mu_m, \sigma_m)_m = \frac{1}{\sqrt{2\pi} \cdot \sigma_m \cdot x} \cdot \exp\left[-\frac{(\ln x - \mu_m)^2}{2\sigma_m^2}\right] \quad (3)$$

where lognormal distribution function $t(x)_m$ represents the fraction of the population with disposable income x in year m ; and μ_m and σ_m are the mean and standard deviation of the natural logarithm of x , determining the shape of the curve in year m . For the lognormal distribution, the mean of variable x , which represents the per-capita disposable income in year m ($\overline{x_m}$), is given by

$$\overline{x_m} = \exp(\mu_m + \sigma_m^2 / 2) \quad (4)$$

The income distribution function can also be used to evaluate the income inequality-related indicators such as Lorenz curve and Gini index. The Lorenz curve is a graph that shows the relationship between the cumulative share of income earned and the cumulative share of people when arranged in ascending order according to their incomes. As the best single measure of inequality, the Gini index can be computed as the ratio of the area that lies between the egalitarian line and the Lorenz curve to the total area under the egalitarian line [46]. For the disposable income function in the form of lognormal distribution, the Gini index in year m can be expressed explicitly as

$$Gini_m = 2\Phi \cdot (\sigma_m / \sqrt{2}) - 1 \quad (5)$$

where Φ is the cumulative standard normal distribution [47].

With projected per-capita disposable income and Gini index, parameters μ and σ of the lognormal distribution can be derived by solving Equations (4) and (5), and then the disposable income distribution function $t(x)$ can be determined. Table 2 summarizes the projected per-capita disposable income and Gini index in China. Because the historical per-capita disposable income had a strong linear relationship with per-capita GDP in China ($R^2=0.993$ during 1980–2017, *China Statistical Yearbook* [1]), we project the per-capita disposable income in China on the basis of population and GDP forecasts. The future population through 2050 is from the United Nations' *World Population Prospects* [48]. The GDP growth rates are projected on the basis of the datasets and publications of a number of organizations including the *Economic and Commodity Forecast* by the Economist Intelligence Unit (EIU) [49], the *World Economic Outlook Database* by the International Monetary Fund (IMF) [50], the *Economic Outlook* by the Organization for Economic Co-operation and Development (OECD) [51], and the *International Energy Outlook* by the Energy Information Administration (EIA) [52]. For Gini index values, we use the projections by Huo and Wang [23] and Lu [53] directly.

3.3.2 Stock Projection of Commercial LDPVs

The commercial LDPVs include both taxi LDPVs and business/fleet LDPVs owned by companies and government bodies. Their stock share relative to the total number of LDPVs in China has decreased dramatically from 43.4% in 2002 to 5.4% in 2017 due to the rapid increase of private LDPVs (Figure 4). This share is in the range of 1–5% in developed countries such as the United States, Japan, and the Republic of Korea (South Korea) [16, 18, 23, 54]. In the *Base Case* of the China Vehicle Fleet Model, we assume the share of commercial LDPVs would continue dropping to 4% by 2050. According to the *Code for Transport Planning on Urban Road* developed by the Ministry of Housing and Urban-Rural Development of China [55], the taxi ownership in urban areas is suggested to be no less than 2 per 1000 people for large (urban population > 1 million) and 0.5 per 1000 people for small (urban population < 0.5 million) cities, respectively. In fact, this ownership level has been relatively stable around 1.8–2.0 during the past 15 years. We therefore assume the taxi LDPV ownership would be 2 per 1000 urban population in 2050. Finally, the stock of the business/fleet LDPVs is calculated as the stock differences between the commercial LDPVs and taxi LDPVs.

3.3.3 Stock Projection of Buses

The stocks of buses are estimated as a product of projected bus ownership and the corresponding population. We adopt the same assumption as Huo and Wang [23] that the bus ownership in China would increase from the current level of ~1.7 to 3 per 1000 people by 2050. The *Code for Transport Planning on Urban Road* [55] provides the suggestion to the urban bus ownership in Chinese cities, which is around 1 per 1000 people. From 2002 to 2017, the urban bus ownership in China gradually increased from 0.48 to 0.80 per 1000 urban population (Figure 4). Thus, we assume this number would increase to the guideline value of 1 by 2050.

3.3.4 Stock Projection of Trucks

Figure 6 shows the relationship between truck stocks and GDP in China and 20 other countries/regions. Unlike for LDPVs, the truck stocks in different countries/regions do not have saturation levels and, in general, increase linearly with the national/regional GDP. In the past 10 years, the ratios of truck stocks to GDP have remained relatively stable in these selected countries. The average ratio of China was ~2.4 trucks per million in 2010 U.S. dollars, which was close to the levels for developed Asia-Pacific countries such as Japan (~2.3), South Korea (~2.7), and Australia (~2.6); higher than developed European countries (e.g., ~2.0 for EU-28 and ~1.8 for EU-15); and significantly lower than the United States (~3.5) and Russia (~3.5). In the *Base Case* of the model, we assume the ratio of 2.4 trucks per million in U.S. dollars GDP does not change until 2050. Therefore, the total number of trucks in China can be estimated based on the GDP projection in Table 2.

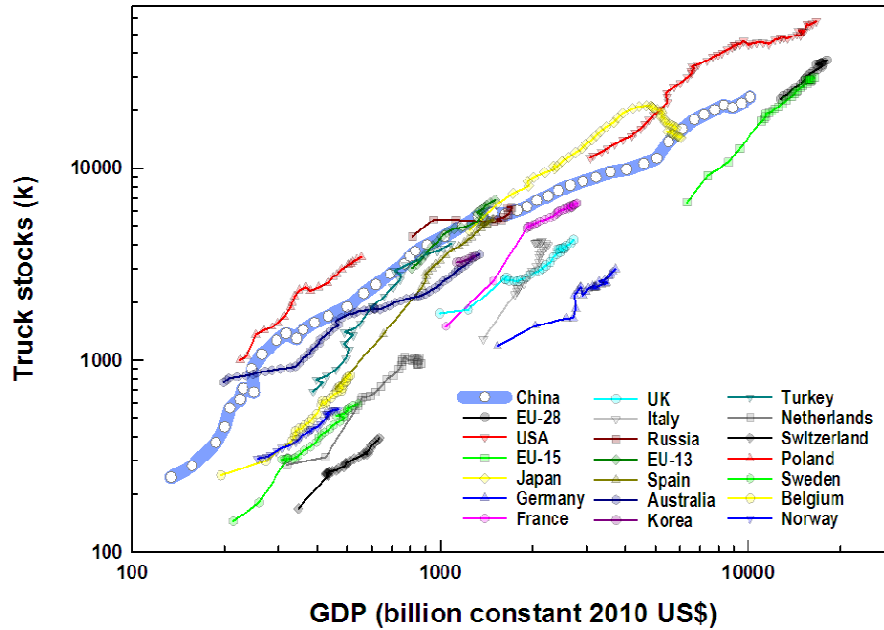


Figure 6. The relationship between truck stocks and GDP in selected countries or regions.

Truck stocks by type are estimated by multiplying the projected total number of trucks by corresponding stock shares. Figure 7 shows the stock shares of different truck types in China from 2002 to 2017. The shares of HDT and LDT increased from 18.3% and 43.6% in 2002 to 26.8% and 53.7% in 2017, respectively. The MDT share shrank continuously, going from 26.9% in 2002 to 5.6% in 2017. In the *Base Case* of the model, we assume these trends continue, and the stock shares of HDT, MDT, LDT, and MiniT in 2050 would be 30%, 2%, 58%, and 10%, respectively.

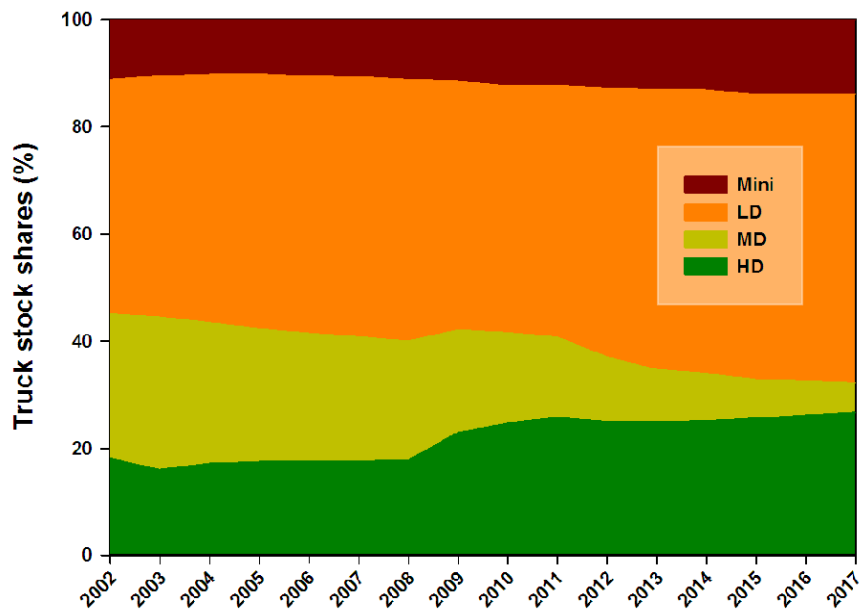


Figure 7. Stock shares by truck type in China from 2002 to 2017.

3.4 SURVIVAL FUNCTIONS

The vehicle survival function describes the relationship between the survival ratio of vehicles and the vehicle age. In this work, we use a two-parameter logistic model to simulate the survival rate of vehicles [56-59]. The equation of survival rate (r) for vehicle type i in year m as a function of vehicle age j is

$$r(j | \alpha_{i,m}, L_{50,i,m})_{i,m} = \frac{1}{1 + \exp[\alpha_{i,m} \cdot (\frac{j}{L_{50,i,m}} - 1)]} \quad (6)$$

where L_{50} is the vehicle age at which 50% of the vehicles have retired; and α is a shape factor related to the onset of significant vehicle retirement. Although some previous works have used the Weibull function (and its variants) to model vehicle survival rates (e.g., [23, 30, 60-62]), we choose the logistic function because it can closely match any types of Weibull-like distributions with appropriate parameters [59, 63] and, more importantly, its parameter L_{50} has a practical meaning of the median lifetime of vehicles.

The survival (or scrappage) patterns of vehicles are affected by a number of factors, including vehicle age, new vehicle price, vehicle repair price, distance traveled, fuel price, government regulations on vehicle emissions, fuel consumption, and scrappage subsidies, etc. [59, 63-67]. Therefore, it normally requires substantive historical data about vehicle fleets to determine the survival rates for vehicles, which is difficult to obtain in developing countries such as China. Yang et al. [62] collected the fleet data for newly registered, total registered, and scrapped LDPVs before 2003 and estimated the survival pattern of LDPVs in Beijing. This work as well as works by Wang et al. [8], Huo et al. [5], and Hao et al. [61] indicate that the scrappage of vehicles in China is mainly affected by the mandatory scrappage standards. China implemented its first automobile mandatory scrappage standard in 1986 [68], which specified the upper limits for service years and mileage by vehicle type. Vehicles that meet either the scrappage limits for service years or mileage should be scrapped. This standard was revised with minor changes three times — in 1997 [69], 1998 [70], and 2000 [71]. In May 2013, the Chinese government implemented a new automobile scrappage standard [72], in which a more detailed vehicle classification is included and the upper limits of service years and mileage for most of vehicle types were adjusted.

Table 3 summarizes the scrappage mileage and years for a number of vehicle types related to the vehicle classification in this work (i.e., Table 1). In addition to these limits, the standards also specify the other requirements related to the vehicle scrappage. For example, certain types of vehicles could be allowed to extend their service years; private LDPVs older than 15 years must be inspected twice a year and four inspections are needed if their age exceeds 20 years; vehicles with serious damage or vehicles that fail to meet national standards on fuel consumption or emissions must be scrapped.

