A Study on Evolution and Driving Forces of Carbon Dioxide Emissions

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Abstract

According to theoretical analysis and empirical verification based on IPAT identity, the evolutionary process of carbon dioxide emissions driven by technical advances over time generally follow in sequence three inverted U shape curves in the long run, which are the inverted U shape curve of carbon dioxide emissions intensity, carbon dioxide emissions per capita, and total carbon dioxide emissions respectively. According to three inverted U shape curves, the evolutionary process of carbon dioxide emissions can be divided into four stages, that is: stage before the peak of carbon dioxide emissions intensity, stage between the peak of carbon dioxide emissions intensity and the peak of carbon dioxide emissions per capita, stage between the peak of carbon dioxide emissions per capita and the peak of total carbon emissions, the last stage comes behind total carbon dioxide emissions. Four stages' driving forces are: carbon-intensive technological advance, economic growth, carbon-reducing technical advances, carbon-reducing technical advances respectively. Finally, our conclusion is: carbon dioxide emissions evolutionary process follows the law of three inverted U shape curves in turn, if we take measures to dealing with climate change, we should not be divorced from the basic development stage.

Keywords: carbon dioxide emissions, environmental kuznets curve, evolution, driving force, stage, IPAT identity, technical advance

1. Introduction

Global environmental degradation has been inspiring more and more researchers to investigate the causes of environmental degradation and the complex relationship between environmental changes and its driving forces including economic growth and environmental degradation (McPherson & Nieswiadomy, 2005). Environmental policy and resolution to environmental issues could be better designed and handled based on these studies.

As the most significant environmental challenge in the 21st century, human development is facing global climate change whose main feature is climate warming. Global climate change has caused serious consequences on natural ecosystems and the environment of human survival and development. In order to deal with climate change, reducing greenhouse gas emissions, carbon dioxide emissions which is the top priority to be considered in taking intensive action. However, the carbon dioxide emissions has been affected by population growth, economic growth, technical advances, social system and some other factors such as human values change directly or indirectly. Some factors will play a decisive role in the long-term trend of carbon dioxide emissions, so it's of great importance to figure out which factors are the leading factor of greenhouse gas emissions and carbon dioxide emissions.

Since the UNFCCC (United Nations Framework Convention on Climate Change) and the "Kyoto Protocol" were signed, the research on the driving forces of carbon dioxide emissions has become a hotspot.

For the time being ,the research on the driving forces of carbon dioxide emissions is basically carried out along two main streams: one stream just focuses on the evolutionary relationship between economic growth and carbon emissions, the other stream is to explore the relationship among carbon dioxide emissions and a number of factors/driving forces.

Research on evolutionary relationship between economic growth and carbon emissions which not only reflects the growth of carbon emissions, but also reveals whether the laws of Environmental Kuznets Curve (Environmental Kuznets Curve, referred to as EKC) exists between economic growth and carbon emissions. EKC describes a situation that environmental pollution or degradation increases along with increasing income per capita in the early stages of economic development, when it reaches a certain peak, the environment would be improved along with increasing income per capita (Dinda, 2004). However, the research on the EKC relationship between economic growth and carbon dioxide emissions has not yet made a clear conclusion. It has been verified that there are linear, quadratic and cubic forms of decline relationship between carbon dioxide and per capita income respectively, in which opinions supporting the effective evidence of carbon dioxide emissions EKC curve are the majority. However, EKC curve peak in the literature corresponding to income per capita are of great difference, from nearly 8000 U.S. dollars (Calculated in 1985 constant prices) to more than 35,428 U.S. dollars (Calculated in 1986 constant prices) (Huang W. M. et al., 2008; Richmond & Kaufmann, 2006).

