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Energy Efficiency and Energy Conservation in China's Transportation Industry: A Three-stage Data Envelopment Analysis Approach

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ABSTRACT

China's transportation industry holds high energy consumption. The energy consumption of China's transportation industry climbs up gradually with progress in urbanization and growing volume of passenger and freight traffic, which causes heavy environmental pollution. Improving energy efficiency is an important factor and management goal that influences the sustainable development of the transportation industry. In this study, an energy efficiency evaluation system of transportation industry was initially constructed, and the three-stage data envelopment analysis (DEA) model was adopted to estimate the energy efficiency of China's transportation industry during 2001-2016. Subsequently, environmental variables were introduced to further perfect the calculation results. Results demonstrate that the technical efficiency (TE) of China's transportation industry is 1 in 6 years during the study period in the traditional DEA model, reaching the technological frontier level. TE still has a large potential for improvement. The input redundancy of energy efficiency in China's transportation industry may increase as per capita gross domestic product increases. However, such input can be effectively decreased by increasing the total export-import volume and total retail sales of consumer goods. After eliminating environmental and random factors, the low energy efficiency of China's transportation industry is mainly caused by scale inefficiency. Conclusions in this study can provide theoretical references to understand and improve the energy efficiency of the transportation industry and thus formulate effective transportation energy and environmental policies.

INTRODUCTION

Energy crisis and climate change are common challenges in human society and economic development at present. Given the new development situation, the total energy consumption of the transportation industry increases yearly, as shown in Fig. 1. It has increased from 116.13 million tons of standard coal in 2001 to 396.51 million tons of standard coal in 2016, indicating an annual growth of 16%. The essential problem of energy conservation and emission reduction of transportation industry is how to improve energy utilization in transportation activities to realize maximum economic benefits and minimum environmental pollution. The key to implementing the energy conservation and emission reduction of transportation industry lies in the improvement of energy efficiency, including environmental benefits. Therefore, development strategies to improve energy utilization in transportation activities are the most practical and effective ways to relieve the current energy and environmental crisis and to realize the goal of energy conservation and emission reduction in the transportation industry.

With economic and social development, transportation demand continuously increases, and the conflict between energy demand and supply in the transportation industry gradually intensifies. Such a conflict becomes a new challenge for transportation development. Instead of inadequate transport capacity, inadequate energy supply caused by failure in the reduction of energy consumption per unit transport capacity and limited energy import may restrict the increasing transport demands. Although increasing transport capacity is the most direct measure to meet transport demands, the equal energy consumption can serve additional transport demands if the energy efficiency is improved. Therefore, energy efficiency and energy-saving problems in the transportation industry must be solved, and relevant keys should be identified to explore the energy-saving potential of the transportation industry.

OVERVIEW OF THE STUDY AREA

Transportation is a field of national economy, which shows the highest growth rate of energy consumption and exerts the greatest influence on the environment. Increasing the energy efficiency of the transportation industry and relieving influences on ecological environment are important in realizing sustainable economic and social development. Abundant studies on the estimation of transportation en-