Table 3. Automobile mandatory scrappage standards of selected vehicle types in China

Vehicle type	1986 standard and its revisions [68-71]		2013 standard [72]	
	Scrappage mileage (km)	Scrappage years	Scrappage mileage (km)	Scrappage years
LDPV not for revenue	500000	15	600000	No limit
Taxi LDPV	500000	8	600000	8
Urban bus	500000	10	400000	13
Other bus for revenue	500000	10	500000 (medium)	15
			800000 (large)	15
Other bus not for revenue	500000	20	500000 (medium)	20
			600000 (large)	20
MiniT	300000	8	500000	12
LDT, MDT	400000	10	600000	15
HDT	400000	10	700000	15

Table 4 summarizes the parameters α and L_{50} used in survival function Equation (6) for different vehicle types. The corresponding survival rates are plotted in Figure 8. In this work, the survival rates by vehicle type for the historical vehicle fleet in China are derived from various sources and approaches. The survival patterns of private and business/fleet LDPVs are from Hao et al. [61], which were estimated based on more than 4000 first-hand scrappage records collected from a scrappage company in Beijing during 2006–2010. Because the same mandatory scrappage standards were applied to not only Beijing, but also other areas of China, the survival patterns derived by Hao et al. [61] are believed to represent the overall situation in China. For MDTs and HDTs, the survival patterns are from Hao et al. [61], too, which were regressed based on historical sales and stocks data of MDTs and HDTs. Applying a similar method, we derive the overall survival pattern of MiniTs and LDTs (see Sections 3.5 and 3.3 for the data sources for sales and stocks, respectively).

In China, the survival patterns of taxis and urban buses depend mainly on their service condition and mandatory scrappage standards [23, 61]. Table 3 shows that the upper limits of scrappage years and mileage are 8 years and 500,000–600,000 km, respectively, for taxi LDPVs, and 10–13 years and 400,000–500,000 km, respectively, for urban buses. It has been reported that the VKT are ~100,000 km and ~60,000 km for taxis and urban buses, respectively [61, 73] (also see Section 3.7). Therefore, the expectation is that taxis and urban buses will be scrapped at the vehicle ages of ~5 and ~8 years (0-based ages), respectively, both of which are lower than the mandatory scrappage years. Here, we assume the L_{50} values of taxis and urban buses in Equation (6) are 4.5 and 7.5, respectively, and set α to ten times of the L_{50} values to reflect the mandatory scrappage patterns (i.e., survival rates at vehicle ages younger than L_{50} are approximately 1 and those at vehicle ages older than L_{50} are approximately 0).

Table 4. Parameters α and L_{50} of the survival functions by vehicle type for the historical vehicle fleet

Vehicle type	α	L_{50}	Remarks
Private LDPV	7.1	13.3	Regressed based on the survival pattern in Hao et al. [61]
Taxi LDPV	45	4.5	Estimated based on VKT and mandatory scrappage standards
Business/fleet LDPV	7.9	12.2	Regressed based on the survival pattern in Hao et al. [61]
Urban bus	75	7.5	Estimated based on VKT and mandatory scrappage standards
Intercity bus	7.7	10.6	Regressed based on the survival pattern in Huo et al. [6, 23]
MiniT and LDT	8.3	6.1	Estimated based on the vehicle sales and stocks
MDT	8.3	9.4	Regressed based on the survival pattern in Hao et al. [61]
HDT	8.3	11.9	Regressed based on the survival pattern in Hao et al. [61]
Japan: general cars	4.0	12.7	Regressed based on the survival pattern in Huo and Wang [23]
Germany: cars	6.1	14.1	Regressed based on the survival pattern in Huo and Wang [23]
USA: 1990 MY cars	3.9	17.3	Regressed based on the survival pattern in Huo and Wang [23]

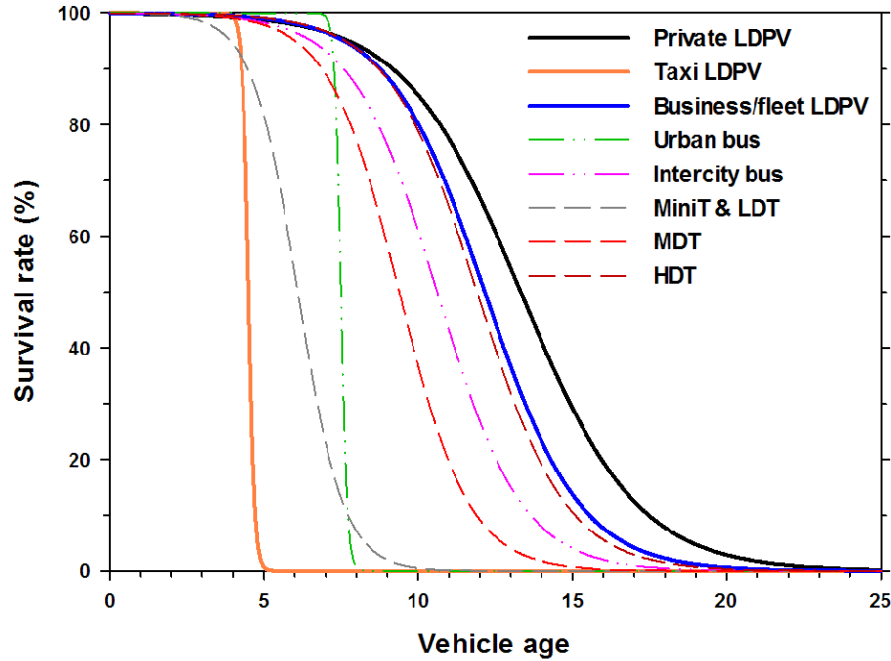


Figure 8. Survival rates by vehicle type for the Chinese highway vehicle fleet.

The survival patterns for future vehicles in China may depend on technology improvements as well as government policies to stimulate the automobile industry. Following the assumptions by Huo and Wang [23], we provide several survival functions for the future private LDPVs in China such as Japan [74], Germany [75], and U.S. patterns [16]. The regressed α and L_{50} for these patterns are also provided in Table 4.

3.5 NEW VEHICLE SALES

In the China Vehicle Fleet Model, new vehicle sales refer to the number of new vehicles entering into the vehicle fleet each year. The historical data related to the new vehicle sales of total LDPVs, total buses, and trucks by type in China are taken from a series of publications released by the China Association of Automobile Manufacturers (CAAM) such as the *China Automotive Industry Yearbook* [2], the *China Automotive Industry Newsletter of Production and Sales* [76], etc. In CAAM's statistics, the reported vehicle sales include sales to both the domestic and foreign (i.e., export) markets, but exclude sales of imported vehicles. Meanwhile, reported sales also include vehicles produced domestically in China and assembled domestically with imported components in China (i.e., completely knocked-down [CKD] vehicles) [8]. It should be noted that the CKD vehicle numbers are also included in the imported vehicle statistics. Taking all these aspects into account, we therefore calculate the total number of new type i vehicles entering into the Chinese fleet in year m ($Sale_{i,m}$) as

$$Sale_{i,m} = Sale_{CAAM,i,m} + Import_{CAAM,i,m} - Export_{CAAM,i,m} - CKD_{CAAM,i,m} \quad (7)$$

where $Sale_{CAAM,i,m}$, $Import_{CAAM,i,m}$, $Export_{CAAM,i,m}$, and $CKD_{CAAM,i,m}$ represent the CAAM-reported vehicle sales, imports, exports, and CKD for vehicle type i in year m , respectively. For the period prior to 1994, CAAM only reported production data by vehicle type. Accordingly, we replaced $Sale_{CAAM,i,m}$ with $Production_{CAAM,i,m}$ in Equation (7) to calculate the new vehicle sales by type prior to 1994.

Theoretically, with known historical vehicle sales and survival function for vehicle type i , the vehicle stock in year m ($Stock_{i,m}$) can be determined as

$$Stock_{i,m} = \sum_{j=0}^{\sigma} [Sale_{i,m-j} \cdot r(j)_i] \quad (8)$$

where j and σ represent the vehicle age and the potential longest vehicle service years, respectively; $Sale_{i,m-j}$ represents the new vehicle sales of type i vehicles in MY $m-j$; and $r(j)_i$ is the survival function described in Equation (6). Equation (8) can be rewritten as

$$Stock_{i,m} = Sale_{i,m} \cdot r(0)_i + \sum_{j=1}^{\sigma} [Sale_{i,m-j} \cdot r(j)_i] \quad (9)$$

Then, new vehicle sales of vehicle type i can be expressed as

$$Sale_{i,m} = \frac{Stock_{i,m} - \sum_{j=1}^{\sigma} [Sale_{i,m-j} \cdot r(j)_i]}{r(0)_i} \quad (10)$$

Equation (10) provides a method to back-calculate the vehicle sales through vehicle stocks. In the *Base Case* of the model, we use this approach to determine the historical vehicle sales of private LDPVs, taxis, business/fleet LDPVs, urban buses, and intercity-buses, because stock information is only available for

these vehicle types. We also use Equation (10) to estimate future vehicle sales by type from the projected vehicle stocks in Section 3.3.

Figure 9 shows the historical highway vehicle sales by type in China from 1980 to 2017. Since 1980, highway vehicle sales in China have increased by more than 100 times from 0.27 million to 28.6 million in 2017, with an AAGR of 13.4%. Private LDPV was the single largest contributor to the increase of vehicle sales, and its share of the total vehicle sales increased remarkably, from 3.6% in 1980 to 84.0% in 2017. Meanwhile, the share of trucks shrank from 79.6% to 11.3%.

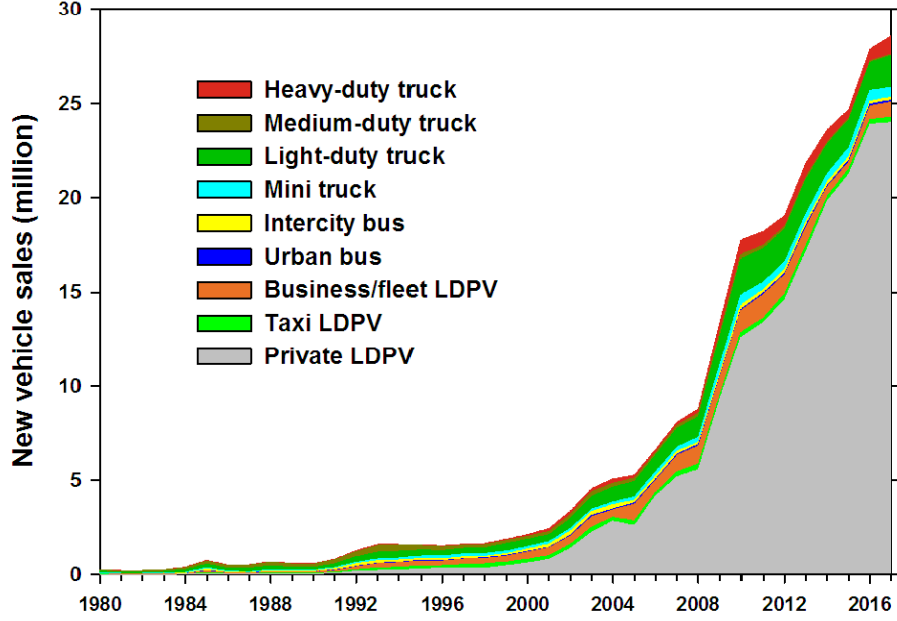


Figure 9. Highway new vehicle sales by type in China from 1980 to 2017.

3.6 MARKET SHARES OF VEHICLE FUEL/TECHNOLOGIES

The market share of vehicle fuel/technology i in year m ($Share_{i,m}$) is defined as

$$Share_{i,m} = Sale_{i,m} / Sale_{i^*,m} \quad (11)$$

where i^* represents the vehicle type that the vehicle fuel/technology i belongs to (see Table 1 for details). With known market share, the total number of vehicles with fuel/technology i at age j in year m can be determined as

$$Stock_{j,m,i} = Sale_{m-j,i^*} \cdot Share_{m-j,i} \cdot r(j)_i \quad (12)$$

In this work, the historical new vehicle sales by vehicle fuel/technology are collected and/or estimated from a variety of data sources, including the *China Automotive Industry Yearbook* [2] and *China Automobile Industry Newsletter of Production and Sales* [76] by CAAM, the *Statistical Bulletin of the Transportation and Communication Development* [15] by the Ministry of Transport of China (MoT), the

Yearbook of Energy-Saving and New Energy Vehicles [77], and the *Annual Report on Automotive Energy-Saving in China* [78] by the China Automotive Technology and Research Center (CATARC), and official and industrial data posted at the websites of the Ministry of Industry and Information Technology of China (MIIT, <http://www.miit.gov.cn/>) and China Passenger Car Association (CPCA, <http://www.cPCA1.org/>). For future market shares until 2030, the *Base Case* of the China Vehicle Fleet Model is mainly configured based on the *Technology Roadmap for Energy Saving and New Energy Vehicles* (hereafter referred to as the *Technology Roadmap*) released by SAE China in October 2016 [9]. This roadmap was consigned by the National Manufacturing Strategy Advisory Committee (NMSAC) and MIIT, and provides comprehensive guidelines for energy-saving and new energy vehicles (NEVs, including battery electric vehicles [BEVs], plug-in hybrid electric vehicles [PHEVs], and fuel cell vehicles [FCVs]) to achieve the goals of the Chinese government, particularly, the initiative of “Made in China 2025.”