Research on exploring the relationship among carbon dioxide emissions and a number of factors/driving forces, these factors/driving forces are divided into two categories ----socio-economic factors (Fan Y. et al., 2006; York R. et al., 2003) such as population, economic growth, economic structure, energy structure, technological advance, urbanization, policies and systems, as well as natural factors (Neumayer, 2002), with an overemphasis on positive side. For example, in order to analyze and express the environmental impact on human activities, Ehrlich etc. had proposed the environmental impact equation that is IPAT equation in the early 1970s. They have attributed the environmental impact to the product of three key drivers that are population, affluence and technology degree (Ehrlich & Ehrlich, 1970). Some scholars disagreed with the view of Ehrlich etc. Schulze believes that the equation ignores the impact of behavioral choices on the environment and suggests that the model should be rewritten as an IPBAT model (Schulze, 2002), but Diesendorf takes the opposite view that behavioral factors should not be included in the IPAT equation, for the impact of behavior choices is implicated in the equation of factors (Diesendorf, 2002). In order to link use intensity and environmental impact and other drivers as clear as possible, based on the traditional IPAT equation, Waggoner etc. proposes ImPACT model where the environmental impact is the combined result of factors of population, affluence degree, intensity and efficiency of usage (Waggoner & Ausubel, 2002). However, York argues that neither IPAT nor ImPACT model is allowed to make hypothetical test on the omissions, and both of them can not reflect the effect of non-monotonic or non-proortion among the function relationship of driving forces, so he proposes a stochastic model ---- STIRPAT model to compensate for the shortcomings of the model (York et al., 2003). Although the IPAT equation may have defects in some aspects, this model is still widely used as it can give us relatively clear and concise explanations on how the environmental impact follows the driving force change. This article is trying to reveal the evolutionary law on carbon dioxide emissions under the driving force of technological advances and its different driving forces at different stages based on the IPAT equation.

2 Methodologies

2.1 Theory about Carbon Dioxide Emissions Driving Force

As a basic tool to analyze impact of human activities on the environment, the specific expression of IPAT equation is $I = P \times A \times T$, where I is environmental impact, P is population, A is wealth degree which is usually expressed with GNP or GDP, T is technical level in the broad sense which is often characterized with environmental impact of unit output (GDP).

$$CO_2 = P \times (GDP / P) \times (CO_2 / GDP) \tag{1}$$

Equation (1) shows that population growth, economic growth and technological advance have comprehensive effect on carbon dioxide emissions, therefore, control carbon dioxide emissions can take above three factors into consideration theoretically.

By taking logarithm and derivative by time on both sides of the equation (1), we can obtain:

$$\overline{CO_2} = \overline{P} + \overline{GDP / P} + \overline{CO_2 / GDP} \tag{2}$$

According to equation (2), we can draw the conclusion that the growth of carbon emissions is a synthetic effect of population growth, economic growth and technological progress. Therefore, the three factors mentioned above should be controlled over the rapid growth of carbon emissions, but due to the strong inertia of the population growth, even if strict measures are carried out, significant change within a short time is of great difficult, especially for developing countries. Generally, the economic growth is the goal which most of the countries are perusing. It’s unrealistic to try to achieve the decline in carbon emissions at the cost of reducing the rate of economic growth. Instead, we mainly hope the technological progress which is very active and dynamic can attain this object. Considering technological progress, equation (2) can be divided into three cases for further discussion.

Case 1: When the situation of $\overline{CO_2 / GDP} > 0$ occurs, it indicates that technological progress is based on the cost of carbon emissions increase. This situation not only stimulates the growth of carbon emissions rapidly, but also reflects a very extensive economic growth mode. The situation of $\overline{CO_2 / GDP} < 0$ demonstrates that technological advances begin to help alleviate the growth of carbon emissions resulting from the population and economic growth. In order to curb carbon emissions growth, one of the feasible action is to change the situation from $\overline{CO_2 / GDP} \geq 0$ to $\overline{CO_2 / GDP} < 0$, which means carbon emissions intensity transfer from continuous increase to a steady decline. It is the prerequisite to control the total carbon emissions. This transformation leads to the occurrence of inverted U-curve of carbon emissions intensity evolution.

Case 2: When the situation of $\overline{GDP / P} \leq \left|\overline{CO_2 / GDP}\right| < \overline{P} + \overline{CO_2 / GDP}$ occurs, according to eq.(1), we can find that carbon emissions per capita achieve a zero growth, meanwhile, carbon emissions per capita show a steady downward trend due to the continuous technology advances. All the conditions above form an inverted U-curve of carbon emissions per capita. This stage means that the decline speed of carbon emissions intensity resulting from technological advances may balance or offset the increase speed of carbon emissions due to economic growth.