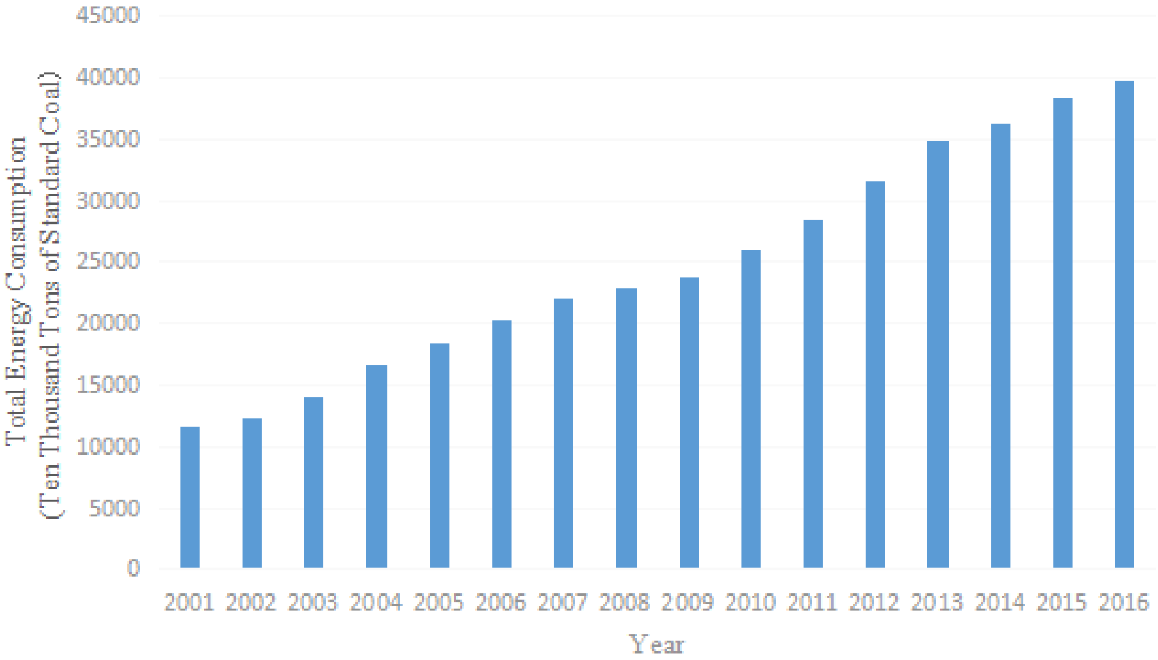

Fig. 1: Energy consumption of China's transportation industry during 2001-2016.
(Data source: *China Energy Statistical Yearbook*)

ergy efficiency and strategies of reducing transportation energy consumption have been reported in developed countries. Erickson et al. (1988) conducted case studies in Tunisia and Costa Rica and proposed specific measures to reduce transportation energy consumption in developing countries. Bose (1996) analysed transportation demand and energy consumption and proposed the total energy demands of traffic department in Delhi to reduce future fuel consumption and air pollution. Utlu et al. (2006) evaluated energy efficiency in four transportation modes (highway, railway, aviation, and sea transportation) in Turkey from 2000 to 2020. Horvath (2006) studied the life cycle list of air emissions (CO_2, nitric oxide, PM10, and CO) related with highway, railway, and air freight transportation in America. Shim et al. (2006) analysed the relationship between transportation energy consumption characteristics and urban morphological element and found that transportation energy efficiency can facilitate sustainable development of environment. Timilsina et al. (2009) analysed the influencing factors of CO_2 emission in 20 regions in America and revealed that economic growth and changes of environmental influencing index of the transportation industry are the main causes of increased CO_2 emission in the transportation industry in America. Zhang et al. (2011) analysed the current situations of China's transportation energy consumption and relevant influencing factors. He concluded that energy utilization of the transport department gradually decreases as energy consumption intensity increases. Transportation activity effect is the most important cause of the increased energy consumption of the transport department. Wang et al. (2013) strategically evaluated fuel pricing to realize energy-saving and emission reduction goal in highway transportation in China and found that appropriate fuel pricing is very effective in reducing excessive fuel consumption. Klinsrisuk et al. (2013) discussed how to coordinate and integrate policies of Thailand to reduce greenhouse gas emission and transport energy consumption. Cui et al. (2014) estimated transportation energy efficiency on the basis of the data of 30 provincial administrative regions from 2003 to 2012 and found that traffic structure and management measures can influence transportation energy efficiency. Phoualavanh et al. (2015) applied the long-term energy alternative plan to predict traffic demand in Laos and revealed that four relieving measures can decrease energy consumption and CO_2 emission by 9.3% and 20%, respectively. Zhen et al. (2016) evaluated transportation energy efficiency in different provinces of China from 1995 to 2013 and found that the energy efficiency of China's transportation industry gradually declined due to decreased technical efficiency. Achour et al. (2016) identified the driving factors of transportation energy consumption in Tunisia during 1985-2014 and revealed positive effects of economic yield, transport intensity, population scale, and traffic structure on energy consumption. Chen et al. (2018) investigated transportation energy efficiency in 15 cities in Yangtze River Delta during 2009-2013 and found negative influences of per capita GDP and per capita area of road on transportation energy efficiency. Moreover, the occupancy of public traffic mode can increase transportation energy efficiency. Feng et al. (2018) analysed the energy efficiency and energy-saving potential of China's transportation industry during 2006-2014. He concluded that the decreased energy efficiency of China's transportation industry is mainly the consequence of decreased management efficiency and increased regional gaps in technological level. According to existing studies on energy efficiency and energy utilization of transportation industry, most studies on transportation energy efficiency are qualitative and propose relevant countermeasures to address the current low energy efficiency. However, quantitative analyses on energy efficiency are few. Moreover, existing associated studies mainly measure energy efficiency by energy consumption per unit traffic volume and lack a systematic research on comprehensive energy consumption in the transportation industry. In the present study, a contrast analysis on the relative energy efficiency of China's transportation industry is performed on the basis of the data during 2011-2016 by using the three-stage data envelopment analysis (DEA). Relevant energy-saving and emission reduction measures for the transportation industry are also proposed. Research conclusions are expected to provide theoretical references for understanding the status of transportation energy efficiency and the keys of energy saving and developing a sustainable energy development for the transportation industry.

