Probability distribution and recommended values of passenger car external dimensions in mechanical parking garage design

Jingshu Zhang\textsuperscript{a,b}, Hongbo Yang\textsuperscript{a,b}, Zhuo Chen\textsuperscript{a,b}, Ting Yu\textsuperscript{a,b} and Haiyang Liu\textsuperscript{a,b}

\textsuperscript{a}Key Laboratory of Mechanics on Disaster and Environment in Western China of the Ministry of Education, Lanzhou University, Lanzhou, China; \textsuperscript{b}College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, China

\textbf{ABSTRACT}
In order to determine the external dimensions of passenger car, to meet the current parking needs when designing a mechanical parking garage. In this study, 7193 groups of external dimensions and sales volume data of passenger car in the Chinese market from 2009 to 2020 are collected. Then, appropriate probability distributions are used to fit the collected data. Combined with their actual market share, the recommended external dimensions of sedan, SUV and MPV, separately, as well as all of them together, defined as general vehicles, are given by using probability statistics method. It is concluded that the external dimensions of sedan and SUV obey the t Location-Scale distribution, while MPV follows the mixed normal distribution. The length and width of general vehicles follow the t Location-Scale distribution and the height obeys the mixed normal distribution. The length, width and height of sedan are 5100 mm, 1890 mm and 1560 mm, respectively. The ones of SUV are 4950 mm, 1940 mm and 1850 mm, respectively, and for MPV they are 5300 mm, 1900 mm and 2000 mm, respectively. The corresponding dimensions of the general vehicles are 5150 mm, 1930 mm and 1900 mm, respectively. The proposed passenger car external dimensions can provide guidance for the garage design, aiming at the optimum space exploitation.

\section{1. Introduction}
The mechanical parking garage, formed by a steel structural system, has the advantage of small occupying area and large capacity. It can effectively alleviate the parking problem that the drivers of passenger cars have to encounter in the city. Japan started to develop mechanical parking garages in the 1960s and China began to implement and develop further this foreign technology in the 1980s (Parking Equipment Management Committee of China Heavy Machinery Industry Association (PEMCCHMIA) 2001). By 2015, China had built more than 3.36 million parking spaces for mechanical parking garage, ranking first country in the world for the utilization of these facilities (China Business Industry Research Institute (CBIRI) 2017). The key problem to solve firstly for the design of mechanical parking garage is to determine the dimensions of each parking space. If the dimensions are larger than required, the construction cost will be increased and the parking space could be wasted. On the contrary, if the dimensions are smaller than required, some vehicle models will not be able to park, wasting thus the limited garage resources. The dimensions of the parking space consist of the external dimensions of the passenger car plus the safe distance around it. However, as the safe distance is fixed (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2015), the dimensions of the parking space are actually determined by the external dimensions of the passenger car, which directly affect the serviceability and cost-efficiency of the garage.

In 1998, following a statistical analysis for the vehicle dimensions, the Chinese code regarding the basic parameters for the design of such garages classified the external dimensions of vehicles into 6 groups (Ministry of Machine-Building Industry of the People’s Republic of China 1998). This classification is used to this day. It is also fully adopted by the current codes (China Machinery Industry Federation 2011; Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2014, 2015) providing guidelines for the design of mechanical parking garages. However, the GB 3730.1–1988 (China Automotive Technology and Research Centre (CATRC) 1988) has been invalidated, which gave JB/T 8713–1998 the basis of distinguishing 6 groups of vehicles. The current code GB/T 3730.1–2001 (China Automotive Technology and Research Centre (CATRC) 2001), regarding the terms and definition of vehicles, no longer classifies vehicles, so the vehicle groups used in the current codes GB/T 26559–2011, JGJ/T 326–2014 and JGJ 100–2015 have no basis.

More than 20 years have passed since 1998. Currently, China has earned the place of the world’s largest automobile producer and consumer market...
and the number of motor vehicle sales always ranks at the top in the world. For example, the number of sedan vehicles has grown from 4 million in 1997 (Parking Equipment Management Committee of China Heavy Machinery Industry Association (PEMCHMIA) 2001) to 146.44 million in 2019 (National Bureau of Statistics (NBS) 2019). The external dimensions of the vehicles have changed significantly since 1998 as new models are launched, such as SUV and MPV with larger dimensions than the ones of sedan. Therefore, the mechanical parking garages designed in the late 1990s, based on the vehicle external dimension statistics of that time, are nowadays too small, thus, unsuitable for the parking of these new models. This leads to further waste of resources, as the number of bigger vehicles increases. Therefore, it is important to update the codes for the design of these garages with the data of the external dimensions of the modern passenger car, so that the new structures can meet the requirements of the current situation.

However, there are few researches on the external dimensions of the passenger car that are suitable for parking in mechanical garages. Kwak and Song (2000a, 2000b) investigated five types of small and medium vehicles in South Korea and proposed the standard design vehicle dimensions with a total length of 5.0 m and a total width of 2.5 m. However, the study surveyed fewer vehicle types, while there was no information regarding the height of the vehicles. Chen (2013) collected the external dimensions of 500 passenger cars, fitted the data with the normal distribution, and proposed the recommended vehicle external dimensions. Nevertheless, the fitting effect of some probability distribution graphs was not adequate in that study. Mau and Venhovens (2014) studied the internal and external dimensions of the vehicle according to SAE J1100 (SAE J1100:2009 2009), and built a parametric model of the vehicle external dimensions. Sun et al. (2015) took Chinese sedan as samples to analyze the external dimensions and established the internal relationship between the external dimensions of sedan. However, neither Mau and Venhovens (2014) nor Sun et al. (2015) gave specific external dimensions of the vehicles.

In this investigation, the recommended external dimensions of the passenger car are determined, representing more than 95% of the passenger cars available in the market that usually park in a garage. These dimensions should be used as design parameters for the best exploitation of the parking spaces in a garage. First, information is collected regarding length, width, height and sales volume data of sedan, SUV and MPV, sold in China in the past 12 years. Then, in order to fit the probability distribution of the external dimensions, the data of the dimensions is used as a benchmark sample, while sales and vehicle types are taken as influencing factors. Finally, the recommended dimensions of the passenger car for parking garage design are provided by using the principle of probability statistics, taking into account the current market conditions. The study aims to determine the passenger car external dimensions that would lead to the optimization of the design of mechanical parking garage and provides recommendations for revision of the current codes.