Case 3: When the speed of technological progress is fast enough to offset population and economic growth which lead to the growth rate of carbon emissions $\left|\overline{CO_2 / GDP}\right| \geq \overline{P} + \overline{CO_2 / GDP}$, carbon emissions will achieve zero growth and enter into a steady decline phase. This process leads to the occurrence of inverted U-curve of total carbon emissions.

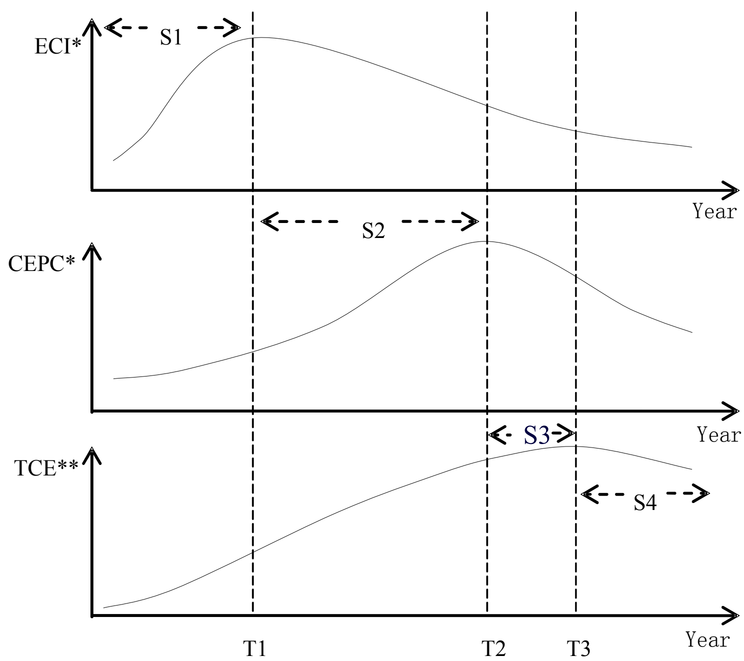

Figure 1. Diagram of three inverted U shape curves about carbon dioxide emissions evolution
(Description about CEI*, CEPC**, TCE***, please see note 1)

Since technological advance is a time-varying evolution, which determines the basic characteristics of the order of the three inverted U-curve emergence. Driven by technological advance, the evolution of carbon dioxide emissions will follow the law of three “inverted U-curve” successively in the long term, which is the inverted U-curve of carbon intensity, the inverted U-curve of carbon dioxide emissions per capita and the inverted U-curve of total carbon dioxide emissions (see Figure1). According to the law of three inverted U-curves, the evolution process can be divided into four stages, namely: the previous stage of carbon emission intensity peak (the S1 phase in Figure 1), the phase of carbon intensity peak to carbon dioxide emissions per capita peak (the S2 phase of Figure 1), carbon dioxide emissions per capita peak to total carbon dioxide emissions peak (the S3 phase of Figure 1), and the phase of steady decline in total carbon dioxide emissions (the S4 phase of Figure 1). If the carbon dioxide emissions per capita peak is overlapped with the total carbon dioxide emissions peak at the same time (this situation is relevant with population change), then four stages will change into three stages, that is the stage of S1, S2, S4, three stages can be seen as a special situation of the four stages evolution.

Indicators' change of carbon dioxide emissions intensity, carbon dioxide emissions per capita, total carbon dioxide emissions in different stages are also different (see Table 1). Indicators of carbon dioxide emissions intensity, carbon dioxide emissions per capita, total carbon dioxide emissions are all go up in Stage S1, carbon dioxide emissions intensity goes down and both of carbon dioxide emissions per capita, total carbon dioxide emissions go up in Stage S2, both of carbon dioxide emissions intensity, carbon dioxide emissions per capita go down, total carbon dioxide emissions goes up in Stage S3, carbon dioxide emissions intensity, carbon dioxide emissions per capita, total carbon dioxide emissions are all go down in Stage S4. Realize human fossil energy consumption or carbon dioxide emissions reduce radically while not with economic development as the price is an ultimate goal of low carbon development. There will be an absolute decouple between economic development and total carbon dioxide emissions in Stage S4 which is one of key targets of low carbon development.