3.7 VEHICLE KILOMETERS TRAVELED

Vehicle use intensity, expressed as kilometers traveled per vehicle per year (i.e., VKT), is an important parameter determining the energy use and emissions of the vehicle fleet. Due to the lack of officially released data, our understanding of VKT levels by vehicle type in China is poor. We have drawn the VKT values by vehicle type from literature reporting the VKT survey results, or estimated them based on VKT-related statistics from commercial transport companies and/or government agencies.

3.7.1 VKT of Private LDPVs

Table 5 summarizes the fleet average VKT levels by vehicle type used in the *Base Case* of the model. Huo et al. [73] systematically reviewed the available VKT survey data from various sources and conducted additional surveys between 2004 and 2010 to derive vehicle-use intensities for private, taxi, and business/fleet LDPVs. They found that the VKT level of the LDPVs decreased by ~13% from 2002 to 2009, mainly due to the dramatic increase in LDPV ownership in China. In this work, the fleet average VKT results for LDPVs estimated by Huo et al. [73] for the period from 2002 to 2009 are used directly. The long-term surveys conducted by Beijing Transport Institute [79] indicate that VKT levels for private and business LDPVs in Beijing decreased continuously after 2009. The trend seems to be same at the national level. According to the national VKT survey studies conducted by Lin et al. [80] (sample size: 430,000), CATARC [78] (sample size: 150,000), and Liu et al. [81] (sample size: 71,000) for the years 2007, 2013, and 2015, respectively, the VKT of private LDPVs decreased by 26% from 2007 to 2013, and another 4% from 2013 to 2015. These ratios are used to determine the fleet average VKT of private LDPVs between 2010 and 2015.

Table 5. Fleet average VKT levels by vehicle type used in the *Base Case* (unit: 1000 km/year)

Vehicle type	2005	2010	2015	2020	2030	2040	2050
Private LDPV ^a	18.0	15.9	12.5	10.1	10.4	11.3	11.5
Taxi LDPV	85.3	99.2	94.0	85.0	75.0	65.0	55.0
Business/fleet LDPV	23.5	20.7	13.3	10.1	10.4	11.3	11.5
Urban bus	59.7	61.4	50.9			40.0	
Intercity bus				37.0			
MiniT and LDT	30.0	12.0	17.0			17.0	
MDT and HDT	30.0	30.0	40.0			40.0	

^a VKT levels of private LDPVs are projected based on the ultimate saturation level of vehicle ownership of 450 vehicles/1000 people, the theoretical stable per-capita car travel distance of 8000 km/person, and the macro socioeconomic indicators in Table 2.

To project future VKT levels of private LDPVs, we follow a similar method presented by Huo et al. [73] and use the updated historical VKT data described above. The VKT level in year m can be calculated as

$$VKT_{private_LDPV,m} = \frac{u(g)_m \cdot TP_m}{n_m \cdot Stock_{private_LDPV,m}} \quad (13)$$

where $u(g)$ represents the per-capita LDPV distance traveled; TP represents total population (see Table 2); $Stock$ represents the stock of LDPVs that are projected in Equation (1) in Section 3.3.1; and n represents the average number of persons carried per trip. Due to the lack of data, we follow Huo et al.'s assumption that n would increase gradually from the current level of 1.5 to 1.7 in 2050 [73]. The per-capita LDPV distance traveled u has been found to be correlated with economic development. A cumulative Weibull function is used here to describe the relationship between per-capita LDPV distance traveled u and per-capita GDP g

$$u(g | u^*, g_0, \lambda, \gamma)_m = u^* \cdot [1 - e^{-\left(\frac{g_m - g_0}{\lambda}\right)^\gamma}] \quad (14)$$

where u^* is the theoretical stable level of per-capita LDPV distance traveled, which is assumed to be 8000 km/person in the *Base Case* of the model and g_0 is the initial per-capita GDP level at which per-capita LDPV distance traveled starts to increase significantly. Based on the historical data discussed in the first paragraph of this section, we determine g_0 to be 15900 RMB/person (2015 RMB); λ and γ are shape factors of the cumulative Weibull function. Please refer to Huo et al. [73] for details of the methodology.

As shown in Table 5, we project that the fleet average VKT for private LDPVs will continue to decrease until 2020 and then increase moderately until 2050 in the *Base Case* of the model. Based on Equations (13) and (1), the VKT trend for private LDPVs is determined mainly by the ratio trend of per-capita LDPV distance traveled (i.e., u in Equation (14)) to per-capita LDPV ownership (i.e., the integration of the product of private LDPV ownership function s in Equation (2) and disposable income distribution function t in Equation (3)). We project VKT of private LDPVs to be continuously decreasing until ~2020

because per-capita LDPV ownership increases much faster than per-capita LDPV distance traveled. Based on the parameterization of the functions of u , s , and t in the *Base Case* of the model, per-capita LDPV distance traveled would increase at about the same rate as per-capita LDPV ownership after 2020 and would be slightly faster than the increase in per-capita LDPV ownership after 2030. This yields a moderate increase of VKT projected between 2030 and 2050. This trend may be reasonable in the real world. During market expansion periods in the automobile industry, people tend to own more vehicles than they use. When the market becomes mature, people tend to drive more to meet their increasing travel needs. For example, the VKT of light-duty vehicles in the United States increased in general after 1950 and are expected to continue increasing until 2050 [54].

3.7.2 VKT of Commercial LDPVs and Buses

In China, business/fleet LDPVs usually have designated drivers and travel more than private LDPVs. Surveys conducted by the Beijing Transport Institute [79] suggested that the VKT of business LDPVs was ~30% higher than that of private LDPVs before 2010, but the difference became smaller in recent years. Here, we assume the VKT ratios of business/fleet to private LDPVs were 1.15 in 2013 [78] and 1.07 in 2015 [79], and the VKT of business/fleet LDPVs will be same as that of the private LDPVs after 2020.

For taxi LDPVs and urban buses, we use the VKT estimated by Huo et al. [73] for the period before 2009. The VKT trends reported in the *Statistical Bulletin of the Transportation and Communication Development* [15] are further used to derive the VKT levels for these two types of vehicles in recent years. Based on the statistics of the MoT [15], VKT levels of both taxi LDPVs and urban buses have been continuously decreasing since 2009. This may be related to the increase in ownership of private LDPVs and/or increased congestion in urban areas, so that vehicles travel less in the same number of operating hours. For taxi LDPVs, we assume this decreasing trend continues at a rate of 1000 km/year until 2050. For urban buses, we assume that VKT would decrease to 40000 km/year in 2020 and keep constant in the following years.

Previous studies rarely reported VKT levels for intercity buses. CATARC [78] conducted VKT surveys for major bus manufacturers in China and determined that the stock-weighted VKT of all buses (including large, medium, and small buses) was 41000 km/year in 2013. Cai [82] reviewed the VKT of Chinese buses from different models and studies and found that the bus VKT was ~40000 km/year during 2000–2005, in good agreement with CATARC's survey results [78]. In this work, we use the CATARC results and constrain the VKT levels of intercity buses in China by subtracting the urban bus portion from the total distance traveled by all buses:

$$VKT_{\text{intercity bus}} = \frac{VKT_{\text{bus}} \cdot Stock_{\text{bus}} - VKT_{\text{urban bus}} \cdot Stock_{\text{urban bus}}}{Stock_{\text{bus}} - Stock_{\text{urban bus}}} \quad (15)$$

Based on Equation (15), we estimate the VKT of intercity buses in 2013 was ~37000 km/year. Due to the lack of data, we assume this value does not change over time in the *Base Case* of the model.

3.7.3 VKT of Trucks

Similar to situation with intercity buses, regular official statistics do not report on VKT levels of trucks. In the past decade, several survey studies have been conducted to determine VKT levels for trucks. For example, the 2008 *National Road Transportation Census* conducted by MoT of China [83] showed that the average VKT by LDTs and HDTs were 25000 and 65000 km/year, respectively. Huo et al. [73] collected VKT data for 513 trucks in three Chinese cities during the 2006–2010 timeframe and estimated that LDTs and HDTs traveled approximately 30000 and 60000 km/year, respectively. The surveys conducted by CATARC [78] in 2013 showed that the VKT of MiniTs, LDTs, MDTs, and HDTs were 19500, 28000, 35000, and 55000 km/year, respectively. Liu et al. [81] studied the Global positioning System (GPS) and Chinese BeiDou Navigation Satellite System (BDS) data from more than two million commercial trucks in 2015 and found that the VKT of LDTs, MDTs, and HDTs were in the range of 19000–45000, 21000–60000, and 24000–98000 km/year, respectively, depending on truck age.

The aforementioned survey results may not be applicable to the entire truck fleet in China, because these surveys mainly targeted trucks operating for commercial purposes, which have relatively high VKT. Alternatively, we constrain the average VKT levels of truck type i in year m by

$$VKT_{i,m} = \frac{V_m \cdot VS_{i,m}}{\theta_{i,m} \cdot C_i \cdot Stock_{i,m}} \quad (16)$$

where V is the total freight turnover volume for all trucks (in tonne-km); VS is the shares of freight turnover volume for different truck types; θ is the actual freight load rate; and C is the load capacity (in tonne). The historical freight turnover volume of trucks are obtained from the *China Statistical Yearbook* [1]. The load capacity of MiniTs, LDTs, MDTs, and HDTs are determined to be 1, 3.9, 10, and 30 tonnes, respectively, based on the vehicle classification standard GB/T3730.1-88. For the shares of freight turnover by truck type and the corresponding actual freight load rates, we use the results reported by MoT and Chang'an University [84], which were based on the database of expressway network toll system and the typical sampling investigation data at toll stations in China from 2006 to 2016. Here, we combine MiniTs and LDTs together and MDTs and HDTs together due to the structure of available data.

Figure 10 shows the derived truck VKT between 2006 and 2016. We estimate that the VKT of mini and LD trucks decreased from ~30000 km/year in 2006 to ~17000 km/year in 2016. In contrast, the VKT of MDTs and HDTs increased from ~30000 km/year in 2006 to ~40000 km/year in 2016. It seems that the VKT levels of trucks do not change significantly after 2013. Without further information, we assume the VKT of trucks would maintain current levels until 2050 in the *Base Case* of the model (Table 5).

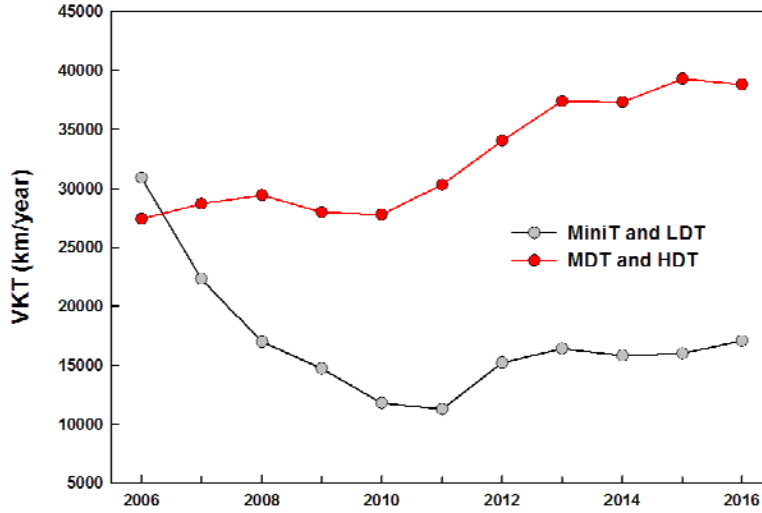


Figure 10. Estimated VKT for trucks from 2006 to 2016.