2. Data and methods
2.1. Sample data
In the recent years, most of the vehicles parked in the mechanical garages are either sedan, SUV or MPV types. In this study, 7193 sets of external dimensions and sales data of passenger cars sold in China from 2009 to 2020 are collected. The external dimensions are mainly obtained from Sohu Automotive Network (http://auto.sohu.com/) and Pacific Automotive Network (https://www.pcauto.com.cn/). The sales volume data is acquired from the China Automotive Industry Yearbook (China Automotive Technology Research Centre, and China Automotive Industry Association 2009–2020), hereinafter referred to as the yearbook. The sample data includes all passenger car manufacturers and vehicle types recorded in the yearbook. As most of the manufacturers are well-known automobile companies from China and other countries, the sample data is representative for the whole world. Hence, the results and conclusions of this study are applicable not only in China, but also worldwide.

It should be noted that data before 2009 are not considered because the information about the external dimensions of passenger car are limited in Sohu Automotive Network and Pacific Automotive Network. Typical sample surveys are shown in Table 1.

2.2. Dimensional statistical results and probability density functions
Generally, the probability of each type of passenger car parked in the mechanical garage is related with its market share, which means that the most popular models will use the garage more often and occupy more places than the less popular ones. In order to study whether sales volume has an effect on the passenger car external dimensions probability distribution, the probability distribution of the statistical passenger car external dimensions is fitted with and without sales consideration. At present, the mechanical parking garage is still designed to meet the parking requirements of sedan, SUV and MPV, simultaneously. In this study, sedan, SUV and MPV are taken into account separately, but they are also considered simultaneously, as a whole, denoted as general vehicles.
Table 1. Typical sample surveys.

| Vehicle types | Data (set) | Total sales volume | Representative manufacturers | Typical brands and models |
|---------------|------------|--------------------|-----------------------------|----------------------------|
| Sedan         | 4528       | 118958164          | Changan Ford, Shanghai General Motors, Beijing Benz BMW Brilliance, FAW-VOLKSWAGEN, Changan Mazda Soueast Motor, Guangqi Honda, Guangqi Toyota Dongfeng Nissan, Beijing Hyundai, Zhejiang Geely Dongfeng Peugeot Citroen Automobile | Focus, Chevrolet, Benz BMW, Audi, Mazda Ling yue, Accord, Camry Sylyph, Vema, Emgrand Peugeot |
| SUV           | 2098       | 55488945           | Changan Ford, FAW-Volkswagen, Beijing Benz BMW Brilliance, Shanghai General Motors, FAW Car Soueast Motor, Guangqi Honda, Guangqi Toyota Dongfeng Nissan, Great Wall Automobile, Beijing Hyundai Dongfeng Peugeot Citroen Automobile | Ecosport, Tiguan, Benz X1, Kopeck, Besturn Zinger, Honda, Highlander X-Trail, Haver, Tucson Peugeot |
| MPV           | 567        | 10454833           | Changan Ford, Shanghai General Motors, Fujian Mercedes FAW-Volkswagen, FAW Car, Guangqi Honda Brilliance jinbei, Dongfeng Nissan, Anhui jianghuai Dongfeng xiao kang | S-MAX, Buick, We whether Touran, Mazda, Odyssey Jinde, Geniss, JAC Refine Dongfeng xiao kang |

Figure 1. Probability distribution histogram of general vehicles external dimensions CSV.

When considering the sales volume (CSV), the probability distribution histogram of general vehicles external dimensions is shown in Figure 1.

Based on the histograms of Figure 1 (a), Figure 1 (b) it can be noted that the probability distribution histogram of the length and width of general vehicles is unimodal. The probability distribution types may include normal, lognormal, t Location-Scale and logistic distribution (hereinafter abbreviated as Norm, Logn, t L-S, and Logi, respectively). In this study, R is used for data analysis and visualization (Abedin and Mittal 2014). Currently, the CRAN package repository features more than 17,770 available packages (https://mirror.lzu.edu.cn/CRAN/). The package of fitdistrplus provides many functions for data fitting (Delignette-Muller and Dutang 2015). However, as shown in Figure 1(c), the probability distribution histogram of height is multimodal. Hence, a mixed normal distribution is proposed, which is composed of multiple single normal distributions according to their weights to fit the multimodal distribution.

2.2.1. **T L-S, Logi, and mixed normal distribution**

(1) t L-S distribution and its confidence interval

The t L-S distribution, which comes from the Student’s t distribution, is often used to fit data with outliers. It has heavier tails than the Norm distribution, which is commonly used in testing and monitoring (Faraji and Kohansal 2018; Morteza and Amirmazlaghani 2020; Zhao et al. 2019). The probability density function (PDF) of Student’s t distribution with n degrees of freedom and t L-S distribution are expressed by Equation (1) and Equation (2), respectively (Hines et al. 2003):

\[
f(x) = \frac{\Gamma\left(\frac{nu}{2}\right)}{n\pi\Gamma\left(\frac{n}{2}\right)} \left[ 1 + \frac{x^2}{n} \right]^{-\frac{n+1}{2}}
\]

\[
f(x) = \frac{\Gamma\left(\frac{nu}{2}\right)}{\sigma\sqrt{n\pi\Gamma\left(\frac{n}{2}\right)}} \left[ \frac{v + \left(\frac{x-\mu}{\sigma}\right)^2}{v} \right]^{-\frac{nu}{2}}
\]

In Equation (2): \(\Gamma(x)\) is the gamma function, \(\mu (\mu \in R)\) is the location parameter, \(\sigma (\sigma > 0)\) is the scale parameter, and \(v (v > 0)\) is the shape parameter. It should be noted that \(\sigma\) represents the standard deviations of the sample.

Confidence interval can be used to measure the confidence of a random variable within that interval. No relevant research results of t L-S distribution confidence interval have been found. Therefore, confidence interval for the t L-S distribution is provided. The confidence interval establishment process is shown as follows.

Suppose the PDF of the random variable \(X\) that obeys the t L-S distribution is \(f_t(x)\). Linear transformation is applied for the random variable \(X\)
\[ Y = \frac{X - \mu}{\sigma}. \]  

Thus, if \( Y = \frac{x - \mu}{\sigma} \), then \( x = h(y) = \sigma y + \mu \). Hence, it is true that \( h'(y) = \sigma (\sigma > 0) \). Then, the PDF of the random variable \( Y = \frac{X - \mu}{\sigma} \) is equal to:

\[
f_Y(y) = f_X[h(y)]|h'(y)| = \frac{1}{\sqrt{\sigma^2 + \nu}} \left[ \frac{\nu}{\nu + (\mu + \nu)^2} \right]^{\frac{\nu + (\mu + \nu)^2 \sigma^2}{\nu}} 
\]

\[
= \frac{1}{\sqrt{\sigma^2 + \nu}} \left[ \frac{\nu}{\nu + (\mu + \nu)^2} \right]^{\frac{\nu + (\mu + \nu)^2 \sigma^2}{\nu}} = \frac{1}{\sqrt{\sigma^2 + \nu}} \left[ \frac{\nu}{\nu + (\mu + \nu)^2} \right] \cdot \sigma = \frac{1}{\sqrt{\nu + \sigma^2 \nu}} \left[ 1 + \frac{\nu}{\sigma^2} \right]^{\frac{\nu + \sigma^2 \nu}{\nu}} \tag{3}
\]

By comparing Equation (3) with Equation (1), it can be seen that \( Y \) obeys the Student’s \( t \) distribution of \( \nu \) degrees of freedom. That is, \( Y = \frac{X - \mu}{\sigma} \).