There are significant differences in dominant driving forces among four stages (Figure 2). In stage S1, although the population growth, economic growth and technological advance have strengthened carbon emissions, the increase of carbon dioxide emissions is mainly driven by carbon-intensive technological advance. In stage S2, economic growth played a leading role in carbon dioxide emissions growth; technological advance can mitigate the growth of carbon dioxide emissions to some extent, but it still cannot offset the speed of carbon dioxide emissions growth caused by the rapid growth of population and economic development. In stage S3 and S4, carbon dioxide emissions are mainly driven by the progress of carbon emission reduction technology.

Table 1. Changes of indicators of CEI, CEPC, and TCE in different stages

Indicators \ Stage	Stage S1	Stage S2	Stage S3	Stage S4
Carbon dioxide emissions intensity	↑	↓	↓	↓
Carbon dioxide emissions per capita	↑	↑	↓	↓
Total Carbon Emissions	↑	↑	↑	↓

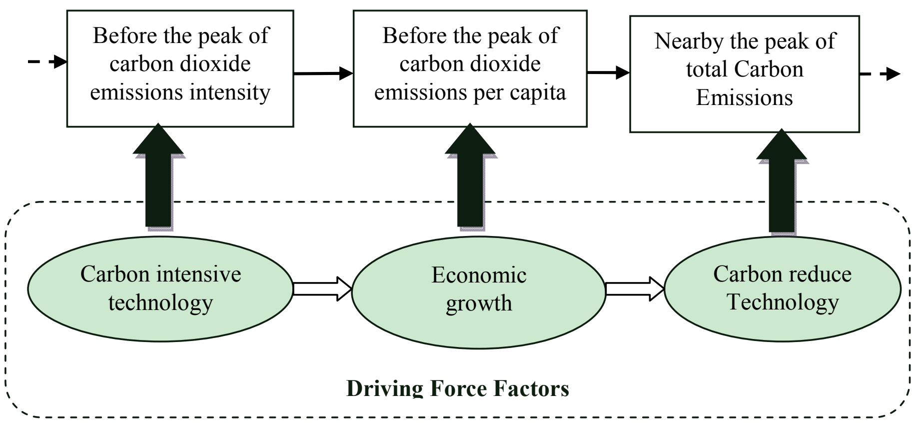

Figure 2. Different evolutionary stages and its leading driving force of carbon emissions

It must be mentioned that the judgment is based on the stringent assumptions that the intensity of carbon dioxide emissions would continue to reduce or the step of technology advances would not cease. Due to fluctuations in the economy, structural adjustment, policy changes, and possibly technical or economic limits (Neumayer, 2002), it is possible that carbon dioxide emissions intensity will not always maintain a downward trend, or even fluctuate within a short period or some years, but in the long term, carbon dioxide emissions intensity generally shows a more obvious downward trend which is in line with the above assumptions.

2.2 Data

Since some patterns experienced by developed countries can represent the trends of what would happen for most of the developing countries to some extent, in order to confirm the above basic judgments on evolution rules of carbon dioxide emissions and its driving forces, we have made an empirical analysis by applying a long period of carbon dioxide emissions historical data on the world's major developed economies which are recommended by International Monetary Fund (IMF). Population, GDP per capita and fossil fuel combustion emissions data are from OECD (OECD, 2006) and CDIAC (CDIAC, 2008) respectively.

3. Results

3.1 Verification on the Evolution Rules of Three Inverted U-Curves

The empirical results are used to confirm the existence of three inverted U-curves, and the inverted U-curve of carbon dioxide emissions intensity is the most obvious one. We will make figures to show the trends of four typical developed countries' (that is Britain, France, Germany, United States) carbon dioxide emissions intensity (CEI), carbon dioxide emissions per capita (CEPC), total carbon dioxide emissions (TCE) respectively in hundred years (see Figure 3-6), We will set 1 as initial value of indicators of CEI, CEPC, TCE, so as to eliminate different impact of units of CEI, CEPC, TCE.