3.7.4 VKT Ratios by Age

According to the VKT data for developed countries (e.g., [16, 73]), the vehicle-use intensities tend to decrease as vehicle age increases. This trend has also been observed in the surveys by Huo et al. [73], Lin et al. [80], and Yang et al. [85] for different types of vehicles in China. As shown in Table 6, we take into account the VKT variation over vehicle lifetime in the China Vehicle Fleet Model, and relevant ratios are taken from Huo et al. [73] directly.

Table 6. Annual VKT variations by age over vehicle lifetime

Age (year)	Private LDPV and Business/fleet LDPV	Taxi LDPV	Urban bus	Intercity bus	MiniT and LDT	MDT and HDT
0	1.000	1.000	1.000	1.000	1.000	1.000
1	0.980	1.000	0.790	0.990	0.870	0.920
2	0.950	0.980	0.670	0.910	0.750	0.830
3	0.930	0.930	0.590	0.730	0.650	0.740
4	0.900	0.810	0.540	0.580	0.560	0.660
5	0.850	0.620	0.500	0.460	0.490	0.580
6	0.800	0.410	0.480	0.360	0.440	0.500
7	0.670	0.350	0.460	0.280	0.440	0.430
8	0.520	0.350	0.440	0.210	0.440	0.360
9	0.450	0.350	0.440	0.160	0.440	0.310
10	0.400	0.350	0.440	0.120	0.440	0.260
11	0.370	0.350	0.440	0.090	0.440	0.210
>=12	0.350	0.350	0.440	0.070	0.440	0.170

3.8 NEW VEHICLE FUEL CONSUMPTION RATES

3.8.1 Labeled Fuel Consumption Rates

In the past decade, China has implemented a series of fuel economy (FE) standards to lower the fuel consumption rates (FCR, measured in L/100 km) of gasoline and diesel-fueled vehicles and reduce the overall oil demand of the on-road transportation sector. Table 7 summarizes the target vehicle types, effective periods, and FCR decreases between different phases of these standards as of June 2017. A detailed review can be found in Hao et al. [86].

Since 2010, the MIIT of China has started to report the FCRs of all gasoline- and diesel-fueled models of light-duty vehicles (including LDPVs and trucks with GVW ≤ 3.5 tonnes) on an official website [87]. The FCRs are tested in the laboratory under the New European Driving Cycle (NEDC) and results must be shown on the window labels of each new vehicle. In addition, the Chinese government began releasing the calculation of Corporate Average Fuel Consumption (CAFC, similar to the concept of Corporate Average Fuel Economy, CAFE, in the United States) for new passenger vehicles annually in 2012 [88]. These official data provide the estimates of labeled FCRs for new LDPVs after 2012. Data for the sales-weighted average FCRs of new LDPVs before 2012 come from the studies by CATARC [78], the Innovation Center for Energy and Transportation [89], Ma et al. [90], Huo et al. [91, 92], Wagner et al. [93], and Wang et al. [94].

Table 7. Summary of fuel consumption rate standards for different highway vehicles in China. Applied to gasoline and diesel-fueled vehicles only

Vehicle type	Description	Standard	Effective period a	FCR decrease
Passenger vehicle	Passenger vehicles with nine seats or fewer, including passenger cars, sport-utility vehicles, multi-purpose vehicles, and crossovers	GB 19578-2004	2005–2007 (Ph-I)	
		GB 19578-2004	2008–2011 (Ph-II)	~10% compared to Ph-I
		GB 19578-2004 GB 27999-2011	2012–2015 (Ph-III)	~19% compared to Ph-II
		GB 19578-2014 GB 27999-2014	2016–2020 (Ph-IV)	~30% compared to Ph-III
Light-duty commercial vehicle	Vehicles with GVW ≤ 3.5 tonnes	GB 20997-2007	2009–2010 (Ph-I)	
		GB 20997-2007	2011–2017 (Ph-II)	~8% compared to Ph-I
		GB 20997-2015	From 2018 (Ph-III)	Cannot be compared b
Heavy-duty commercial vehicle	Vehicles with GVW > 3.5 tonnes	QC/T 924-2011 GB/T 27840-2011	2012–2014 (Ph-I)	
		GB 30510-2014	2014–2019 (Ph-II)	~12% compared to Ph-I
		GB xxxxx-xxxx under discussion	From 2019 (Ph-III)	~15% compared to Ph-II

^a Ph: Phase.

^b Ph-III standard for light-duty commercial trucks cannot be compared to standards for previous phases because the vehicle segment basis was changed from GVW/engine displacement-based in Ph-I and Ph-II to vehicle curb weight (VCW)-based in Ph-III.

Unlike for LDPVs, the Chinese government rarely reports the sales-weighted FCRs for buses and trucks. On the basis of limited data collected from bus drivers in several Chinese cities, Huo et al. [91] estimated that the real-world FCRs for conventional diesel urban buses and intercity buses were 40 and 22 L (diesel)/100 km, respectively, in 2009. These estimates are used directly in this work. Additionally, we extrapolate the historical FCRs for intercity buses based on the sales-weighted FCR trends of large-size and mid-size buses reported by CATARC [78]. For trucks, although MIIT has reported FCRs of MiniTs and partial LDTs with GVW of no more than 3.5 tonnes since 2010, the detailed vehicle sales by model and FCRs of MDTs and HDTs are not publicly available. Similar to intercity buses, we use Huo et al.'s [91] FCR estimates by truck type in the year 2009 and the FCR trends reported by CATARC [78] to derive the historical FCRs of trucks.

Regarding BEVs and PHEVs, detailed vehicle production and vehicle specification data are collected from the *Yearbook of Energy-Saving and New Energy Vehicles* [77], the *Trend Report on Vehicle Fuel Consumption in China* [95], the Energy-Saving and New Energy Automobile Network (www.chinaev.org), and a series of forthcoming *Catalogue[s] of the Models of New Energy Vehicles Exempt from Vehicle Purchase Tax* announced by the Chinese government. Based on these data, we calculate the production-weighted electricity consumption rates (e.g., kWh/100 km) of BEVs and the electricity and fuel consumption rates of the charge-depleting (CD) and charge-sustaining (CS) modes of PHEVs for the period between 2009 and 2016. Similar to the VISION model [3], we use the utility factor (UF) defined in SAE J2841 [96] to estimate electric VKT shares (i.e., the fraction of distance traveled in the CD mode of the PHEVs). Here, we use the production-weighted all-electric ranges of PHEVs in the calculation due to the lack of the traveling characterization studies for PHEVs in China.

For advanced vehicle technologies, the FCRs of which are not available, we estimate their FCRs through

$$FCR_{i,m} = FCR_{base,m} / \eta_{i,m} \quad (17)$$

where $\eta_{i,m}$ represents the FCR ratio of the base vehicle technology to the vehicle technology i in year m . In the China Vehicle Fleet Model, the base vehicle technologies are conventional internal combustion engine vehicle (ICEV)-gasoline for LDPVs and MiniTs and conventional ICEV-diesel for buses, LDTs, MDTs, and HDTs. We determine $\eta_{i,m}$ with the VISION model [3] by assuming that this ratio in China in year m would be similar to that in the United States when the U.S. FCR_{base} is comparable to the Chinese $FCR_{base,m}$. In the VISION model, U.S. FCR ratios are calculated based on FCRs for different vehicle technologies reported in the EIA's *Annual Energy Outlook* [3].

The future FCRs of new vehicles in the *Base Case* of the model are aligned with the *Technology Roadmap* [9] until 2030, which was published by SAE China to achieve a series of goals set by the Chinese government. For example, taking into account the contributions of NEVs, the *Energy-Saving and New Energy Vehicle Industrialization Plan* released by China's State Council in 2012 set fleet average targets of 6.9 L/100 km in 2015 (already achieved) and 5.0 L/100km in 2020 for new passenger vehicles [97]. In the recent "Made in China 2025" plan, the Chinese government further lowered this target to 4.0 L/100 km by 2025. For light-duty and heavy-duty commercial vehicles, "Made in China 2025" expected the fuel consumption rates could reach the levels of developed countries by 2025, which means a ~30% decrease in fuel consumption rates relative to the 2015 level. For all vehicle technologies after

2030, we assume that labeled FCRs for new vehicles in the *Base Case* will decrease at a fixed rate of 0.5%/year until 2050.

3.8.2 Real-world to Labeled Fuel Consumption Rate Ratios

It has been widely reported that there are differences between labeled and real-world FCRs because the driving cycles used in laboratory tests cannot fully reflect the real-world driving conditions [91, 92, 98–102]. Huo et al. [92] examined the differences between the labeled and real-world FCRs of LDPVs by using the data reported voluntarily by real-world drivers on the internet in China. They found that the real-world sales-weighted average FCR for new LDPVs in 2009 was 15% higher than the labeled ones. A 9–27% increase in real-world FCRs were also found for MiniTs and LDTs [91]. To reflect this impact on vehicle fleet energy consumption, we use a real-world-to-labeled FCR ratio of 1.15 for LDPVs, MiniTs, and LDTs. For inter-city buses, urban buses, MDTs, and HDTs, the real-world FCRs were either in good agreement with the labeled FCRs or used directly in this work [91]. Therefore, the real-world-to-labeled FCR ratios for these vehicles are set at 1. For BEVs and the CD mode of PHEVs, we assume the real-world-to-labeled FCR ratio at 1.4, based on earlier Argonne studies [3, 103, 104].

3.9 WELL-TO-WHEELS ENERGY USE AND GREENHOUSE GAS EMISSIONS

The well-to-wheels (WTW) analysis of the vehicle fleet covers both the well-to-pump (WTP, including the processes related to the production and the distribution of fuels/energies before fueling or charging vehicles) and the pump-to-wheels (PTW, vehicle operation) stages. The PTW energy use of the vehicle fleet in year m ($Energy_{PTW,m}$) can be determined by the number of vehicles, vehicle-use intensity, and vehicle fuel/energy consumption rate as

$$Energy_{PTW,m} = \sum_k Energy_{PTW,k,m} = \sum_k \sum_i \sum_j (Stock_{i,j,k,m} \cdot VKT_{i,j,k,m} \cdot FCR_{i,j,k,m}) \quad (18)$$

where k , i , and j represent fuel/energy type, vehicle technology, and vehicle age, respectively. $Stock_{i,j,k,m}$, $VKT_{i,j,k,m}$, and $FCR_{i,j,k,m}$ represent vehicle stock, annual vehicle kilometers traveled per vehicle (in km), and fuel/energy consumption rate (in, e.g., J/km), respectively, by vehicle technology i powered by fuel/energy k at vehicle age j in year m .

Similar to the VISION model [3], the WTP energy consumption for the vehicle fleet in year m ($Energy_{WTP,m}$) is divided into the fuel/energy production and fuel/energy feedstock production periods, and they are calculated as

$$\begin{aligned} Energy_{WTP,m} &= \sum_k Energy_{WTP,k,m} = \sum_k (Energy_{WTP_fuel,k,m} + Energy_{WTP_feedstock,k,m}) \\ &= \sum_k (Energy_{PTW,k,m} \cdot EI_{WTP_fuel,k,m} + Energy_{PTW,k,m} \cdot EI_{WTP_feedstock,k,m}) \end{aligned} \quad (19)$$

where $EI_{WTP_fuel,k,m}$ and $EI_{WTP_feedstock,k,m}$ represent energy intensities of fuel/energy k (i.e., energy consumption rate per unit of end use fuel/energy k , in, e.g., J/J) in year m during the fuel production and the feedstock production periods, respectively.

The WTW energy use of the vehicle fleet in year m ($Energy_{WTW,m}$) is then determined as

$$Energy_{WTW,m} = \sum_k Energy_{WTW,k,m} = \sum_k (Energy_{WTP,k,m} + Energy_{PTW,k,m}) \quad (20)$$

And the corresponding WTW GHG emissions for the vehicle fleet in year m ($GHG_{WTW,m}$) are calculated as

$$GHG_{WTW,m} = \sum_k GHG_{WTW,k,m} = \sum_k (Energy_{PTW,k,m} \cdot GI_{WTW,k,m}) \quad (21)$$

where $GI_{WTW,k,m}$ is the WTW GHG emission intensity of fuel/energy k (i.e., GHG emissions per unit of end use fuel/energy k , in , e.g., g CO₂-equivalent/J) in year m . Note that GHG emissions include the contributions of not only carbon dioxide (CO₂), but also methane (CH₄) and nitrous oxide (N₂O). Their global warming potentials (GWP, 100-year perspective) are from the *Fifth Assessment Report* (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC) [105], whereby 1g of CO₂, CH₄, and N₂O corresponds to 1g, 30g, and 265g of CO₂-equivalent (CO₂-eq), respectively.