If the random variable \( X \) obeys the \( L-S \) distribution, then the random variable \( Y = \frac{X - \mu}{\sigma} \) obeys the Student’s \( t \) distribution with \( \nu \) degrees of freedom.

The distribution diagram of upper \( \alpha \)-fractile on the \( t \) distribution is shown in Figure 2.

Based on Figure 2:

\[
P\left\{ \frac{X - \mu}{\sigma} < t_\alpha(\nu) \right\} = 1 - \alpha \tag{4}
\]

So \( P(X < \mu + \sigma t_\alpha(\nu)) = 1 - \alpha \).

Therefore, the unilateral confidence interval of \( 1 - \alpha \) confidence level for the random variable \( X \) obeying the \( L-S \) distribution is equal to \((-\infty, \mu + \sigma t_\alpha(\nu))\), where \( \mu + \sigma t_\alpha(\nu) \) is the upper limit of the unilateral confidence interval and \( \alpha \) is the significance level. Parameter \( t_\alpha(\nu) \) can be obtained from the Student’s \( t \) distribution table.

(2) Logi distribution

The shape of the Logi is similar to the Norm, but the tail of the Logi is longer and the kurtosis, i.e., the peak of the distribution curve, is higher. The PDF of Logi is expressed by Equation (5):

\[
f(x) = \frac{\exp\left\{-\frac{x - \mu}{\sigma} \right\}}{\sqrt{\pi} \sigma (1 + \exp\left\{-\frac{x - \mu}{\sigma} \right\})} \tag{5}
\]

In Equation (5): \( \mu (\mu \in R) \) is the location parameter, \( \sigma (\sigma > 0) \) is the scale parameter.

(3) Mixed normal distribution

The PDF of mixed normal distribution is expressed by Equation (6):

\[
f(x) = \sum_{i=1}^{n} p_i f_i(x) = \frac{p_1}{\sqrt{2\pi b_1}} \exp\left(-\frac{(x-a_1)^2}{2b_1^2}\right) + \frac{p_2}{\sqrt{2\pi b_2}} \exp\left(-\frac{(x-a_2)^2}{2b_2^2}\right) + \cdots + \frac{p_n}{\sqrt{2\pi b_n}} \exp\left(-\frac{(x-a_n)^2}{2b_n^2}\right) \tag{6}
\]

In Equation (6): \( n \) is the kurtosis number of frequency distribution histogram; \( 0 < p_i < 1 \) characterizes the respective weights of the normal distribution, \( p_1 + p_2 + \cdots + p_n = 1 \); \( a_i \) is mean \( \mu \), \( \mu \) is standard deviation \( \sigma \).

![Figure 2. The distribution diagram of upper \( \alpha \)-fractile on the Student’s \( t \) distribution.](image)

### 2.2.2. Fitting index

Akaike Information Criterion (AIC) (Akaike 1973, 1974) and Bayesian Information Criterion (BIC), also known as the Schwarz criterion (Schwarz 1978), can be used for the model evaluation. AIC provides effective rules for model selection, but it also has shortcomings. When the sample size is large, the information provided by the fitting error in the AIC criterion will be amplified by the sample size. In this case, BIC can be used to minimize this error and give more accurate results. Due to the large sample size in this article, we use BIC to select the optimal model. When comparing different models, the smaller the BIC value, the better the fitting effect of the model.

\[
\text{AIC} = -2(\log \text{maximized likelihood}) + 2(\text{number of parameters})
\]

\[
\text{BIC} = -2(\log \text{maximized likelihood}) + (\log N)(\text{number of parameters}) \tag{7}
\]

where \( N \) is the sample size used for the computation of the maximum likelihood estimates.

### 3. Results

#### 3.1. Probability distribution and recommended values of sedan external dimensions

##### 3.1.1. Probability distribution of sedan external dimensions

The probability density function fitting diagram (PDFF) of sedan length is shown in Figure 3.

As can be seen in Figure 3, the fitting index BIC is the smallest when the t L-S distribution is adopted for sedan length, regardless of whether the sales factor is taken into account.

The PDFF of sedan width is shown in Figure 4.

As shown in Figure 4, the fitting curves of the t L-S and Logi distributions tend to overlap and fit the histogram of the sedan width. Therefore, sedan width can be fitted by these two distributions. As the fitting index BIC of t L-S distribution is slightly smaller than the one of Logi distribution and sedan length follows the t L-S distribution, the t L-S distribution is used in order to obtain the uniform probability distribution type of
sedan external dimensions. In addition, with or without considering the sales factor, sedan width obeys the t L-S distribution.

The PDFF of sedan height is shown in Figure 5.

In Figure 5 it is noted that sedan height also obeys the t L-S distribution whether sales are considered or not, as the fitting index BIC is the smallest for this distribution.

3.1.2. Recommended values of sedan external dimensions

Based on the fitting results, presented in section 3.1.1, the sedan external dimensions obey the t L-S distribution, considering or not the sales volume. Hence, the t L-S distribution is used to provide the Recommended Values (RV) of sedan external dimensions.
For sedan external dimensions following the t L-S distribution, the significance level of $\alpha = 0.05$ can be used to obtain the dimensions satisfying the 95% guarantee rate. Hence, as shown in Table 2, the RV of sedan external dimensions can be obtained by referring to the 95% Guarantee Rate Values (GRV), taking into account the latest passenger car market situation.

In Table 2, the standard deviations of sedan external dimensions data without considering the sales volume are all larger than those considering the sales volume, indicating that the former is more discrete. In addition, both the 95% GRV and RV of the dimensions without considering the sales are larger than the ones that consider them. Therefore, the mechanical parking garage should be built according to the RV considering the sales, if the designer selects the most economical solution. Otherwise, the garage should be designed according to the RV without considering the sales volume, if the requirement of serving more sedan vehicles needs to be met.

Taking the data of the 2020 edition of the yearbook as an example, Table 3 shows the sedan brands that exceed the RV of sedan external dimensions when CSV.

As shown in Table 3, the proportion of sedan vehicles in the latest yearbook with external dimensions exceeding the RV is very small. Therefore, this study suggests that the length, width and height of sedan should be considered equal to 5100 mm, 1890 mm and 1560 mm, respectively.