MODELS AND DATA SPECIFICATION

Models (Three-stage DEA)

Stage 1 - Traditional DEA model: Banker (1984) proposed the DEA-BCC model on the basis of the traditional DEA model. The DEA-BCC model decomposes technical efficiency in CCR model into pure technical efficiency and scale efficiency. This model can accurately reflect operation management level of decision-making units (DMUs). With respect to the evaluation of the production efficiency of railway, the input of railway production is easy to be controlled, whereas the output is not. As a result, the input-oriented BCC model is selected for this study.

Assume n DMUs exist, and each DMU has m inputs and s outputs. $x_{ik}(i=1,2,\cdots,m)$ reflects the input variable i of DMU k. $y_{jk}(j=1,2,\cdots s)$ is the output variable j of DMU k. The calculation of the total efficiency of DMU P is transformed into a linear planning problem:

$$\min\theta$$
$$s.t\begin{cases}\sum_{k=1}^{n}X_k\lambda_k+s^-=\theta X_t\\ \sum_{k=1}^{n}y_k\lambda_k-s^+=Y_t\\ \sum_{k=1}^{n}\lambda_k=1\\ \lambda_k\geq 0,k=1,2,\cdots,n\\ s^+\geq 0,s^-\geq 0\end{cases}, \quad ...(1)$$

Where, $X_1=(x_{11},x_{22},\cdots,x_{m1})$, and $Y_1=(y_{11},y_{22},\cdots,y_{s1})$. θ is the total efficiency of the investigated DMU, and $0\leq\theta\leq 1$. When $\theta=1$, the investigated DMU is a point on the leading surface of efficiency and it is effective. When $\theta<1$, the investigated DMU is invalid. $1-\theta$ is the surplus proportion of the investigated DMU.

Stage 2 - Adjust input variables: The input-output slack variable, which is analysed from Stage 1, is sensitive to external environmental factors, random error, and internal management factors. The traditional DEA model cannot accurately recognize influences of internal management, external environment, and random error but ascribe all influencing factors as internal management. Hence, Timmer (1971) proposed stochastic frontier analysis (SFA), which involves influences of external environmental factors on relative efficiency. If the value of input n of DMU i is X_{ni}, then the slack variable is S_{ni}. Thus, $S_{ni}=X_{ni}-X_n$. The relation model between slack variable and environmental variable is shown in formula (2):

$$S_{ni}=f(Z_i,\beta^n)+V_{ni}+U_{ni}$$
$$n=1,2,\cdots,N,i=1,2,\cdots,I\text{'} \quad ...(2)$$

Where, S_{ni} is the slack variable of input n of DMU I, and $Z_i=(z_{1i},z_{2i},\cdots,z_{ki})$ is the environmental variable k. $f(Z_i,\beta^n)$ is the influence of environmental variables on the input slack variable S_{ni}, which is generally determined by $f(Z_i,\beta^n)=Z_i\times\beta^n$. $V_{ni}+U_{ni}$ is a mixed error, which is hypothesized to reflect the random error. U_{ni} reflects invalid management and hypothesizes that U_{ni} obeys the truncated global distribution. Moreover, V_{ni} and U_{ni} are mutually independent. When $\gamma=\frac{\sigma_{un}^2}{\sigma_{un}^2+\sigma_{vn}^2}$ approaches 1, management factors take the dominant role. When $\gamma=\frac{\sigma_{un}^2}{\sigma_{un}^2+\sigma_{vn}^2}$ approaches 0, random error takes the dominant role.