The energy and GHG emission intensities of fuels and energies produced from different feedstock and pathways come from the simulation results calculated by the China GREET model. Developed by Argonne, GREET[®] is a widely used model for analyzing life-cycle energy and environmental impacts of alternative and new transportation fuels and advanced vehicle technologies [106]. We will document development details for the China GREET model in a separate report. In the beta version of the China Vehicle Fleet Model, we use previous estimates of energy and GHG emission intensities for fuels/energies [6] as placeholders. We will update these energy and GHG emission intensities in later versions of the China Vehicle Fleet Model once the China-GREET model is released.

4 MODEL USER GUIDE

4.1 GENERAL INFORMATION

The China Vehicle Fleet Model is a standalone, spreadsheet-type tool developed using Microsoft Excel 2016. The model has been tested with Microsoft Excel 2010 and later versions in Windows operating systems. It is not known whether the model will run in earlier versions of Excel or on Macintosh computers.

When opening the fleet model, if Excel asks if you want to enable the macro functions built into the file; click the *Enable* button so that the macro functions embedded in the model can operate properly.

By default, the *automatic* calculation feature of Excel is disabled to improve the model performance (i.e., the *manual* calculation feature is enabled when opening the model). Although turning on the *automatic* calculation will not affect the model's simulation results, we recommend not doing so in order to avoid slow calculation response. To check the current calculation mode setting or switch between *manual* and *automatic* calculation, in Excel 2010 and later versions, proceed to the *Ribbon*, select the *Formulas* tab, and click on the *Calculation Options* button of the *Calculation* grouping. When the model is closed, the Excel's calculation mode will return to its original status before the model was opened.

4.2 CHINA VEHICLE FLEET MODEL STRUCTURE

The China Vehicle Fleet Model consists of 57 Excel worksheets. These are divided into five function types, described briefly below:

1. **Overview**. This worksheet tab has a white background and presents the fleet model copyright statement, the model introduction, and a brief description of each of the worksheets. If you are a first-time user, we recommend that you read this sheet before using the China Vehicle Fleet Model.
2. **Index**. This worksheet tab has a light red background and shows the main user interface of the model. It includes hyperlinks to all worksheets, all inputs and results sections of the model, as well as a color-coding section for cells.
3. **Input worksheets**. These worksheet tabs have a light yellow background and present key control variables and key input parameters and assumptions for simulations. There are five input worksheets:
 - **Inputs VType**. This worksheet presents key parameters and assumptions at the vehicle type level, such as vehicle stocks and vehicle sales. Table 1 shows detailed vehicle classifications by type for the Chinese highway vehicle fleet. This worksheet also provides options for the calculation strategies of vehicle sales and vehicle stocks.

- Inputs VTechnology. This worksheet presents key parameters and assumptions at the vehicle technology level such as vehicle technology market shares, survival patterns, VKT and VKT by age patterns, and fuel consumption-related inputs. Table 1 shows detailed vehicle classification by technology for the Chinese highway vehicle fleet.
 - Inputs Upstream. This worksheet presents key parameters and assumptions related to the end-use fuels/energies consumed and their upstream processes such as the fuel blended shares for market-available gasoline and diesel, WTW GHG emission intensities by fuel/energy type, and energy use intensities of WTP fuel production and fuel feedstock production stages by fuel/energy type.
 - Macro Data. This worksheet presents macro-socioeconomic data used by the model, such as population and GDP.
 - Fuel Specification. This worksheet presents specifications for individual fuels, including carbon contents, densities, and lower heating values (LHV). This worksheet also lists unit conversion factors.
4. Model Results. This worksheet has a light green background and summarizes the model simulation results by vehicle technology, vehicle type, and fuel/energy type (if applicable). Results include PTW energy use in both energy and physical units, WTP fuel and fuel feedstock production stages energy use, PTW GHG emissions, WTW GHG emissions, vehicle stocks, new vehicle sales, total VKT of the vehicle fleet, fleet average VKT per vehicle, new vehicle FCRs, and fleet average FCRs, etc.
 5. Vehicle fleet turnover calculation worksheets. The model contains a total of 49 worksheets with orange background color, corresponding to the 49 vehicle technologies identified for the Chinese highway vehicle fleet (see Table 1 for these vehicle technologies). These worksheets present the detailed fleet turnover calculation processes and results for each vehicle technology.

In the following sections, we first introduce the general features and designs applied throughout the model's inputs and/or results worksheets. Later, we present a more detailed introduction to the model's main worksheets.

4.3 FEATURES APPLIED THROUGHOUT THE MODEL

4.3.1 Color-coding

The China Vehicle Fleet Model uses a color-coding system to help you easily identify different types of worksheets and cells. As introduced in Section 4.2, the white tab is used for the model Overview; the light red tab is used for the Index worksheet; the light yellow tabs are for input parameters/assumptions; the light green tab is used for results summaries; and the orange tabs are the vehicle fleet turnover calculation worksheets for individual vehicle technologies.

In addition, cells in the worksheets with different font colors and/or background colors have different meanings. Figure 11 summarizes the legend for color-coding of cells in the model. This information is also provided in the [Index](#) worksheet.



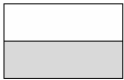
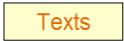





	Yellow cells are model input parameters that users can change
	Red cells indicate that input parameters are missing and needed to be filled
	Clear and gray cells are primarily for calculation. They should not be changed unless indicated by texts to change
	Explanation texts
	Blue numbers are pre-entered historical data
	Bold red numbers are in Scenario Case only, indicating they are different from corresponding numbers in Base Case
	Comment cells. Users are advised to read the comments
	Check boxes are in Scenario Case only: checked: use Base Case numbers; unchecked: use Scenario Case numbers
	

Figure 11. Color-coding of cells in the China Vehicle Fleet Model.

- All yellow cells represent input parameters/assumptions that you can change for your own simulations. If you forget to provide a required input parameter/assumption or delete it by accident, the yellow cell will automatically turn to red as a reminder to enter a parameter/assumption in it. Once you provide the input, the cell background will turn back to yellow.
- A cell with a clear or grey background typically indicates a calculated value. We do not recommend changing the values in these cells, unless you fully understand the potential consequences of those changes.
- Cells with a light yellow background color and an orange font provide instructions or explanations.
- Cells with blue numbers are historical data pre-entered by the model developer. We do not recommend changing the values in these cells, unless you fully understand the potential consequences of those changes.
- Cells with red triangle in the upper right corner contain important comments, which you should read.
- Cells with bold red numbers/contents are found in the *Scenario Case* section only; their numbers/contents are different from those in the corresponding cells of the *Base Case* section. Please refer to Section 4.3.4 for details.

- Checkboxes are Excel form controls that are also used in the *Scenario Case* section to help you configure scenario cases. The background color of checkboxes is light green when they are unchecked, indicating that the model is using the input parameters/assumptions given in the *Scenario Case* section. If the checkboxes are checked, their background color will change to light blue automatically, indicating that the model is using the default input parameters or assumptions given in the *Base Case* section. Please refer to Section 4.3.4 for details.

4.3.2 Layout of the Time Series Inputs

The China Vehicle Fleet Model uses a consistent design for nearly all the time series input sections to help you configure the model easily. Figure 12 shows a part of the *Vehicle Technology Market Shares* section in the *Inputs VTechnology* worksheet to illustrate the general steps for entering time series inputs data into the China Vehicle Fleet Model.

Vehicle Technology Market Shares								
Private LD Passenger Vehicle								
	ICE-Gasoline	EV	DCE-Diesel	DCE-CNG_LPG_LNG	DHEV-Gasoline	SI PHEV-Gasoline	F-CV	DCE-Methanol
		0.10%	0.20%	0.05%	0.01%	0.05%	0.01%	
2016	95.04%	0.35%	1.37%	2.60%	0.41%	0.24%	0.00%	0.00%
2020	82.42%	4.13%	1.50%	2.51%	8.00%	1.44%	0.00%	0.00%
2025	61.22%	10.26%	2.50%	2.47%	20.00%	3.50%	0.01%	0.04%
2030	27.85%	30.96%	3.50%	2.47%	25.00%	9.47%	0.03%	0.72%
1980	98.74%	0.00%	1.26%	0.00%	0.00%	0.00%	0.00%	0.00%
1985	96.88%	0.00%	3.12%	0.00%	0.00%	0.00%	0.00%	0.00%
1990	96.75%	0.00%	3.25%	0.00%	0.00%	0.00%	0.00%	0.00%
1995	96.67%	0.00%	3.33%	0.00%	0.00%	0.00%	0.00%	0.00%
2000	94.55%	0.00%	5.45%	0.00%	0.00%	0.00%	0.00%	0.00%
2005	95.19%	0.00%	3.31%	1.50%	0.00%	0.00%	0.00%	0.00%
2010	96.17%	0.01%	2.11%	1.70%	0.02%	0.00%	0.00%	0.00%
2015	95.18%	0.25%	1.68%	2.50%	0.17%	0.22%	0.00%	0.00%
2020	82.42%	4.13%	1.50%	2.51%	8.00%	1.44%	0.00%	0.00%
2025	61.22%	10.26%	2.50%	2.47%	20.00%	3.50%	0.01%	0.04%
2030	27.85%	30.96%	3.50%	2.47%	25.00%	9.47%	0.03%	0.72%
2035	25.75%	31.46%	4.50%	2.72%	25.05%	9.72%	0.08%	0.72%
2040	23.65%	31.96%	5.50%	2.97%	25.10%	9.97%	0.13%	0.72%
2045	21.55%	32.46%	6.50%	3.22%	25.15%	10.22%	0.18%	0.72%
2050	19.45%	32.96%	7.50%	3.47%	25.20%	10.47%	0.23%	0.72%

Figure 12. Screenshot of the input area of the “Vehicle Technology Market Shares” section.

As shown in Figure 12, the input section of *Vehicle Technology Market Shares* is organized in two dimensions: by variable type (i.e., vehicle technology type in this case) in columns and by year in rows. According to the color-coding described in Section 4.3.1, the yellow cells in Zone 1 of Figure 12 are input data representing vehicle technology market share projections you provide for a number of years. Cells with blue numbers in Zone 2 are historical market shares pre-entered by the model developer. Zone 3 provides you with some instructions. Based on the inputs entered in Zone 1, the model automatically interpolates the market shares linearly for all years, showing the results in Zone 2. Although the years displayed in Zone 1 should be presented in ascending order, they are not necessarily presented for equal time intervals (e.g., every five or ten years).

Following the instructions in Zone 3 of Figure 12, you can add more years' input data to the model. You should add years in ascending order following the existing years displayed in the input area (i.e., Zone 1). Figure 13 shows an example of adding an additional year (i.e., 2042) in Zone 1. Automatically, a new row with red cells will be added, reminding you to provide vehicle technology market shares for the newly added year 2042. Once you enter the inputs, the background color of these red cells will turn to yellow.

Private LD Passenger Vehicle								
	ICE-Gasoline	EV	ICE-Diesel	ICE-CNG_LPG_LNG	HEV-Gasoline	SI PHEV-Gasoline	FCV	ICE-Methanol
Default annual market share increase per year-->		0.10%	0.20%	0.05%	0.01%	0.05%	0.01%	
2016	95.04%	0.35%	1.37%	2.60%	0.41%	0.24%	0.00%	0.00%
2020	82.42%	4.13%	1.50%	2.51%	8.00%	1.44%	0.00%	0.00%
2025	61.22%	10.26%	2.50%	2.47%	20.00%	3.50%	0.01%	0.04%
2030	27.85%	30.96%	3.50%	2.47%	25.00%	9.47%	0.03%	0.72%
2042	100.00%							
Add more years (in ascending order) here -->								

Figure 13. Screenshot of adding a year in the input area of the “Vehicle Technology Market Shares” section.

To avoid potential calculation errors in calculation, please ensure that there is no year gap between the first year of inputs in Zone 1 of Figure 12 and the last year of the historical data in Zone 2 (i.e., the latest year with blue numbers).