### 3.2. Probability distribution and recommended values of SUV external dimensions

#### 3.2.1. Probability distribution of SUV external dimensions

The PDFF of SUV external dimensions is shown in Figure 6.

Based on Figure 6, SUV external dimensions obey the t L-S distribution with or without considering the sales factor, as for these distribution functions of length, width and height the fitting index is the smallest.

#### 3.2.2. Recommended values of SUV external dimensions

The RV of SUV external dimensions, presented in Table 4, is obtained by referring to the 95% GRV, considering also the latest passenger car market situation.

In Table 4 it is noted that the standard deviations of SUV external dimensions data NCSV are all larger than the ones CSV, indicating that the data without CSV is more discrete. Hence, the mechanical parking garage should be built according to the RV when CSV, leading to the most economical solution.

Taking the data of the 2020 edition of the yearbook as an example, Table 5 shows the SUV brands that exceed the RV of SUV external dimensions when CSV.

As listed in Table 5, the proportion of SUV in the latest yearbook with external dimensions exceeding the RV is very small. Therefore, this study suggests that the length, width and height of SUV should be considered equal to 4950 mm, 1940 mm and 1850 mm, respectively.
Figure 6. PDFF of SUV external dimensions.

Table 4. Recommended values of SUV external dimensions.

| External dimensions | Sales factor | μ (mm) | σ (mm) | ν | t0.05 (ν) | 95% GRV (mm) | RV (mm) |
|---------------------|--------------|--------|--------|---|-----------|--------------|---------|
| Length              | CSV          | 4518.50| 183.30 | 16.80 | 1.74      | 4837         | 4950    |
|                     | NCSV         | 4543.70| 211.80 | 10.70 | 1.80      | 4925         | 5000    |
| Width               | CSV          | 1830.76| 36.74  | 4.09  | 2.12      | 1909         | 1950    |
|                     | NCSV         | 1830.76| 45.81  | 5.44  | 1.98      | 1921         | 1970    |
| Height              | CSV          | 1682.56| 41.10  | 3.37  | 2.27      | 1776         | 1850    |
|                     | NCSV         | 1689.63| 64.09  | 3.88  | 2.16      | 1828         | 1900    |
3.3.1. Probability values

The length of the data distribution, the probability density function (PDF) of the data, can be expressed by the equation:

\[ f(x) = \frac{p_1}{\sqrt{2\pi b_1}} \exp\left(-\frac{(x-a_1)^2}{2b_1^2}\right) + \frac{p_2}{\sqrt{2\pi b_2}} \exp\left(-\frac{(x-a_2)^2}{2b_2^2}\right) + \frac{p_3}{\sqrt{2\pi b_3}} \exp\left(-\frac{(x-a_3)^2}{2b_3^2}\right) \] (8)

As can be seen in Figure 7, the probability distribution fitting index \( R^2 \) of MPV length is larger than 0.95 whether considering the sales factor or not. This value indicates that the fitting degree of the mixed normal distribution is satisfactory, thus the MPV length can follow the mixed normal distribution.

The PDF of MPV width is shown in Figure 8.

In Figure 8, it can be noted that the width is mainly concentrated in two regions around 1700 mm and 1800 mm, meaning that the histogram of probability

### Table 5. Vehicles that exceed the recommended SUV external dimensions.

| External dimensions | SUV brands and models | Dimensions (mm) | Percentage of sales in 2020 \( \times 10^{-3} \) |
|---------------------|----------------------|----------------|----------------------------------|
| Length              | CX-8 2WD 2.5 L, Avenir 2WD 2.0 T                       | 4955, 4981     | 0.16, 0.13                       |
|                     | Avenir 4WD 2.0 T, MAXUS D90 2WD 2.0                    | 4981, 5005     | 0.50, 0.11                       |
|                     | MAXUS D90 4WD 2.0, PRADO 3.5 L                         | 5005, 5010     | 0.22, 3.95                       |
|                     | NIO ES8BEV, Hong Qi HS73.0 T                           | 5022, 5035     | 0.91, 0.45                       |
|                     | Teramont 2WD2.0 T, Teramont 4WD 2.0 T                  | 5039, 5039     | 1.51, 5.69                       |
|                     | Teramont 4WD 2.5 T, Cadillac XT6 2WD 2.0 T             | 5039, 5056     | 0.43, 0.43                       |
|                     | Cadillac XT6 4WD 2.0 T, Ricky BEV                      | 5056, 5095     | 0.80, 0.03                       |
| Width               | Avenir 2WD 2.0 T, Avenir 4WD 2.0 T                     | 1953, 1953     | 0.13, 0.50                       |
|                     | NIO ES8BEV, Cadillac XT6 2WD 2.0 T                    | 1962, 1964     | 0.91, 0.43                       |
|                     | Cadillac XT6 4WD 2.0 T, NIO ES8BEV                    | 1964, 1965     | 0.80, 1.34                       |
|                     | TeramontX 2WD 2.0 T, TeramontX 4WD 2.0 T              | 1989, 1989     | 0.37, 1.28                       |
|                     | TeramontX 4WD 2.5 T, Teramont 2WD 2.0 T               | 1989, 1989     | 0.12, 1.51                       |
|                     | Teramont 4WD 2.0 T, Teramont 4WD 2.5 T                | 1989, 1989     | 5.69, 0.43                       |
|                     | Hong Qi HS73.0 T                                      | 1989           | 0.45                             |
| Height              | JMC 2.0 T, MAXUS D90 2WD 2.0                           | 1852, 1875     | 0.17, 0.11                       |
|                     | MAXUS D90 4WD 2.0, Savanna                              | 1875, 1885     | 0.22, 0.05                       |
|                     | PRADO 3.5 L, Haver H9 WD diesel                         | 1890, 1900     | 3.95, 0.23                       |
|                     | Haver H9 WD gasoline                                    | 1900           | 1.27                             |

Figure 7. PDFF of MPV length.

### 3.3. Probability distribution and recommended values of MPV external dimensions

#### 3.3.1. Probability distribution of MPV external dimensions

The sample of MPV in the statistics is relatively small, with only 567 groups. The data included small, medium and large MPVs with five to nine seats. Therefore, MPV external dimensions fluctuate significantly and its data dispersion is large, especially the one regarding the length of this kind of vehicles. The PDFFF of MPV length is illustrated in Figure 7.

The collected data of MPV length vary between 3601 mm and 5380 mm. The probability distribution histogram of MPV length presents a multi-peak distribution characteristic. In Figure 7, the length that corresponds to the three kurtoses from left to right is the length of small, medium and large MPV, respectively.