The regression results of the SFA model are applied to adjust the input variables of n DMUs. Influences of environmental factors and random error are eliminated. The efficiency that reflects the management level simply is calculated. The adjustment formula is shown as follows:

$$X_{ni}^{*} = X_{ni} + \left[\max_{i}\left\{Z_i \times \beta^n\right\} - Z_i \times \beta^n\right] + \left[\max_{i}\left\{V_{ni}\right\} - V_{ni}\right]$$
$$n = 1, 2, \cdots, N, i = 1, 2, \cdots, I \quad ...(3)$$

Where, X_{ni}^{*} is the adjusted input variable, and X_{ni} is the original input. The first square brackets adjust all DMUs to relevant external environment. The second square brackets adjust the random error of all DMUs to become equal to make each DMU face with the same external environment and probability.

Stage 3 - Adjusted DEA model: The adjusted input data and original output data are substituted into the BCC model to recalculate the efficiency values of different DMUs. The third-stage DEA "filters" influences of external factors by using information in the slack variable, thereby obtaining management efficiency only. Moreover, how environmental variables adjust the input slack variable can be investigated by analysis in Stage 2, thereby adjusting the influence of the direction and degree of technical efficiency.

Data Specification

Transportation system is a dynamic complicated system with multiple factor inputs and multiple outputs. Inputs of the transportation system involve labour, material, and capital, whereas outputs include passenger and freight volumes. According to the total factor productivity theory in the theory of economic growth, the capital input (1,000 billion yuan) of the transportation industry, labour population (10,000 persons), and total energy consumption (10,000 tons of standard coal) are used as input variables, whereas passenger turnover (100 million people/km), freight turnover (100 million of tons/km), and CO_2 emission (10,000 tons) are used as output variables. Environmental variables should meet the "separation hypothesis". Factors that can influence transportation energy efficiency but are beyond the subjective control range are selected. Considering the characteristics of the transportation production industry, per capita GDP (yuan), total import-export volume (100 million yuan), and total retail sales of consumer goods (100 million yuan) are chosen as three environmental variables, which correspond to three perspectives of macroeconomic development, international trade, and domestic consumption. Sample data are collected from China Statistical Yearbook and China Energy Statistical Yearbook. The investigation period is 2001-2016.

RESULT ANALYSIS

Traditional DEA results in Stage 1: In the first stage, TE, pure technical efficiency (PTE), and scale efficiency (SE) in different years are gained using the input-oriented BCC model. The results are presented in Table 1. In addition, the difference between ideal value and practical value of the input variable, that is, the slack variable of input variable, can be gained. This value is applied in the calculation in Stage 2.

Table 1 shows that ignoring the influences of external environmental factors and random error, mean TE, mean PTE, and mean SE of China's transportation industry are 0.898, 0.999, and 0.900, respectively. TE in 2008, 2010, 2012, 2013, 2015, and 2016 even reached 1, indicating the technological frontier. TE in the rest of the study period is invalid, and the energy efficiency of China's transportation industry must be further increased. Moreover, PTE is higher than SE in most years, implying that technical inefficiency is attributed to scale inefficiency. According to the results in Stage 1, scale inefficiency is the main constraint against energy efficiency of transportation industry, which conforms to most research conclusions. However, the possibility of overestimation and underestimation of PTE and SE under influences of external environment and random error is neglected, and further estimation is needed.

SFA regression results in Stage 2: In Stage 2 of DEA, slack variable of capital input, labour population, and total energy consumption, which are estimated in Stage 1, are used as the explained variables of a function. Per capita GDP, total import-export volume, and total retail sales of consumer goods are selected as explanatory variables. The influences of the three environmental variables on the input

Table 1: Transportation energy efficiency during 2001-2016.