It can be drawn from the Figure 3-6 that the carbon dioxide emissions intensity peaks of Britain, France, Germany, and United States appeared in the year of 1883, 1930, 1917, and 1917 respectively. By observing the evolution of carbon dioxide emissions per capita trends in more countries and regions, we can find that 16 developed economies have generally stepped over the peak of carbon dioxide emissions per capita, which are Australia, Belgium, Canada, Denmark, France, Germany, Hong Kong, Ireland, Israel, Netherlands, New Zealand, Singapore, Sweden, Switzerland, Britain and United States. Although China has experienced the peak of carbon dioxide emissions intensity, its carbon dioxide emissions intensity value still fluctuating significantly, there is neither sign of steady decline in carbon dioxide emissions intensity, nor sign of decline in the carbon dioxide emissions per capita. From the aspect of evolution trends in carbon dioxide emissions, we find that there are fewer countries and regions (11 developed economies) have stepped over the peak of total carbon emissions, which are Belgium, Denmark, France, Germany, Hong Kong, Netherlands, New Zealand, Singapore, Sweden, Switzerland and Britain. Furthermore, the basic rules that the inverted U-curve of carbon dioxide emissions intensity, carbon dioxide emissions per capita and total carbon dioxide emissions appear in turn is confirmed. From observed time of major developed economies and some developing countries step over the carbon emission peak, it will take a relatively long time from carbon dioxide emissions intensity peak to carbon dioxide emissions per capita peak, generally in 24-91 years, 55 years on average , including the Britain 88 and Germany 62 years, the United States 56 years, Netherlands 66 years, New Zealand 91 years, Canada 58 years, Belgium 44 years, Denmark 53 years, France 43 years , Hong Kong and Singapore 24 years, Sweden 33 years, Switzerland 60 years. Whereas, it will experience a relatively short time from carbon dioxide emissions Per capita peak to the peak of total carbon emissions. Except France and Hong Kong experienced 6 years, Belgium, Denmark, Germany, Netherlands, New Zealand, Singapore, Sweden, Switzerland and Britain overlapped two peaks, this also means that if carbon dioxide emissions can leap from carbon dioxide emissions intensity peak to carbon dioxide emissions per capita peak, there will be relatively easy to step over the peak of total carbon emissions.