According to Equation (6), the three-peak distribution, shown in Figure 7, can be fitted with a mixed normal distribution, which is formed by combining three normal distributions according to their respective weights. Hence, the probability density function can be expressed by Equation (8).
distribution presents a bimodal feature. According to Equation (6), the two-peak distribution can be fitted with a mixed normal distribution, as expressed by Equation (9).

\[
f(x) = \frac{p_1}{\sqrt{2\pi b_1}} \exp\left(-\frac{(x - a_1)^2}{2b_1^2}\right) + \frac{p_2}{\sqrt{2\pi b_2}} \exp\left(-\frac{(x - a_2)^2}{2b_2^2}\right)
\]

In Figure 8, the fitting index of probability distribution \( R^2 \) is given, which is larger than 0.95 when considering sales, indicating a high degree of fitting. Due to the high dispersion of MPV width data, when the sales volume is not considered, the fitting index \( R^2 \) results equal to 0.877. Thus, the fitting degree is moderate when NCSV.

The PDFF of MPV height is shown in Figure 9.

As shown in Figure 9, the MPV height presents a bimodal characteristic when considering sales. The mixed normal distribution as given in Equation (9) is used for fitting. Fitting index \( R^2 \) results larger than 0.97, indicating a high degree of fit. The data is too discrete and does not have probability distribution characteristics when sales volume is not taken into account, so it is not fitted. Therefore, the MPV height can still be fitted by the mixed normal distribution.

3.3.2. Recommended values of MPV external dimensions
MPV external dimensions are expressed by mixed normal distribution. The mixed normal distribution can be considered as the sum of multiple normal distributions. \( \mu + 1.645\sigma \) is the 95% GRV of normal distribution. The first kurtosis of the probability distribution fitting diagram of MPV length corresponds to the size of about 4400 mm, which is small and should not be used as maximum value of recommended dimensions.

In Table 6, the RV of MPV external dimensions can be obtained by referring to the 95% GRV, based on the right kurtoses taking into account the latest passenger car market situation.
Table 6. Recommended values of MPV external dimensions.

| External dimensions | Sales factor | Left kurtosis | Right kurtosis |
|---------------------|--------------|---------------|---------------|
|                     | μ(mm)        | σ(mm)         | 95% GRV (mm)  |
|                     | μ(mm)        | σ(mm)         | 95% GRV (mm)  | RV (mm) |
| Length              | CSV          | 4732.08       | 98.03         | 4893     | 5158.39 | 110.08 | 5339 | 5300 |
| NCSV               | 4754.87      | 110.51        | 4937          | 5169.70 | 98.44   | 5332   |
| Width               | CSV          | 1699.76       | 22.40         | 1737     | 1811.58 | 31.17  | 1863 | 1900 |
| NCSV               | 1708.82      | 17.86         | 1738          | 1817.16 | 47.09   | 1895   |
| Height              | CSV          | 1753.57       | 72.80         | 1837     | 1964.73 | 24.29  | 2005 | 2000 |

Note: The left and right kurtoses of length correspond to the second and third kurtoses in Figure 7, respectively.

Based on Table 6, the 95% GRV of the length and width, which the left kurtosis corresponds to, is close to the one of sedan, given in Table 2. Including also the height, the 95% GRV of Table 6, referring to the left kurtosis, corresponds to the one of SUV, presented in Table 4. For the length and width of MPV, the 95% GRV of the external dimensions, which the right kurtosis corresponds to, under the influence of the two different sales factors, is similar. Therefore, the RV of these two dimensions are given regardless of the influence of sales factor. This study suggests that the length, width and height of MPV should be considered 5300 mm, 1900 mm and 2000 mm, respectively.

Taking the data of the 2020 edition of the yearbook as an example, Table 7 shows the MPV brands that exceed the RV of MPV external dimensions.

As can be seen from Table 7, the proportion of MPV in the latest yearbook with external dimensions exceeding the RV is small. Therefore, the recommended values of external dimensions, given in this study, are satisfactory.

3.4. Probability distribution and recommended values of general vehicles external dimensions

3.4.1. Probability distribution of general vehicles external dimensions

The PDFF of general vehicles length and width are shown in Figure 10.

Based on Figure 10, it can be noted that general vehicles length and width obey the t L-S distribution with or without considering the sales factor.

The PDFF of general vehicles height is shown in Figure 11.

As can be seen from Figure 11, the height of general vehicles is mainly concentrated in two regions around 1500 mm and 1700 mm, and the histogram of probability distribution presents a bimodal feature. According to the above analysis of passenger car external dimensions, the first kurtosis of 1500 mm represents mainly sedan, while the second one refers to SUV and MPV. The mixed normal distribution expressed by Equation (9) is still used to fit the general vehicles height. Regardless of whether the influence of sales is considered or not, the fitting degree is high and the fitting index $R^2$ is larger than 0.995, confirming that the general vehicles height follows the mixed normal distribution.

3.4.2. Recommended values of general vehicles external dimensions

As shown in Table 8, the RV of general vehicles external dimensions can be obtained by referring to the 95% GRV and considering the latest passenger car market situation. As the height of the general vehicles that corresponds to the left kurtosis is small, only the height of the right kurtosis is considered.

As shown in Table 8, due to the small width and height of sedan and the small length of SUV, the recommended external dimensions of general vehicles are not larger than the ones of sedan, SUV and MPV. Therefore, this study suggests that the length, width and height of general vehicles should be 5150 mm, 1930 mm and 1900 mm, respectively. The mechanical parking garage designed according to these recommended values can efficiently combine applicability and economy.

Table 7. Vehicles that exceed the recommended MPV external dimensions.

| External dimensions | MPV brands and models | Dimensions (mm) | Percentage of sales of MPV in 2020 $\times 10^{-3}$ |
|---------------------|-----------------------|-----------------|---------------------------------------------------|
| Length              | Grace 2.4, Grace 2.7  | 5350, 5350      | 0.34, 0.16                                        |
|                     | Vito 2.0 L            | 5370            | 8.61                                              |
| Width               | Brilliance 7 2.0 T, Geely Jiayi 1.5 T | 1909, 1909 | 0.86, 21.17                                      |
|                     | Geely Jiayi 1.8TPHEV, Trumpchi GM8 2.0 T | 1909, 1923 | 2.65, 16.69                                      |
|                     | Mercedes V level 2.0 T, Vito 2.0 L | 1928, 1928 | 11.75, 8.61                                      |
|                     | MAXUS EG10BEV, MAXUS G101.9 | 1980, 1980 | 0.16, 6.85                                       |
|                     | MAXUS G102.0, MAXUS G102.4 | 1980, 1980 | 10.46, 0.05                                      |
|                     | Tourneo 2.0 T         | 2032            | 1.11                                              |
| Height              | MP-X, HYOSOW H61.5   | 2030, 2115      | 5.36, 0.004                                       |
Figure 10. PDFF of general vehicles length and width.