4.3.3 Buttons to Show Time Series Data

On the left side of Figure 12, there are three buttons that help you review the data in Zone 2. Clicking these buttons will expand or collapse Zone 2 to show historical and/or calculated results every 1, 5, or 10 years. For example, Figure 12 shows the screenshot after clicking the button **Every 5 Yrs**. Figure 14 shows the screenshots resulting from clicking the **Show All Yrs** and **Every 10 Yrs** buttons. This feature

applies not only to the time series input sections, but also to all the output sections in the **Model Results** worksheet.

Private LD Passenger Vehicle									
	ICE-Gasoline	EV	ICE-Diesel	ICE-CNG_LPG_LNG	HEV-Gasoline	SPHEV-Gasoline	FCV	ICE-Methanol	
Default annual market share increase per year-->		0.10%	0.20%	0.05%	0.01%	0.05%	0.01%		
2016	95.04%	0.35%	1.37%	2.60%	0.41%	0.24%	0.00%	0.00%	
2020	82.42%	4.13%	1.50%	2.51%	8.00%	1.44%	0.00%	0.00%	
2025	61.22%	10.26%	2.50%	2.47%	20.00%	3.50%	0.01%	0.04%	
2030	27.85%	30.96%	3.50%	2.47%	25.00%	9.47%	0.03%	0.72%	
Add more years (in ascending order) here -->									
Show All Yrs	Every 5 Yrs	Every 10 Yrs							
1980	98.74%	0.00%	1.26%	0.00%	0.00%	0.00%	0.00%	0.00%	
1981	97.66%	0.00%	2.34%	0.00%	0.00%	0.00%	0.00%	0.00%	
1982	97.49%	0.00%	2.51%	0.00%	0.00%	0.00%	0.00%	0.00%	
1983	97.95%	0.00%	2.05%	0.00%	0.00%	0.00%	0.00%	0.00%	
1984	97.53%	0.00%	2.47%	0.00%	0.00%	0.00%	0.00%	0.00%	
1985	96.88%	0.00%	3.12%	0.00%	0.00%	0.00%	0.00%	0.00%	
1986	98.40%	0.00%	1.60%	0.00%	0.00%	0.00%	0.00%	0.00%	
1987	98.71%	0.00%	1.29%	0.00%	0.00%	0.00%	0.00%	0.00%	
1988	97.94%	0.00%	2.06%	0.00%	0.00%	0.00%	0.00%	0.00%	

Private LD Passenger Vehicle									
	ICE-Gasoline	EV	ICE-Diesel	ICE-CNG_LPG_LNG	HEV-Gasoline	SPHEV-Gasoline	FCV	ICE-Methanol	
		0.10%	0.20%	0.05%	0.01%	0.05%	0.01%		
2016	95.04%	0.35%	1.37%	2.60%	0.41%	0.24%	0.00%	0.00%	
2020	82.42%	4.13%	1.50%	2.51%	8.00%	1.44%	0.00%	0.00%	
2025	61.22%	10.26%	2.50%	2.47%	20.00%	3.50%	0.01%	0.04%	
2030	27.85%	30.96%	3.50%	2.47%	25.00%	9.47%	0.03%	0.72%	
1980	98.74%	0.00%	1.26%	0.00%	0.00%	0.00%	0.00%	0.00%	
1990	96.75%	0.00%	3.25%	0.00%	0.00%	0.00%	0.00%	0.00%	
2000	94.55%	0.00%	5.45%	0.00%	0.00%	0.00%	0.00%	0.00%	
2010	96.17%	0.01%	2.11%	1.70%	0.02%	0.00%	0.00%	0.00%	
2020	82.42%	4.13%	1.50%	2.51%	8.00%	1.44%	0.00%	0.00%	
2030	27.85%	30.96%	3.50%	2.47%	25.00%	9.47%	0.03%	0.72%	
2040	23.65%	31.96%	5.50%	2.97%	25.10%	9.97%	0.13%	0.72%	
2050	19.45%	32.96%	7.50%	3.47%	25.20%	10.47%	0.23%	0.72%	

Figure 14. Screenshots of clicking the “Show All Yrs” button (left) and the “Every 10 Yrs” button (right) in the “Vehicle Technology Market Shares” section.

4.3.4 Base Case vs. Scenario Case

The China Vehicle Fleet Model allows you to configure a *Base Case* and a *Scenario Case* simultaneously for the model simulation. Here, *Base Case* is a reference case defined by the model developer (or further revised by the user). The default *Base Case* in the model is configured based on the method described in Section 3 and reflects Argonne’s up-to-date understanding of the Chinese highway vehicle fleet and relevant Chinese policies, regulations, and standards in the future. For the *Scenario Case*, you can make a number of changes relative to the *Base Case* to see how these changes influence the results. In the China Vehicle Fleet Model, *Base Case* and *Scenario Case* sections for all inputs and results worksheets are designed with the following color scheme:

Base Case

Scenario Case

Again, we use the *Vehicle Technology Market Shares* section in the **Inputs_VTechnology** worksheet as an example to illustrate the steps to configure the *Scenario Case*. As shown in Figure 15, the *Base Case* section is on the left side and the *Scenario Case* section is on the right side (note that a number of columns in *Base Case* are hidden). Different from the *Base Case* section, there are checkboxes above each series of inputs in the *Scenario Case* section (i.e., BV5:CB5 in Figure 15). If a checkbox is checked, its background color will change to light blue (i.e., color scheme of *Base Case*) and its corresponding Zone 1 area in *Scenario Case* will turn grayed. In this case, the cells in Zone 2 below the checkbox will be equal to the corresponding Zone 2 cells in the *Base Case*. Using Figure 15 as an example, the checkboxes for the market shares of all private LDPV technologies (except for ICEV-Gasoline, because its market share is automatically calculated to comprise the proportion of the remaining share) are

[illegible]

AB	C	D	E	F	G	H	I	J	K	L	BT	BU	BV	BW	BX	BY	BZ	CA	CB	
1	Return to Index		Base Case			Base Case			Base Case			Scenario Case			Scenario Case					
2																				
3																				
4	Vehicle Technology Market Shares																			
5																				
6			Private LD Passenger Vehicle									Private LD Passenger Vehicle								
7			ICE-Gasoline	EV	ICE-Diesel	ICE-CNG_LPG_LNG	HEV-Gasoline	SIPHEV-Gasoline	FCV	ICE-Methanol		ICE-Gasoline	EV	ICE-Diesel	ICE-CNG_LPG_LNG	HEV-Gasoline	SIPHEV-Gasoline	FCV	ICE-Methanol	
8	Default annual market share increase per year-->			0.10%	0.20%	0.05%	0.01%	0.05%	0.01%											
9		2016	96.04%	0.35%	1.37%	2.60%	0.41%	0.24%	0.00%	0.00%	2016									
10		2020	82.42%	4.13%	1.50%	2.51%	8.00%	1.44%	0.00%	0.00%	2020									
11		2025	61.22%	10.26%	2.50%	2.47%	20.00%	3.50%	0.01%	0.04%	2028									
12		2030	27.65%	30.96%	3.50%	2.47%	25.00%	9.47%	0.03%	0.72%	2033									
13	Add more years (in ascending order) here -->										2047									
14																				
15																				
16																				
17																				
18																				
19																				
20																				
21	Show All Yrs	Every 5 Yrs	Every 10 Yrs	1980	98.74%	0.00%	1.26%	0.00%	0.00%	0.00%	0.00%	1980	98.74%	0.00%	1.26%	0.00%	0.00%	0.00%	0.00%	
22				1990	96.75%	0.00%	3.25%	0.00%	0.00%	0.00%	0.00%	1990	96.75%	0.00%	3.25%	0.00%	0.00%	0.00%	0.00%	
23				2000	94.55%	0.00%	5.45%	0.00%	0.00%	0.00%	0.00%	2000	94.55%	0.00%	5.45%	0.00%	0.00%	0.00%	0.00%	
24				2010	96.17%	0.01%	2.11%	1.70%	0.02%	0.00%	0.00%	2010	96.17%	0.01%	2.11%	1.70%	0.02%	0.00%	0.00%	
25				2020	82.42%	4.13%	1.50%	2.51%	8.00%	1.44%	0.00%	2020	85.42%	4.13%	1.50%	2.51%	5.00%	1.44%	0.00%	
26				2030	27.85%	30.96%	3.50%	2.47%	25.00%	9.47%	0.03%	2030	42.68%	30.96%	3.50%	2.47%	6.40%	9.47%	3.80%	
27				2040	23.65%	31.96%	5.50%	2.97%	25.10%	9.97%	0.13%	2040	34.88%	31.96%	5.50%	2.97%	7.50%	9.97%	6.50%	
28				2050	19.45%	32.96%	7.50%	3.47%	25.20%	10.47%	0.23%	2050	28.88%	32.96%	7.50%	3.47%	8.00%	10.47%	8.00%	

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If the checkbox is unchecked, its background color will change to light green (i.e., the color scheme of the *Scenario Case*). In this case, the input cells in Zone 2 below the checkbox will be shown, enabling you to provide your own inputs (see steps described in Section 4.3.2). The China Vehicle Fleet Model will further use these user-defined inputs in the model simulation. Figure 16 is an example showing that the checkboxes for hybrid electric vehicle (HEV)-Gasoline and FCV for the private LDPV are unchecked and some random market shares of these two vehicle technologies have been entered.

For convenience, we design a feature in the *Scenario Case* section to automatically highlight the input parameters/assumptions that are different from the corresponding ones in the *Base Case* section. As shown in Figure 16, these contents have red bold font, implying that they are different from the values in *Base Case*.

Additionally, we provide checkboxes in the first column of the *Scenario Case* section (e.g., cell BT5 in Figure 15 and Figure 16) that enable you to check or uncheck all checkboxes simultaneously in this input section (e.g., i.e., *Vehicle Technology Market Shares* in Figure 15 and Figure 16).

4.4 “INDEX” WORKSHEET

The [Index](#) worksheet is the main user interface for the model. It provides hyperlinks to all other model worksheets and all inputs and results sections. It also includes color-coded worksheet tabs and cells. For all the other worksheets (except for [Overview](#)), there are [Return to Index](#) buttons, allowing you to navigate back to the [Index](#) worksheet.

4.5 “INPUTS_VTYPE” WORKSHEET

The [Inputs_VType](#) worksheet presents key input parameters and assumptions related to stocks and sales at the vehicle-type level. From top to down, it includes three sections:

- [Vehicle Stocks](#)
- [Vehicle Sales](#)
- [Stock Correction Factors](#)

The China Vehicle Fleet Model allows you to choose one of these three options to provide inputs for stocks or sales by vehicle type for the model simulation. The options are designed as Excel radio button form controls and you can only select one option at a time. [Option 1](#) and [Option 2](#) are used for the stock inputs and they are in the [Vehicle Stocks](#) section. [Option 3](#) is used for the sale inputs and it is in the [Vehicle Sales](#) section.

4.5.1 Vehicle Stocks

[Option 1](#) is the default option for the China Vehicle Fleet Model that determines the future vehicle stocks by type through a number of key parameters. For private LDPVs, the model provides pre-calculated stock projections at different LDPV ownership saturation levels on the basis of the method described in Section 3.3.1. The model allows you to set an ownership saturation level so that the LDPV stock

projection can be linearly interpolated through these pre-calculated cases. For other vehicle types, the model projects stocks based on either (a) their ownership or (b) stock ratios relative to known vehicle types in the year 2050 (see Section 3.3.2). You should not change the pre-calculated LDPV stock projections; they will be updated in future releases of the model.

Option 2 allows you to enter the future vehicle stock levels directly into the model in cases where you have your own projections of vehicle stocks by type. Sections 4.3.2 and 4.3.4 describe the steps for entering time series data and configuring the *Scenario Case*.

4.5.2 Vehicle Sales

In the case of either **Option 1** or **Option 2**, vehicle sales by type in the future are back-calculated through the vehicle stock changes and the vehicle fleet scrapped stocks (i.e., Equation (10) in Section 3.5). Additionally, the China Vehicle Fleet Model provides a third option that allows you to enter projected vehicle sales by type directly. In this case, the vehicle stocks by type in the future are calculated through Equation (12). Sections 4.3.2 and 4.3.4 describe the steps for entering time series data and configuring the *Scenario Case*.