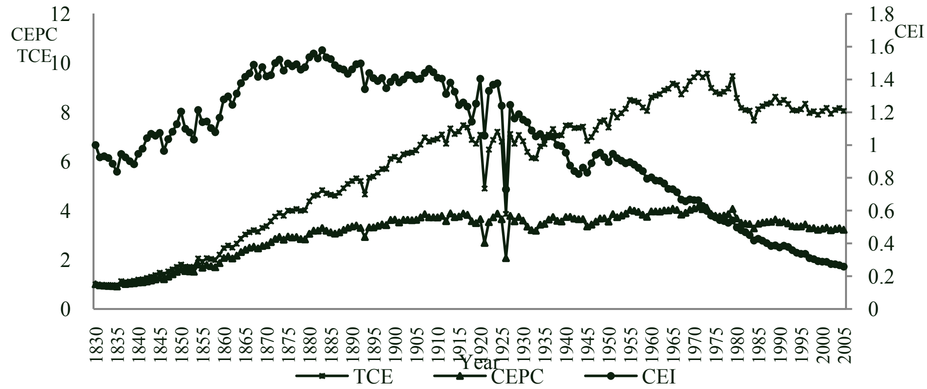

Figure 3. Britain indicators of CEI, CEPC, TCE trends in hundred years

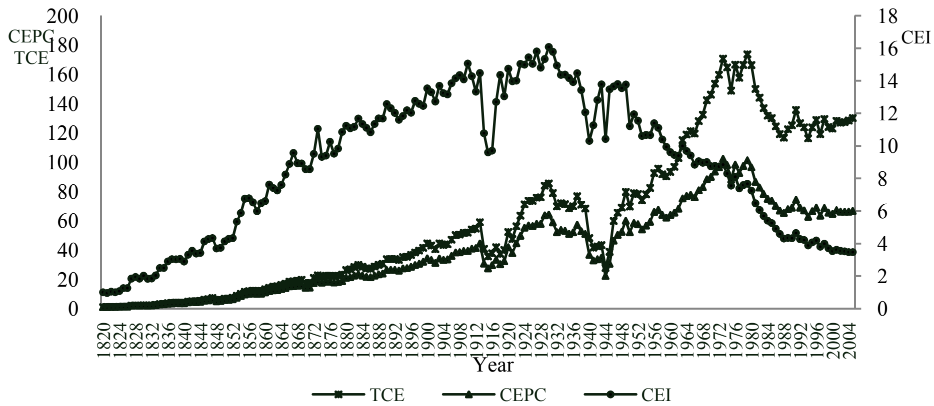

Figure 4. France indicators of CEI, CEPC, TCE trends in hundred years

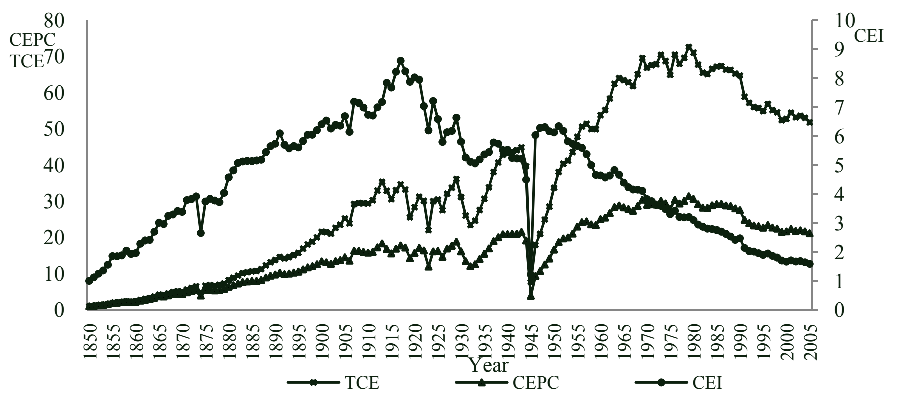

Figure 5. Germany indicators of CEI, CEPC, TCE trends in hundred years

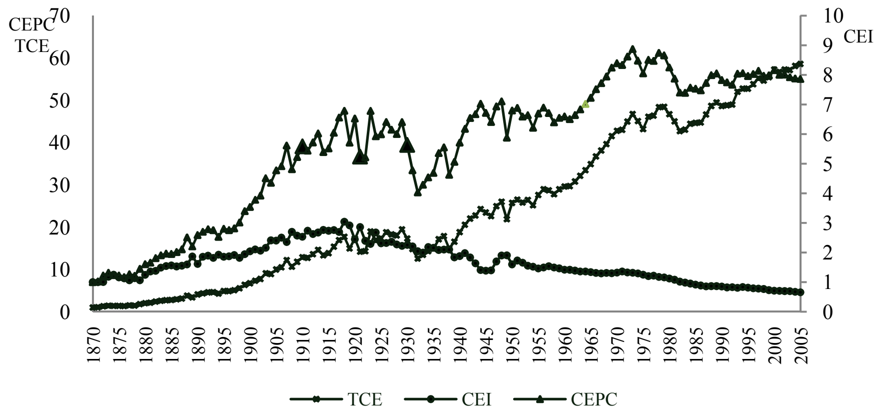

Figure 6. United States indicators of CEI, CEPC, TCE trends in hundred years

3.2 Verification on the Different Evolution Stages of Carbon Emissions' Driving Forces

According to equation (3), we give a further analysis on the contribution of different evolution stages of carbon emissions' driving forces to carbon emissions' changes. Due to the short interval from carbon dioxide emissions Per capita peak to the peak of total carbon emissions, we will focus on the contribution of various driving forces of first two phases, shown in Table 2.