Figure 11. PDFF of general vehicles height.

Table 8. Recommended values of general vehicles external dimensions.

| External dimensions | Sales factor | μ(mm) | σ(mm) | ν | t0.05(ν) | 95% GRV (mm) | RV (mm) |
|---------------------|-------------|------|------|---|---------|-------------|--------|
| Length              | CSV         | 4555.51 | 185.80 | 2.99 | 2.36 | 4994 | 5000 |
|                     | NCSV        | 4558.10 | 260.20 | 3.80 | 2.18 | 5125 | 5150 |
| Width               | CSV         | 1783.71 | 63.73 | 9.73 | 1.82 | 1830 | 1900 |
|                     | NCSV        | 1789.00 | 67.10 | 6.50 | 1.92 | 1918 | 1930 |
| Height              | CSV         | 1695.48 | 61.42 | –   | –    | 1797 | 1850 |
|                     | NCSV        | 1690.21 | 84.75 | –   | –    | 1830 | 1900 |
4. Discussion

4.1. Applicability of external dimensions probability distribution

The above-analyzed passenger car data dates back to 2009. The probability distribution of older passenger car external dimensions is studied in this section.

(1) Probability distribution of the passenger car external dimensions prior to 2000

Existing investigations of Mechanical stereo garage (Parking Equipment Management Committee of China Heavy Machinery Industry Association (PEMCCHMIA) 2001), JB/T 8713–1998, and Automobile design (Liu 2001) provide 293, 65, and 29 sets of data, respectively, regarding passenger car external dimensions without counting the sales volume. The corresponding statistics included in Mechanical stereo garage and Automobile design was published in 2001, referring to the period before 2000. The JB/T 8713–1998 code was implemented in 1998. Therefore, its data represents the period prior to 1998. It should be noted that the width of data in the 189th group provided by Mechanical stereo garage was reported equal to 4786 mm, which is considered to be a typo, so in this study it was assumed to be 1786 mm. The height in a set of data provided in Automobile design (Liu 2001) was reported equal to 2752 mm, which was excluded in this analysis, as it is much larger than the other height data.

Based on the aforementioned data, the PDFF of passenger car external dimensions prior to 2000 is shown in Figure 12.

As noted in Figure 12, the length and width of passenger car obey the t L-S distribution. The height probability distribution diagram is still bimodal and obeys the mixed normal distribution.

(2) Probability distribution of the passenger car external dimensions from 2002 to 2011

Chen (2013) collected data of the passenger car external dimensions from 2002 to 2011. A vehicle involved in the original data had a height of 2680 mm and only 183 cars of this kind were sold in that period. The vehicle is Sprinter made by Fujian Daimler Automobile Company. As this height is much larger than the one of the current collected data, it is ignored in this analysis. The PDFF is shown in Figure 13.
Based on Figure 13, it can be noted that the length and width of passenger car obey the t L-S distribution. The height probability distribution diagram is still bimodal and obeys the mixed normal distribution. Therefore, the probability distribution model proposed in this study is still applicable to the passenger car external dimensions from 2002 to 2011.

In conclusion, the probability distribution model fitted in this study can be applied not only for modern passenger car external dimensions but also for passenger cars used before the year 2000. Hence, the proposed model has universal applicability and could be used to estimate the recommended values of the passenger car external dimensions for the design of a garage.

4.2. Sedan external dimensions determined by the parametric model

Due to the continuous increase of people’s requirements for interior space and appearance of a passenger car, its external dimensions have also changed to some extent in recent years. Therefore, it is necessary to further analyze the applicability of the above RV in the future period.
The passenger car external dimensions are affected by many factors, such as technology, economy, environmental protection and human body shape, etc. Its long-term trend is difficult to predict. Mau and Venhovens (2014) connected the internal and external dimensions of the vehicles with the standard dimensions of SAE J1100 (2009) and the other dimensions that they defined. Finally, they built a parametric model of the vehicles external dimensions. In what follows, this model is used to verify the rationality of the RV of sedan dimensions, provided in this study.

(1) Length of sedan
Mau and Venhovens (2014) established the vehicles length model. The wheelbase L101 and the total length L103 of the vehicle can be expressed by Equations (10) and (11), respectively.

\[ L_{101} = L_{113} + L_{99} + L_{50} - 2 + L_{115-2} \]  
(10)

\[ L_{103} = L_{101} + L_{104} + L_{105} \]  
(11)

In Equations (10) and (11): L101 is wheelbase, meaning the distance between the center of the front and rear wheels; L113 is the distance between the center of the front wheel and the datum point of the sole; L99 is the distance between the reference point of the driver’s foot and the reference point of the first row of seats; L50-2 is the coupling distance between the first and the second row; L115-2 is the distance from second row seat datum point to center of rear wheel; L103 is total length; L104 is front overhang; L105 is rear overhang. See SAE J1100 (SAE J1100:2009 2009) for specific content.

As shown in Table 9, Mau and Venhovens (2014) divided the sedan into three types: large, medium and compact. They also gave the typical representative values of the dimensions of each type.

Based on Table 9, it can be noted that the recommended length value in this study can meet the parking needs of medium and compact cars. It is predicted that with the implementation of stricter energy-saving and environmental protection measures and the popularity of new energy vehicles with smaller dimensions, the market share of large vehicles will decrease. Therefore, the recommended length of 5100 mm is reasonable.

(2) Width of sedan
Mau and Venhovens (2014) established the vehicles width model. The relationship between the internal and external widths of the vehicles is expressed by Equations (12) to (14).

\[ W_{3-1} = SW_{16} + 2(W_{20-1} + WG-1) \]  
(12)

\[ W_{117} = W_{3-1} + 2WB-1 \]  
(13)

\[ W_{103} = 0.954 \times W_{117} + 63 \ (R^2 = 0.94) \]  
(14)

In Equations (12) to (14): W3-1 is the shoulder space in the first row; SW16 is seat cushion width of driver; W20-1 is the transverse coordinate of the seat; W117 is the vehicle external width at the driver’s seat reference point; WG-1 is gap width; WB-1 is the width of safety belt. See SAE J1100 (SAE J1100:2009 2009) for specific content.

Typical values for each section size are shown in Table 10.

In the formula established by Mau and Venhovens (2014), both W117 and W103 in Table 10 can be used as the RV of sedan width. Therefore, the RV of sedan width, given in this study, which is 1890 mm includes the theoretical calculation value of Mau and Venhovens (2014).