4.5.3 Stock Correction Factors

The China Vehicle Fleet Model has a built-in module to calculate the stock correction factors automatically for each vehicle type to ensure that the stocks, sales, technology market shares, and survival rates are internally consistent. The stock correction factors are computed as the ratio of the calculated vehicle stocks to the vehicle stock inputs. They are not inputs and you do not need to change them. Stock correction factors are not applicable for future years in **Option 3**, and they are set at 1 in this case.

4.6 “INPUTS_VTECHNOLOGY” WORKSHEET

The **Inputs_VTechnology** worksheet presents key input parameters and assumptions at the vehicle technology level. From top to down, it includes seven sections:

- Vehicle Technology Market Shares
- Survival Patterns
- Fleet Average VKT per Vehicle
- VKT Ratio by Age Patterns
- New Vehicle Labeled FCRs
- New Vehicle FCR Ratios
- Real-world to Labeled FCR Ratios

4.6.1 Vehicle Technology Market Shares

The *Vehicle Technology Market Shares* section allows you to define the shares of the new vehicle sales of individual vehicle technologies for each vehicle type. Note that the market shares of the following vehicle technologies are calculated automatically to comprise the proportion of the remaining market:

- Private LDPV: ICEV-gasoline
- Taxi LDPV: ICEV-gasoline
- Business/fleet LDPV: ICEV-gasoline
- Urban bus: ICEV-diesel
- Intercity bus: ICEV-diesel
- MiniT: ICEV-gasoline
- LDT: ICEV-diesel
- MDT: ICEV-diesel
- HDT: ICEV-diesel

The steps for entering the time series data and configure the *Scenario Case* are described in Sections 4.3.2 and 4.3.4, respectively. In addition, in the first row of the input area, the model allows you to define default annual increases in market shares of individual vehicle technologies. These annual increase rates determine how the market shares change after the maximum year specified in the time series input area.

4.6.2 Survival Patterns

Survival Pattern

Select a survival pattern:
(See table on right for details)

Zone 2

- Sur1-LDPV: China, Hao
- Sur2-Taxi: China, Hao
- Sur3-Intercity Bus: China, Huo
- Sur4-LD truck: China
- Sur5-MD truck: China
- Sur6-HD truck: China
- Sur7-Car: Japan, Huo
- Sur8-Car: Europe, Huo
- Sur9-Car: US, Huo
- Sur10-Car: China to Japan transition, Huo
- Sur11-Car: China to Europe transition, Huo
- Sur12-Car: China to US transition, Huo
- Sur13-Urban Bus: China, Hao
- Sur14-Business: China, Hao

Zone 1

Private LD Passenger Vehicle										Taxi		
ICE-Gasoline	EV	ICE-Diesel	ICE-CNG_LPG_LNG	HEV-Gasoline	SI PHEV-Gasoline	FCV	ICE-Methanol	ICE-Gasoline	EV	ICE-Diesel		
1980 Sur1	r1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur2	Sur2	Sur2		
1990 Sur1	r1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur2	Sur2	Sur2		
2000 Sur2	r1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur2	Sur2	Sur2		
2010 Sur3	r1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur2	Sur2	Sur2		
2020 Sur4	r1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur2	Sur2	Sur2		
2030 Sur5	r1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur2	Sur2	Sur2		
2040 Sur6	r1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur2	Sur2	Sur2		
2050 Sur7	r1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur1	Sur2	Sur2	Sur2		

Figure 17. Screenshot of the input area of the “Survival Patterns” section.

The *Survival Patterns* section allows you to define survival rates of individual vehicle technologies. Figure 17 shows the layout of the *Survival Patterns* section. Each cell in Zone 1 is a dropdown list from which you can specify a specific survival pattern for the selected vehicle technology. The meanings of individual survival patterns in the dropdown list are briefly described in Zone 2 and their detailed explanations and definitions are provided in a table on the far right side of the *Survival Patterns* section (i.e., after *Scenario Case*, see Figure 18). The survival rates in the China Vehicle Fleet Model follow the

Logistic model in Equation (6); Section 3.4 describes the default parameterizations of survival patterns in Figure 18. Section 4.3.4 provides the steps for configuring the *Scenario Case*.

Survival patterns follow Logistic model, i.e., $\text{Survival rate} = 1 / (1 + \exp[a(\text{year} / L_{50} - 1)])$														
L_{50} : the age at which 50% of the vehicles have retired; a: shape factor														
Pattern No.	Sur1	Sur2	Sur3	Sur4	Sur5	Sur6	Sur7	Sur8	Sur9	Sur10	Sur11	Sur12	Sur13	Sur14
L_{50}	13.33	4.5	10.61	6.1	9.38	11.91	12.72	14.07	17.33	11.86	12.53	14.16	7.50	12.16
a	7.1	45	7.71	8.25	8.25	8.25	4.03	6.10	3.93	6.11	7.15	6.07	75.00	7.89
List	Sur1-LDPV: China, Hao	Sur2-Taxi: China, Hao	Sur3-Intercity Bus: China, Huo	Sur4-LD truck: China	Sur5-MD truck: China	Sur6-HD truck: China	Sur7-Car: Japan, Huo	Sur8-Car: Europe, Huo	Sur9-Car US, Huo	Sur10-Car: China to Japan transition, Huo	Sur11-Car: China to Europe transition, Huo	Sur12-Car: China to US transition, Huo	Sur13-Urban Bus: China, Hao	Sur14-Business: China, Hao
Reference														

Figure 18. Screenshot of the survival rate definition table.

4.6.3 Fleet Average VKT per Vehicle

This section allows you to define the fleet average VKT per vehicle at the vehicle technology level. Section 3.7 describes the historical data and default future projections for fleet average VKT. Sections 4.3.2 and 4.3.4 provide the steps to input the time series data and configure the *Scenario Case*.

4.6.4 VKT Ratio by Age Patterns

The *VKT Ratio by Age Patterns* section allows you to define the VKT variation patterns over the vehicle lifetime for individual vehicle technologies. The design of this section is analogous to the *Survival Patterns* section described in Section 4.6.2. Each cell in the input area is a dropdown list from which you can specify a specific VKT ratio by age pattern for the selected vehicle technology. The definitions of individual patterns in the dropdown list can be found in a table on the far right side of the *VKT Ratio by Age Patterns* section (i.e., after *Scenario Case*). Section 4.3.4 provides the steps to configure the *Scenario Case*.

4.6.5 New Vehicle Labeled FCRs

The *New Vehicle Labeled FCRs* section and the following *New Vehicle FCR Ratios* section (described in Section 4.6.6) together determine the labeled FCRs of new vehicles for individual vehicle technologies. Section 3.8.1 describes the method and data sources for labeled FCRs. Figure 19 shows the screenshot of these two sections. Each cell in the first row of the input area of the *New Vehicle Labeled FCRs* section is a dropdown selector that allows you to choose either **FCR** or **Ratio**. If you select **FCR**, the model will use the FCRs specified in the input area of *New Vehicle Labeled FCRs* to calculate the yearly FCRs for the selected vehicle technology. Meanwhile, the input area of the same vehicle technology in the *New Vehicle FCR Ratios* section will turn gray (e.g., BEV for both private and taxi LDPV in Figure 19). Similarly, if you select **Ratio**, the model will use the FCR ratios specified in the *New Vehicle FCR Ratios* section to calculate the yearly FCRs. In this case, the input area of the vehicle technology in the *New Vehicle Labeled FCRs* section will turn gray (e.g., ICEV-diesel, ICEV-NG, HEV-gasoline, FCV, and ICEV-methanol of private LDPV in Figure 19).

New Vehicle Labeled Fuel Consumption Rates												
Unit: Gasoline-eq L/100 km												
Private LD Passenger Vehicle										Taxi LD		
ICE-Gasoline	EV	ICE-Diesel	ICE-CNG_LPG_LNG	HEV-Gasoline	SI PHEV-Gasoline See details here	FCV	ICE-Methanol	ICE-Gasoline	EV	ICE-Diesel		
FCR	FCR	Ratio	Ratio	Ratio		Ratio	Ratio	FCR	FCR	Ratio		
0.00%	0.00%							0.00%	0.00%			
2015	7.04	1.52						7.04	1.52			
2020	5.70	1.60						5.70	1.60			
2025	5.20	1.52						5.20	1.52			
2030	4.80	1.44						4.80	1.44			
Add more years (in ascending order) here ---->												
Show All Yrs	Every 5 Yrs	Every 10 Yrs										
1980	9.15	3.00	7.32	8.17	6.44	5.18	5.98	9.53	9.15	3.00	7.32	
1990	9.15	3.00	7.32	8.17	6.44	5.18	5.98	9.53	9.15	3.00	7.32	
2000	9.15	3.00	7.32	8.17	6.44	5.18	5.98	9.53	9.15	3.00	7.32	
2010	7.71	1.87	6.17	6.88	5.43	4.64	5.04	8.03	7.71	1.87	6.17	
2020	5.70	1.60	5.04	5.09	4.01	2.74	3.80	5.94	5.70	1.60	5.04	
2030	4.80	1.44	4.57	4.29	3.38	2.24	3.80	5.00	4.80	1.44	4.57	
2040	4.80	1.44	4.57	4.29	3.38	2.24	3.80	5.00	4.80	1.44	4.57	
2050	4.80	1.44	4.57	4.29	3.38	2.24	3.80	5.00	4.80	1.44	4.57	
New Vehicle Fuel Consumption Rate Ratios												
Gasoline-eq Ratio												
Private LD Passenger Vehicle										Taxi LD		
ICE-Gasoline	EV	ICE-Diesel	ICE-CNG_LPG_LNG	HEV-Gasoline	SI PHEV-Gasoline	FCV	ICE-Methanol	ICE-Gasoline	EV	ICE-Diesel		
2015		1.25	1.12	1.42		1.53	0.96			1.25		
2020		1.13	1.12	1.42		1.50	0.96			1.13		
2025		1.05	1.12	1.42		1.37	0.96			1.05		
2030		1.05	1.12	1.42		1.26	0.96			1.05		
Add more years (in ascending order) here ---->												
Show All Yrs	Every 5 Yrs	Every 10 Yrs										
1980		1.25	1.12	1.42		1.53	0.96			1.25		
1990		1.25	1.12	1.42		1.53	0.96			1.25		
2000		1.25	1.12	1.42		1.53	0.96			1.25		
2010		1.25	1.12	1.42		1.53	0.96			1.25		
2020		1.13	1.12	1.42		1.50	0.96			1.13		
2030		1.05	1.12	1.42		1.26	0.96			1.05		
2040		1.05	1.12	1.42		1.26	0.96			1.05		
2050		1.05	1.12	1.42		1.26	0.96			1.05		

Figure 19. Screenshot of the “New Vehicle Labeled FCRs” and the “New Vehicle FCR Ratios” sections.

Please note that all FCRs specified in this section should be in the unit of gasoline-equivalent liter per 100 km (i.e., gasoline-eq. L/100km). Furthermore, the following vehicle technologies are treated as bases so that the FCR ratios specified in the [New Vehicle FCR Ratios](#) section can be applied to calculate the FCRs of other vehicle technologies (see Section 4.6.6). For this reason, **FCR** is the only the option available for these base technologies (e.g., ICEV-gasoline of private LDPV in Figure 19).

- | | |
|------------------------------|-----------------------------------|
| • Private LDPV ICEV-gasoline | for all the other LDPVs |
| • Urban bus ICEV-gasoline | for all the other Urban buses |
| • Intercity bus ICEV-diesel | for all the other Intercity buses |
| • MiniT ICEV-gasoline | for all the other MiniTs |
| • LDT ICEV-diesel | for all the other LDTs |
| • MDT ICEV-diesel | for all the other MDTs |
| • HDT ICEV-diesel | for all the other HDTs |

When **FCR** is selected, the second row of the input area allows you to define default annual FCR improvement rates relative to the previous year for individual vehicle technologies. These annual improvement rates determine how the labeled FCRs change after the maximum year specified in the time series input area. Sections 4.3.2 and 4.3.4 provide the steps to input the time series data and configure the *Scenario Case*.