Table 2 confirmed the hypothesis of dominant driving force from various carbon dioxide emissions evolution stages. Carbon-intensive technological advance plays a leading role on the carbon dioxide emissions changes before the stage of carbon dioxide emissions intensity peak. During this period, the carbon dioxide emissions of most of the countries selected in this paper experienced a rapid increase, except a few countries such as Belgium, Hong Kong, Ireland, Israel, Britain, and Brazil. Economic growth was playing a leading role on the carbon dioxide emissions changes during the period between carbon dioxide emissions intensity peak and carbon dioxide emissions per capita peak, at this period technological advance began to play a buffering role at different level on the increase of carbon emissions, but this buffering could still not offset the positive promotion owing to population and economic growth, which led to the still rapid growth of carbon dioxide emissions. Only in a few countries or regions (For example, New Zealand and Brazil), the population changes in stage between carbon dioxide emissions intensity peak and carbon dioxide emissions per capita peak played a leading role on carbon emissions. During the period from carbon dioxide emissions per capita peak to total carbon dioxide emissions peak and the period after the peak of total Carbon Emissions, technological advances which combined with carbon dioxide emissions began to dominate the steady decline in carbon emissions, and carbon dioxide emissions showed a steadily downward trend, then economic growth and carbon dioxide emissions showed strong decouple.

Table 2. Driving forces contributing to the major developed economies and some developing countries of different stages (%)

		Before the stage of Carbon emissions' intensity peak			Stage between the peaks of carbon dioxide emissions intensity and carbon dioxide emissions per capita		
County/Region	Target time	Contribution rate* of Population changes to the changes in total carbon emissions (%)	Contribution rate of changes of GDP Per capita to the changes in carbon emissions (%)	Contribution rate of carbon dioxide emissions intensity changes s to the changes in total carbon emissions (%)	Contribution rate of Population changes to the changes in total carbon emissions (%)	Contribution rate of changes of GDP Per capita to the changes in carbon emissions (%)	Contribution rate of carbon dioxide emissions intensity changes s to the changes in total carbon emissions (%)
Australia	1870-1982	35.4	24.4	38.5	52.5	86.3	-38.6
	1870-1920	28.5	9.6	59.9	48.1	55.8	-4.6
Austria	1870-1908	17	27.2	54.2	/	/	/
Belgium	1846-1929	26	45.8	27.2	53.7	247.1	-197
Canada	1870-1921	20.1	15.8	61.9	59.2	94.6	-53
Denmark	1843-1943	20.3	24.1	54.1	24.3	121.4	-44.8
Finland**	1860-1976	13.5	33.5	51.2	31.2	210	-138.2
France	1820-1930	6.3	30.7	62	32.5	154.3	-85
Germany	1850-1917	18.4	20.1	60.1	23.1	211.9	-131.9
Greece**	1921-1996	12.2	35.5	50.4	7.9	131.5	-38.3
Hongkong	1950-1969	29.9	48.5	18.8	28	87.1	-15.5
Ireland	1924-1939	-4.3	31.2	72.4	20	152.6	-70.6
	1924-1971	-0.7	75.5	24.8	36.9	191	-123
Israel	1950-1953	26.3	3.2	63.7	45.1	57.9	-4.2
	1950-1966	32.8	36	26.9	51.1	55.3	-7.3
Italy**	1861-1973	11.5	31.5	55.4	19.9	206.1	-123.7
Japan**	1874-1914	8.2	11.6	78.2	28.7	90.6	-19.4
	1874-1973	14.8	36.1	46.8	51.5	201.2	-149.9
Korea**	1946-1970	10	22.9	62.2	17.3	97.8	-15.1
	1946-1980	11.3	32.3	51.6	16.5	107	-22.9
Netherlands	1846-1913	30.5	26.1	42.4	47.3	74.3	-21.8
New Zealand	1878-1910	29.8	8	60	69.3	58.8	-28.2
Norway	1865-1915	13.2	22.1	63.2	/	/	/
Portugal**	1872-1913	15.2	13.2	70.5	18.6	87.5	-6.4
Singapore	1957-1970	14.2	25.8	54.8	39.2	117.5	-54.7
Spain	1850-1976	14.6	34.5	49.5	/	/	/
Sweden	1839-1937	10.5	20.2	67.7	21.1	86.4	-7.9
Switzerland	1858-1913	10.3	16.2	71.9	31.8	91	-22.8
Taiwan	1912-1927	11.6	16.9	68.7	/	/	/
United Kingdom	1830-1883	24.1	46.2	28.7	66.2	160.4	-125.2
United States	1870-1917	32.8	26.4	38.8	70.1	114.1	-82.8
Brazil**	1901-1913	21.4	8.9	67.4	51.4	49.1	-1.6
	1901-1978	41.2	41.4	15.6	69.6	28.9	1
China	1950-1960	7.9	16.8	70.4	/	/	/
	1950-1978	18	26.6	52.3	/	/	/
India	1884-1992	15	21.7	62	/	/	/