(3) Height of sedan
Mau and Venhovens (2014) established the vehicles height model. The relationship between the internal and external heights of the vehicles is expressed by Equation (15).

\[ H_{100} \approx H_{111-1} + HH_{1} + H_{30-1} + HR_{1} + H_{37} + (H_{61-1} - 102) \cos 8 \alpha \]  
(15)

In Equation (15): H100 is height of the vehicle body; H111-1 is the height of the front rocker; HH1 is the height of heel; H30-1 is the height of seat; HR1 is the thickness of roof panel; H37 is the thickness of

| Table 9. Calculation dimensions of sedan length. |
|-----------------------------------------------|
| L113 (mm) | L99 (mm) | L50-2 (mm) | L115-2 (mm) | L101 (mm) | L101/L103 | L103 (mm) | RV of sedan length in this study (mm) |
|-----------|---------|-----------|------------|---------|----------|---------|---------------------------------------|
| Large     | 588     | 960       | 882        | 515     | 2945     | 0.544   | 5414                                  |
| Medium    | 398     | 960       | 818        | 496     | 2672     | 0.557   | 4797                                  |
| Compact   | 373     | 960       | 750        | 466     | 2549     | 0.576   | 4425                                  |

Note: L113, L99, L50-2, L115-2 and L101/L103 are given by Mau and Venhovens (2014). L101 and L103 are calculated by data in this study.

| Table 10. Calculation dimension of passenger car width. |
|---------------------------------------------------------|
| SW16 (mm) | W20-1 (mm) | WG-1 (mm) | W3-1 (mm) | WB-1 (mm) | W117 (mm) | W103 (mm) | RV of sedan width in this study (mm) |
|-----------|------------|-----------|-----------|-----------|-----------|----------|---------------------------------------|
| Large     | 524        | 379       | 93        | 1468      | 165       | 1798     | 1778                                  |
| Medium    | 523        | 362       | 89        | 1425      | 165       | 1755     | 1737                                  |
| Compact   | 509        | 355       | 86        | 1391      | 165       | 1721     | 1705                                  |

Note: SW16, W20-1, WG-1 and WB-1 are given by Mau and Venhovens (2014). W3-1, W117 and W103 are calculated by data in this study.
the canopy; H61-1 is head space for the driver. See SAE J1100 (SAE J1100:2009 2009) for specific content.

Typical values for each section size are shown in Table 11.

It is noted that the passenger car height calculated according to the typical value given by Mau and Venhovens (2014) is smaller than the actual car height, although these dimension values derive from data statistics. Incomprehensive vehicle model statistics or small sample size may be the reasons for this result.

### 4.3. Recommended values of external dimensions

According to the above analysis and discussion, all RV of passenger car external dimensions, given in this study, are listed in Table 12.

According to the specifications shown in Table 12, the parking space can be designed taking into account the RV of passenger car external dimensions, adding 200 mm to the length, 150 mm to the width and 50 mm to the height (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2015). Garage design can be divided into three types of vehicles, i.e. considering sedan, SUV and MPV. As shown in Figure 14, a mechanical parking garage design method with plane partitions and vertical stratification is recommended, which aims at the best exploitation of the garage space, leading thus to a cost-effective solution. Moreover, the vertical stratification mode can be adopted when the garage should meet the requirements of general vehicles, as SUVs and MPVs with larger external dimensions and loads can be parked at the lower levels of the garage.

In Table 13, RV reported from codes GB/T 26559–2011, JGJ/T 326–2014 and JGJ 100–2015 are listed.

Table 14 shows a comparison of the RV in this study with the vehicle dimensions given in the current garage specifications. The recommended dimensions of sedan, SUV, general vehicles and MPV are, respectively, compared with the ones of small car, medium car, large car and extra-large car.

**Table 11. Calculation dimension of passenger car height.**

| Vehicle types | H111-1 (mm) | HH1 (mm) | H30-1 (mm) | HR1 (mm) | H37 (mm) | H61-1 (mm) | H100 (mm) | RV of sedan height in this study (mm) |
|---------------|-------------|----------|------------|----------|----------|------------|----------|-------------------------------------|
| Large         | 199         | 59       | 221        | 1        | 16       | 984        | 1369     | 1560                                |
| Medium        | 199         | 59       | 249        | 1        | 16       | 980        | 1393     |                                     |
| Compact       | 199         | 59       | 254        | 1        | 16       | 975        | 1394     |                                     |

Note: H111-1, HH1, H30-1, HR1, H37 and H61-1 are given by Mau and Venhovens (2014). H100 is calculated by data in this study.

**Table 12. Recommended values of passenger car external dimensions.**

| Vehicle types | External dimensions | Width (mm) | Height (mm) |
|---------------|---------------------|------------|-------------|
| Sedan         | 5100                | 1800       | 1560        |
| SUV           | 4950                | 1940       | 1850        |
| MPV           | 5300                | 1900       | 2000        |
| General vehicles | 5150            | 1930       | 1900        |

**Table 13. Recommended values in codes.**

| Vehicle types | Length×Width×Height (mm×mm×mm) |
|---------------|---------------------------------|
| Small car     | ≤4400 × 1750 × 1450             |
| Medium car    | ≤4700 × 1800 × 1450             |
| Large car     | ≤5000 × 1850 × 1550             |
| Extra-large car | ≤5300 × 1900 × 1550         |
| Super car     | ≤5600 × 2050 × 1550             |
| Coach         | ≤5000 × 1850 × 2050             |

**Figure 14. A recommended mechanical partitioning garage design schematic diagram.**
Based on Table 14, different deviation degrees are noted between the external dimensions of the current codes and the RV provided in this study. The deviation degree for height is the largest. This means that the design of mechanical garage according to the specifications is not in line with the actual situation, which may reduce its applicability.

5. Conclusions

In this study, 7193 groups of passenger car external dimensions and sales data from 2009 to 2020 are collected. The following conclusions are drawn:

(1) The probability distribution of passenger car external dimensions is not affected by the sales factor. The external dimensions of sedan and SUV obey the t L-S distribution. The external dimensions of MPV obey the mixed normal distribution. The length and width of general vehicles obey the t L-S distribution. The height of general vehicles obeys the mixed normal distribution.

(2) The recommended length, width and height of sedan are 5100 mm, 1890 mm and 1560 mm, respectively. The corresponding values for the SUV are 4950 mm, 1940 mm and 1850 mm, respectively, and the ones for MPV are 5300 mm, 1900 mm and 2000 mm, respectively. The recommended length, width and height for general vehicles are 5150 mm, 1930 mm and 1900 mm, respectively. The recommended values of this paper are not only suitable for China but also for the rest of the world.

(3) It is suggested to use plane partitions and vertical stratification to park different types of vehicles when designing the garage, so that the design ensures serviceability and cost-efficiency.

(4) Different degrees of deviation are noted between the external dimensions of the codes and the values provided in this study. More particularly, the height recommended by the codes is small with respect to the data collected for this research that represent the dimensions of the most popular passenger cars nowadays. This means that the codes should be revised to include the dimensions of the modern passenger cars.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Natural Science Foundation of China [51678283]; and Education Department of Gansu Province: “Star of Innovation” Project for Outstanding Graduate Students [2021CXZX-123].