Year	TE	PTE	SE
2001	0.698	1.000	0.698
2002	0.702	1.000	0.702
2003	0.712	1.000	0.712
2004	0.768	1.000	0.768
2005	0.823	1.000	0.823
2006	0.902	1.000	0.912
2007	0.918	1.000	0.918
2008	1.000	1.000	1.000
2009	0.951	0.985	0.965
2010	1.000	1.000	1.000
2011	0.923	1.000	0.923
2012	1.000	1.000	1.000
2013	1.000	1.000	1.000
2014	0.976	1.000	0.976
2015	1.000	1.000	1.000
2016	1.000	1.000	1.000
Mean	0.898	0.999	0.900

slack variables are investigated. When the regression coefficient is positive, increasing the explanatory variable may increase the input slack variable, thereby increasing wastes. By contrast, the explanatory variable is beneficial to reducing input slack variables and decreasing wastes when the regression coefficient is negative. The analysis results based on Frontier 4.1 software are provided in Table 2. The following can be observed from Table 2:

1. **Per capita GDP:** The slack variable regression coefficient between per capita GDP and input variables is positive, indicating that input redundancy occurs in transportation industry as per capita GDP increases. Per capita GDP also reveals that high-quality passenger and freight transport demands are gradually increasing despite China's constantly increasing per capita GDP. However, energy efficiency of China's transportation industry is low due to the absence of reasonable scientific allocation of existing resources.
2. **Total import-export volume:** Despite the slack variable regression coefficient between total import-export volume and input variables, the absolute value is low. The total import-export volume is beneficial for decreasing the overall input redundancy of the transportation industry. International trade can effectively drive freight transportation and promote effective use of existing resources, thereby increasing TE. Import-export volume increases as total import-export volume continuously increases. As a result, high import-export volume can stimulate enthusiasm of staffs and make full effective use of existing resources in the industry, thereby promoting the full effective use of all resources.
3. **Total retail sales of consumer goods:** The slack variable regression coefficient between total retail sales of consumer goods and input variables is negative, indicating that the increased total retail sales of consumer goods can lower the input redundancy of the transportation industry. The total retail sales of consumer goods are positively related with people's income level, thereby promoting effective utilization of input elements in the transportation industry. As a result, innovative activities conforming to market demands are implemented in the transportation industry, and energy efficiency is gradually increased.

Adjusted production efficiency in Stage 3: PTE, SE, TE, and returns to scale (RTS) of China's transportation industry during 2001-2016 are recalculated in Stage 3 of DEA on the basis of the adjusted input data and the original output data by using Deap2.1 software. The results are shown in Table 3.

Table 3 presents that considering environmental management factors, the mean TE of China's transportation industry decreased from 0.898 to 0.893, and TE decreases in most years. These results reflect that TE in the traditional DEA is slightly high because environmental conditions and random error are neglected. Moreover, TE reached virtual high levels in certain years with poor environment. Therefore, the traditional DEA cannot reflect the real TE of transportation industry. The mean PTE of transportation industry remains the same after environmental factors. The mean SE decreased from 0.900 to 0.894, proving that the low energy efficiency of the transportation industry is mainly attributed to scale inefficiency. Hence, the overall production efficiency of China's transportation industry must be improved by expanding element input scale.

ENERGY-SAVING MEASURES IN THE TRANSPORTATION INDUSTRY

Optimizing and adjusting the transportation industrial structure: The energy consumption of the transportation industry can be relatively reduced by optimizing the transportation structure, which generally includes structures of market demand, market supply, and actual traffic volume. This study adjusts existing transportation network scale,

Table 2: SFA regression results.

		Constant	Per capita GDP	Total import-export volume	Total retail sales of consumer goods	Sigma-squared	Gamma
Slack variable of capital input	Coefficient	-1.98E+04	1.98E+01	-0.87E+00	-2.21E+00	7.56E+08	1.03E+00
	T-test value	-2.15E+04*	1,85E+01*	-1.56E+01*	-1.92E+01*	8.14E+08*	1.03E+00*
Slack variable of labor population	Coefficient	-1.09E+03	1.73E-01	-0.67E-02	-2.51E-02	0.87E+06	1.01E+00
	T-test value	-1.11E+03*	1.31E+01*	-1.23E+01*	-1.49E+01*	1.24E+06*	2.84E+00*
Slack variable of total energy consumption	Coefficient	-1.15E+02	4.87E-02	-1.53E-03	-5.35E-03	1.08E+04	1.06E+00
	T-test value	-1.98E+02*	2.01E+00**	-0.89E+00	-1.87E+00**	1.23E+04*	6.05E+00*

(Notes: T is the index that examines whether the explanatory variable has significant influences on the explained variables. * means passing the 1% significance test, ** means passing the 5% significance test).