Description about *and **, see note 2

4. Conclusion and Discussion

4.1 Conclusion

According to theoretical and empirical analysis on the driving forces of carbon dioxide emissions evolution, conclusions can be drawn as following:

Based on IPAT identity, it can be found that carbon dioxide emissions evolutionary process follows the law of three inverted U shape curves in turn. The three curves are the inverted-U shape curve of carbon dioxide emissions intensity, inverted-U shape curve of the carbon dioxide emissions per capita, and inverted-U shape curve of total carbon dioxide emissions respectively.

According to the above three inverted U shape curves, the carbon dioxide emissions evolutionary process can be divided into four stages, that is, stage before the peak of carbon dioxide emissions intensity, stage between carbon dioxide emissions intensity and carbon dioxide emissions per capita, stage between carbon dioxide emissions per capita and total carbon emissions, and stage behind total carbon emissions.

- The leading driving factors are varying among different stages. Stage before the peak of carbon dioxide emissions intensity (S1) where carbon emission growth is mainly driven by carbon-intensive technical advance; stage between the peak of carbon dioxide emissions intensity and carbon dioxide emissions per capita (S2) is mainly driven by economic growth; stage between the peak of carbon dioxide emissions per capita and total carbon emissions (S3) is driven by technological advance on reducing carbon emissions, meanwhile technological advance on reducing carbon dioxide emissions is also the leading driving force in terms of stage behind total carbon dioxide emissions.
- The above evolutionary law of carbon inverted U-curve means that reacting to climate change cannot be divorced from the basic development stage but has to be promoted orderly and gradually. Because of the different development stages and foundations between developed and developing countries, the goals and priorities of greenhouse gas emission reduction policy should be differentiated. Developed countries should put their focus on per capita and total carbon dioxide emissions reduction, while developing countries including China should make higher carbon productivity and less carbon dioxide emissions intensity as their objectives. It is improper and unrealistic to let developing countries take the commitment of greenhouse gas emission reduction when their income is still low, which not only violates the fundamental law of development but also hampers their normal development.
- Technological advance plays a fundamental role during the evolutionary process of carbon emissions. As carbon dioxide emissions intensity embodies general technical level affected by multiple factors such as the structure of demand, technology, policies and systems and management etc. Therefore, we can effectively slow down or stop resource consumption or pollutant emissions growth by strengthening the economy structural adjustment, optimizing energy structure, promoting technological innovation, introduce low carbon policies, strengthening supervision and management.

4.2 Discussion

This article is based on the EKC hypothesis, but there are some scholars don't agree with EKC hypothesis or have difference in the peak of EKC, we think reasons are as follows:

- Choose different samples, time and model will lead to different curve fitting effect and different income value Per capita in peak.
- As for lacking of long time series data, most of empirical research often analysis some countries or regions panel data within a short time, which will lead to uncertainty of analysis results.
- Choose different indicators will lead to difference in peak value
- Natural characteristics, historical culture, social economic and technological conditions in different and regions will cause difference in curve shape and peak value.

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Notes:

Note1. We set 1 as initial value of indicators of CEI, CEPC, TCE, so as to eliminate different impact of units of CEI, CEPC, TCE.

Note 2. * Contribution rate = Annual changing rate of target driving force/ Annual changing rate of total carbon emissions

** indicates that these countries' peak value of carbon dioxide emissions per capita are not clarity enough , instead of the relative maximum of recent years. Contribution of each factor may have the relatively small deviations, which does not affect the overall judgment