Notes on contributors

Jingshu Zhang, PhD, is a professor at the Key Laboratory of Mechanics on Disaster and Environment in Western China of the Ministry of Education & College of Civil Engineering and Mechanics, Lanzhou University.

Hongbo Yang is a master degree candidate at the Key Laboratory of Mechanics on Disaster and Environment in Western China of the Ministry of Education & College of Civil Engineering and Mechanics, Lanzhou University.

Zhuo Chen is a master degree candidate at the Key Laboratory of Mechanics on Disaster and Environment in Western China of the Ministry of Education & College of Civil Engineering and Mechanics, Lanzhou University.

Ting Yu is a master degree candidate at the Key Laboratory of Mechanics on Disaster and Environment in Western China of the Ministry of Education & College of Civil Engineering and Mechanics, Lanzhou University.

Haiyang Liu is a master degree candidate at the Key Laboratory of Mechanics on Disaster and Environment in Western China of the Ministry of Education & College of Civil Engineering and Mechanics, Lanzhou University.

References

Abedin, J., and V. H. Mittal. 2014. R Graphs Cookbook. 2nd ed. Birmingham: Packt Publishing.

Akaike, H. 1973. “Information Theory and an Extension of Maximum Likelihood Principle.” Second international symposium on information theory, Budapest, Akademia Kiado, pp. 267–281.

Akaike, H. 1974. “A New Look at the Statistical Model Identification.” IEEE Transactions on Automatic Control AC-19 (6): 716–723. doi:10.1109/TAC.1974.1100705.

Chen, T. T. 2013. “The Study of Design for Mechanical Stereo Garage.” Master’s thesis, Lanzhou University, Lanzhou, China, [in Chinese].

China Automotive Technology and Research Centre (CATRC). 1988. “Motor Vehicles and Semi-trailer-types. Terms and Definitions.” GB 3730.1-1988. China Automobile Industry Federation, [in Chinese].
China Automotive Technology and Research Centre (CATRC). 2001. "Motor Vehicles and Trailers-types-terms and Definitions." GB/T 3730.1-2001. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. [in Chinese].

China Automotive Technology Research Centre, and China Automotive Industry Association. 2009–2020. China Automotive Industry Yearbook. (2009th to 2020th ed. Tianjin: China Automotive Industry Yearbook Journal. [in Chinese]

China Business Industry Research Institute (CBIRI). 2017. "Research Report on the Market Prospect of China's Intelligent Stereo Garage Industry in 2017 (Brief Version)." [EB/OL]. https://www.askci.com/news/chanye/20171013/175021109615.shtml

China Machinery Industry Federation. 2011. "Mechanical Parking System — Classification". GB/T 26559-2011. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. [in Chinese].

Delignette-Muller, M. L., and C. Dutang. 2015. "Fidistriplus: An R Package for Fitting Distributions." Journal of Statistical Software 64 (4): 1–34. doi:10.18637/jss.v064.i04.

Faraji, N., and A. Kohansal. 2018. "MMSE and Maximum a Posteriori Estimators for Speech Enhancement in Additive Noise Assuming a T-location-scale Clean Speech Prior." IET Signal Processing 12 (4): 532–543. doi:10.1049/iet-spr.2017.0446.

Hines, W. W., D. C. Montgomery, D. M. Goldsman, and C. M. Borror. 2003. Probability and Statistics in Engineering. 4th ed. New York: John Wiley & Sons, .

Kwak, H. G., and J. Y. Song. 2000a. "Live Load Factors for Parking Garage Members." Structural Safety 22 (3): 251–279. doi:10.1016/S0167-4730(00)00016-3.

Kwak, H. G., and J. Y. Song. 2000b. "Simplified Slab Design Approach for Parking Garages with Equivalent Vehicle Load Factors." Structural Engineering and Mechanics 9 (3): 305–321. doi:10.12989/sem.2000.9.3.305.

Liu, W. X. 2001. Automobile Design. Beijing: Tsinghua University Press.

Mau, R. J., and P. J. Venhovens. 2014. "Development of a Consistent Continuum of the Dimensional Parameters of a Vehicle for Optimization and Simulation." Proc IMechE Part D: Journal of Automobile Engineering 228 (6): 591–603. doi:10.1177/0954407013497195.

Ministry of Housing and Urban-Rural Development of the People's Republic of China. 2014. "Technical Code for Mechanical Parking Garage Engineering." JGJ/T 326-2014. China Architecture & Building Press. [in Chinese].

Ministry of Housing and Urban-Rural Development of the People's Republic of China. 2015. "Code for Design of Parking Gage Building". JGJ 100-2015. China Architecture & Building Press. [in Chinese].

Ministry of Machine-Building Industry of the People's Republic of China. 1998. "Mechanical Parking Systems-classification, Models and Basic Parameters." JB/T 8713-1998. Institute of Mechanical Standardization, Ministry of Machinery Industry Press. [in Chinese].

Morteza, A., and M. Amirmazlaghani. 2020. "A Novel Statistical Approach for Multiplicative Speckle Removal Using T-locations Scale and Non-sub Sample Shearlet Transform." Digital Signal Processing 107: 1–21. doi:10.1016/j.dsp.2020.102857.

National Bureau of Statistics (NBS). 2019. "Statistical Bulletin of National Economic and Social Development of the People's Republic of China in 2019 [EB/OL]." http://www.stats.gov.cn/tjsj/zxfb/202002/t20200228_1728913.html

Parking Equipment Management Committee of China Heavy Machinery Industry Association (PEMCHMIA). 2001. Mechanical Stereo Garage. Beijing: Ocean Press. [in Chinese]

SAE J1100:2009. 2009. Surface Vehicle Recommended Practice (R): Motor Vehicle Dimensions. Warrendale, Pennsylvania: SAE International.

Schwarz, G. 1978. "Estimating the Dimension of a Model." The Annals of Statistics 6 (2): 461–464. doi:10.1214/aos/1176344136.

Sun, Q., W. Zhang, L. Y. Wan, and X. C. Wang 2015. "Analysis of Vehicle Dimension Definition and Proportion of Coordination in Chinese Market." SAE Technical Paper 2015-01-0477. doi:10.4271/2015-01-0477.

Zhao, H. W., Y. L. Ding, S. Nagarajaiah, and A. Q. Li. 2019. "Behavior Analysis and Early Warning of Girder Deflections of a Steel-truss Arch Railway Bridge under the Effects of Temperature and Trains: Case Study." Journal of Bridge Engineering 24 (1): 05018013. doi:10.1061/(ASCE)BE.1943-5592.0001327.