Table 3: Energy efficiency of transportation industry after adjustment.

Year	TE	PTE	SE
2001	0.667	1.000	0.667
2002	0.698	1.000	0.698
2003	0.708	1.000	0.708
2004	0.753	0.999	0.754
2005	0.812	1.000	0.812
2006	0.899	1.000	0.899
2007	0.912	1.000	0.912
2008	1.000	1.000	1.000
2009	0.924	0.989	0.934
2010	1.000	1.000	1.000
2011	0.921	1.000	0.921
2012	1.000	1.000	1.000
2013	1.000	1.000	1.000
2014	0.998	1.000	0.998
2015	1.000	1.000	1.000
2016	1.000	1.000	1.000
mean	0.893	0.999	0.894

technological equipment, and management level to optimize the supply structure, guide changes of the demand structure, and optimize the actual structure, finally realizing the goal of energy saving in the industry. Adopting effective measures to adjust and optimize the industrial structure, inhibiting blind growth of heavy industries, eliminating backward productivity, making great endeavours to develop service industry and new high-tech industries, decreasing the proportion of the secondary industry and gradually increasing the proportion of the tertiary industry, and lowering energy consumption for excessive transportation activities are suggested. Moreover, the transportation industry should adjust the internal structure and encourage development of railway, waterway, and pipeline transportations, which are characteristics of high transport capacity and low energy consumption and pollution.

Integrating internal management departments in the transportation industry: In the existing management system, five transportation modes are subordinated to different departments because the unified comprehensive transportation management agency is established. A unified management department is lacking, and all departments are separated in functions. This separation is beneficial for neither the construction of a comprehensive energy-saving transportation system nor energy-saving performance in transportation, especially in highway transportation. The implementation of energy-saving laws, regulations, and standards has no guarantee. Reforming existing traffic management system, establishing a unified government department to be responsible for the unified planning and management of five transportation modes, and promoting comprehensive energy-saving transportation system are suggested.

Strengthening technological innovation of the transportation industry: Transportation management departments shall take the initiative to implement relevant energy-saving and emission reduction policies. Meanwhile, to optimize infrastructure construction and develop railway and water transportation according to local conditions is also of vital significance. Changing the transportation development mode and constructing a comprehensive transportation system is useful to speed up technological progresses on energy efficiency and energy structure's optimization. Governments shoulder the obligation to increase energy utilization of vehicles and force to eliminate old vehicles to reduce energy wastes. Improving fuel economy and lowering energy consumption of existing transportation tools, and accelerating to construct a fuel economic standard system for motor vehicles including main vehicle types are suggested.

Increasing energy-saving promotion of transportation industry: Transportation energy consumption continuously increases with the rapid economic development, which intensifies energy-saving problems. Although energy-saving indexes are decomposed to different industries, the public consciousness of energy saving is weak. Hence, popularizing energy-saving transportation to children and adults is suggested. Based on improved service quality of existing public transportation, the public transportation and other private transportation modes should be priced differently to guide the public to select public transportation.

CONCLUSIONS

Improving the energy utilization of the transportation industry, maximizing economic benefits, and minimizing environmental pollution are the essential problems of energy saving and emission reduction in the industry. The development strategy of improving transportation energy utilization is the most practical and effective way to relieve the current transportation energy and environmental crisis and to realize the goal of energy saving and emission reduction. In this study, an energy efficiency evaluation index system of the transportation industry was established. The energy efficiency of China's transportation industry during 2001-2016 was estimated using the three-stage DEA model. The study findings show that TE of China's transportation industry is 1 in 6 years during the study period, reaching the technological frontier level. The input redundancy of energy efficiency in China's transportation industry may increase as per capita GDP increases, but it can be effectively decreased by increasing total export-import volume and total retail sales of consumer goods. After eliminating environmental and random factors, low energy efficiency of

China's transportation industry is mainly caused by scale inefficiency. Further studies on increasing the input and output indexes of transportation energy efficiency, formulating energy-saving and emission reduction measures for specific transportation industries, and analysing energy efficiency variation trends of different provinces are suggested.

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