PHEV vehicle technologies (including PHEV-gasoline for private, taxi, and business/fleet LDPV and PHEV-diesel and PHEV-NG for urban bus) are treated differently from the other single-power-source technologies. The FCR of a PHEV vehicle technology is calculated as the VKT weighted aggregation of the FCRs in the CD (on electricity) and CS (on fuels) modes (e.g., PHEV-gasoline column in Figure 19). To achieve this, the inputs of each PHEV technology are further split across three columns at the end of the main input area (i.e., columns BC:BQ in *Base Case* and columns DS:EG in *Scenario Case*): the first column for electric VKT share, the second column for FCR on fuels (e.g., gasoline, diesel, or NG), and the third column for FCR on electricity within the vehicle's all-electric range. The electric VKT share (i.e., the percentage of VKT traveled on electricity) is automatically calculated based on the all-electric range using a mathematical formula defined in SAE J2841 [96]. The all-electric range is an input parameter located below the electric VKT share in the [New Vehicle FCR Ratios](#) section. The headings for all PHEV technologies provide hyperlinks so that you can easily navigate between the PHEV-related input parameters.

4.6.6 New Vehicle FCR Ratios

The [New Vehicle FCR Ratios](#) section is closely related to the [New Vehicle Labeled FCRs](#) section described in Section 4.6.5. It allows you to specify the FCR ratios of the base vehicle technology to the other technologies. As introduced in Section 4.6.5, selecting the option of **Ratio** for a vehicle technology in the [New Vehicle Labeled FCRs](#) section enables the input area for this technology in the [New Vehicle FCR Ratios](#) section. The model will then calculate the FCRs of this vehicle technology through the FCR ratios specified in this section and the FCRs of the corresponding base technology (see Section 4.6.5 for the list of base technologies) using Equation (17).

The FCR ratios specified in this section should be gasoline-equivalent liter ratios. Section 3.8.1 describes the methodology for determining default FCR ratios. Section 4.3.2 provides the steps to input the time series data. Please note that the New Vehicle FCR Ratios section shares same checkboxes with the New Vehicle Labeled FCRs section (Section 4.6.5) in the *Scenario Case*.

4.6.7 Real-world to Labeled FCR Ratios

The Real-world to Labeled FCR Ratios section defines the difference between the real-world FCRs and labeled FCRs for individual vehicle technologies. Each cell in the first row of the input area is a dropdown selector which asks you whether to consider the difference between real-world FCRs and laboratory condition FCRs. If you select **No**, the input area of the selected vehicle technology will turn gray and the China Vehicle Fleet Model will use the labeled FCRs calculated based on sections of New Vehicle Labeled FCRs and New Vehicle FCR Ratios in model simulations. If you select **Yes**, the model will use the real-world to labeled FCR ratios specified in this section to correct the labeled FCRs. Section 3.8.2 describes the default ratios for difference vehicle types, technologies, and/or operational modes used in the model. Sections 4.3.2 and 4.3.4 provide the steps to input the time series data and configure the *Scenario Case*.

4.7 “INPUTS_UPSTREAM” WORKSHEET

The Inputs Upstream worksheet presents key input parameters and assumptions related to the end-use fuels/energies consumed and their upstream processes by fuel/energy type. From top to down, it includes four sections:

- Blending Levels of Alternative Fuels
- WTW GHG Emission Intensities
- WTP Fuel Feedstock Production Stage Energy Use Intensities
- WTP Fuel Production Stage Energy Use Intensities

4.7.1 Blending Levels of Alternative Fuels

The Blending Levels of Alternative Fuels section allows you to specify the volume percentages of alternative fuels that are blended with the petroleum fuels: ethanol and methanol in market-available gasoline and biodiesel and Fischer-Tropsch diesel (FTD) in market-available diesel. As mentioned in Section 3.9, the PTW energy use of market available gasoline and diesel fuels can be calculated through Equation (18). The China Vehicle Fleet Model further splits the energy uses of these two market fuels to individual blended fuels (i.e., ethanol, methanol, petroleum gasoline, biodiesel, FTD, and petroleum diesel) based on their energy shares. Here, densities and heating values (described in Section 4.9) of these fuels are used to convert the volume market shares to mass and energy market shares.

In the first row of the input area, the model allows you to define default annual increases in blending volume shares of alternative fuels. These annual increase rates determine how the volume market shares change after the maximum year specified in the time series input area. Sections 4.3.2 and 4.3.4 provide

the steps to input the time series data and configure the *Scenario Case*. Note that the volume market shares of petroleum gasoline and petroleum diesel are calculated automatically to comprise the proportion of the remaining market.

The historical volume market shares of alternative fuels are collected or estimated from a variety of data sources, including *World Energy Statistics* by the International Energy Agency (IEA) [107], *China Energy Statistical Yearbooks* [108], *Energy Statistics* by the Energy Foundation [109], *China Chemical Industry Yearbooks* [110], and data released on the websites of industry associations. Future market shares are estimated based on national plans such as the National Development and Reform Commission's "13th Five-Year Plan for the Development of Renewable Energy" and "the Medium and Long Term Renewable Energy Development Plan," and the National Energy Administration's "Development Policies for the Biodiesel Industry."

4.7.2 WTW GHG Emission Intensities

The *WTW GHG Emission Intensities* section allows you to specify the WTW GHG emission intensities (i.e., g CO₂ equivalent emissions per Megajoule [MJ] of fuel or energy) for 10 types of end-use fuels/energies included in the China Vehicle Fleet Model: petroleum gasoline, petroleum diesel, electricity, ethanol, methanol, NG, dimethyl ether (DME), biodiesel, FTD, and hydrogen. Particularly for electricity and ethanol, the model computes share-weighted GHG emission intensities from a number of pathways to produce these two fuels/energies (i.e., electricity generation pathways from coal, oil, NG, nuclear, biomass, geothermal, and other renewable sources, and ethanol production pathways from feedstock of starch, corn, corn stover, switchgrass, forest residue, sugarcane, etc.). You can specify the WTW GHG emission intensities and shares of individual pathways. The headings of the electricity and ethanol sections provide hyperlinks so that you can easily navigate between relevant input parameters. Sections 4.3.2 and 4.3.4 provide the steps to input the time series data and configure the *Scenario Case*. Note that the pathway shares of coal for electricity generation and starch for ethanol production are calculated automatically to comprise the proportion of the remaining shares.

The default GHG emission intensities of fuels and energies produced from different feedstock and pathways are preliminary from Huo et al. [6]. They will be updated later with a China version of the GREET[®] model, the configuration of which will be described in a separate report. For the electricity generation from different sources, the historical generation shares are from the IEA *World Energy Statistics* [107], *China Energy Statistical Yearbooks* [108], and data released on the web site of China Electricity Council (<http://www.cec.org.cn/>). The future electricity generation shares are derived from the reference case of the IEA's *Energy Technology Perspectives* [111].

4.7.3 WTP Fuel Feedstock Production Stage Energy Use Intensities

The *WTP Fuel Feedstock Production Stage Energy Use Intensities* section allows you to specify the energy use intensities (i.e., MJ energy use per MJ fuel/energy produced) during the fuel's feedstock production period for 10 types of end-use fuels/energies. The design of this section is analogous to *WTW GHG Emission Intensities* in Section 4.7.2. Sections 4.3.2 and 4.3.4 provide the steps to input the time series data and configure the *Scenario Case*.

4.7.4 WTP Fuel Production Stage Energy Use Intensities

The *WTP Fuel Production Stage Energy Use Intensities* section allows you to specify the energy use intensities (i.e., MJ energy use per MJ fuel/energy produced) during the fuel production period for 10 types of end-use fuels/energies. The design of this section is analogous to *WTW GHG Emission Intensities* in Section 4.7.2. Sections 4.3.2 and 4.3.4 provide the steps to input the time series data and configure the *Scenario Case*.

4.8 “MACRO_DATA” WORKSHEET

The *Macro Data* worksheet presents macro-socioeconomic data during 1980–2050 including:

- Total population
- Urban population
- Rural population
- GDP at constant 2015 RMB and constant 2010 US\$
- GDP per capita at constant 2015 RMB and constant 2010 US\$

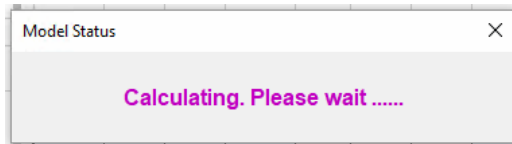
The off-line model described in Section 3.3 uses these macro-socioeconomic data to provide the pre-calculated private LDPV vehicle stocks in **Option 1** of the *Inputs VType* worksheet (Section 4.5). The population and GDP data in this section directly affect the estimates of vehicle stocks for other vehicle types in **Option 1**. The historical population and GDP data are from the *China Statistical Yearbooks* [1]. The future population through 2050 is from *World Population Prospects* by the United Nations [48]. The future GDP projections are based on the datasets and publications of a number of organizations, including the *Economic and Commodity Forecast* by the EIU [49], *World Economy Outlook* by IMF [50], the *Economic Outlook* by the Organization for Economic Cooperation and Development (OECD) [51], and the *International Energy Outlook* by the EIA [52].

4.9 “FUEL_SPECIFICATION” WORKSHEET

This *Fuel Specification* worksheet presents specifications for individual fuels including carbon contents, densities, and lower heating values (LHV). They are mainly from the *China Energy Statistical Yearbooks* [108] and the IEA *World Energy Statistics* [107]. In addition, this worksheet provides unit conversion factors.

4.10 “MODEL_RESULTS” WORKSHEET

The China Vehicle Fleet Model will automatically perform calculations when you navigate to the *Model Results* worksheet or any vehicle fleet turnover calculation worksheets described in Section 4.11. At this time, the message box below will appear on the screen, indicating that the model is in the calculating mode. You should wait until the message box disappears (normally less than 30 seconds).



The Model Results worksheet summarizes the model simulation results at different levels. From right to left, the results are aggregated and organized for both *Base Case* and *Scenario Case* as follows:

- by detailed vehicle technology
- by vehicle type and by end-use fuel (if applicable)
- by vehicle type
- by end-use fuel (if applicable)

From top to down, the results are summarized in this order:

- Vehicle PTW Energy Use in Energy Unit
- Vehicle PTW Energy Use in Physical Unit
- WTP Fuel Production Stage Energy Use
- WTP Fuel Feedstock Production Stage Energy Use
- PTW GHG Emissions
- WTW GHG Emissions
- Vehicle Stocks
- New Vehicle Sales
- Vehicle Travel (Total VKT)
- Fleet Average VKT per Vehicle
- New Vehicle Fuel Consumption Rates
- Fleet Average Fuel Consumption Rates

4.11 VEHICLE FLEET TURNOVER CALCULATION WORKSHEETS

The China Vehicle Fleet Model has 49 vehicle fleet turnover calculation worksheets, corresponding to 49 vehicle technologies of the Chinese highway vehicle fleet (see Table 1). These worksheets present the detailed fleet turnover calculation processes and results for individual vehicle technologies, including:

- Vehicle fleet composition by age
- Scrapped vehicle stock
- Vehicle fleet total VKT, average VKT per vehicle, lifetime VKT per vehicle
- New vehicle and fleet average fuel consumption rates
- PTW fuel consumption by end-use fuel type
- PTW GHG emissions by end-use fuel type
- WTW GHG emissions by end-use fuel type
- WTP fuel production stage energy use by end-use fuel type
- WTP fuel feedstock production stage energy use by end-use fuel type
- etc.

Similar to the Model Results worksheet, the China Vehicle Fleet Model will automatically perform calculations when you navigate to any vehicle fleet turnover calculation worksheets. The worksheets are named as [Vehicle Type]_[Powertrain Type]_[Fuel or Energy Type] (only non-electricity fuel is used for PHEVs). Table 8 lists the abbreviations for vehicle types, powertrain types, and fuel/energy types.

Table 8. Abbreviations for vehicle types, powertrain types, and fuel/energy types used in the names of the vehicle fleet turnover calculation worksheets

Vehicle type		Powertrain technology		Fuel type	
PrivLDPV	private LDPV	ICEV	internal combustion engine vehicles	Gas	gasoline
TaxiLDPV	taxi LDPV	BEV	battery electric vehicle	Ele	electricity
BusiLDPV	business/fleet LDPV	HEV	hybrid electric vehicle	Dsl	diesel
UrbanBus	urban bus	PHEV	plug-in hybrid electric vehicle	NG	natural gas
InterBus	intercity bus	FCV	fuel cell vehicle	H2	hydrogen
MiniTruck	mini truck			MeOH	methanol
LDTruck	light-duty truck			DME	dimethyl ether
MDTruck	middle-duty truck				
HDTruck	heavy-duty truck				

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