

Response to Reviewer 1 Comments

Point 1: I am not familiar with the concept of ‘technological bias’ either. I tried to understand the difference between the bias of technological change and exogenous or ‘neutral’ technological change, but I failed. The two types of changes are represented in Eq. 5 (MTC and BTC), but I do not understand the meaning of the variable ‘S’ in this equation and hence not the equation. According to lines 220&221 ‘S’ stands for desirable output, but my impression is that from line 226 onwards ‘S’ has a different meaning (if this is true it would be better to use different symbols). Line 226 suggests that ‘S’ would mean environmental efficiency (ρ), but S is a function of both input and output factors, so I wonder whether it would only indicate environmental efficiency. Can you give an explanation of ‘S’ in the equations?

Response 1: Thanks very much for this comment. Based on this review, we re-read Sections 3.1–3.3 in this paper and then adjust some equations and add the corresponding explanation of some important parameters or variables in equations. First, considering that ‘S’ is unnecessary in Eq. (2) and the different meanings of ‘S’, we delete ‘S’ in Eq. (2); Second, in fact, the “S” in Sections 3.2 and 3.3 refers to the efficiency value, which also is reflected by ρ_k in Eq. (2). Thus, we replace ‘S’ in Sections 3.2 and 3.3 with ρ_k , and then added the explanation of $\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})$, $\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})$, $\rho_k^t(x^t, y^t, b^t)$, $\rho_k^{t+1}(x^t, y^t, b^t)$, $\rho_k^t(x^{t+1}, y^t, b^t)$ and $\rho_k^{t+1}(x^{t+1}, y^t, b^t)$ in the revision manuscript. The new expression is excerpted from the revision manuscript as follows.

“3.1 Slack-based measure (SBM) with undesirable output

We assume that there are N decision-making units (DMUs) each having M inputs, S desirable outputs, and I undesirable outputs, as represented by $x \in R_M^+$, $y \in R_S^+$, and $b \in R_I^+$, respectively. We also suppose that X , Y , and B are defined as: $X = [x_1, x_2, \dots, x_n] \in R^{M \times N}$; $Y = [y_1, y_2, \dots, y_n] \in R^{S \times N}$, and $B = [b_1, b_2, \dots, b_n] \in R^{I \times N}$, respectively. We then define the DEA production possibility set, $P(x)$, as

$$P(x) = \{(x, y, b) | : x \geq X\lambda, Y \leq Y\lambda, B \geq B\lambda, \lambda \geq 0\} \quad (1)$$

Based on $P(x)$, according to Tone [48], the SBM with undesirable outputs is defined as

$$\rho_k = \min \frac{1 - \frac{1}{M} \sum_{m=1}^M \frac{s_m^{x-}}{x_{mk}}}{1 + \frac{1}{M+I} \left(\sum_{s=1}^S \frac{s_s^{y+}}{y_{sk}} + \sum_{i=1}^I \frac{s_i^{b-}}{b_{ik}} \right)}$$

$$s.t. \quad X\lambda + s^{x-} = x_k, \quad Y\lambda - s^{y+} = y_k, \quad B\lambda + s^{b-} = b_k, \quad \lambda \geq 0, \quad s^{x-}, s^{y+}, s^{b-} \geq 0 \quad (2)$$

where s^{x-} , s^{y+} , and s^{b-} denote the slack value of inputs, desirable outputs, and undesirable outputs, respectively. x_{mk} , y_{sk} , and b_{ik} denote the m th input, s th desirable output, and i th undesirable output of the k th DMU, respectively. ρ_k is the environmental efficiency of the k th DMU, with a value between $[0,1]$. A ρ_k value less than unity indicates that DMU k is inefficient.

3.2 Green Malmquist productivity index

Assume that $\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})$ and $\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})$ are the efficiency values of k th DMU based on period $t+1$ inputs, desirable and undesirable outputs under the periods t and $t+1$ production technology, respectively, while $\rho_k^t(x^t, y^t, b^t)$ and $\rho_k^{t+1}(x^t, y^t, b^t)$ are the efficiency scores based on period t inputs, desirable and undesirable outputs under the period $t+1$ production technology. Based on the DEA production possibility set and model (2), following Fare et al. [52], we defined the green Malmquist productivity index of China's transportation as

$$MPI_k^{t,t+1} = \left[\frac{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^t(x^t, y^t, b^t)} \times \frac{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^{t+1}(x^t, y^t, b^t)} \right]^{1/2} \quad (3)$$

where $MPI_k^{t,t+1} > 1$ ($MPI_k^{t,t+1} < 1$) indicates that green TFP increased (regressed) from period t to $t+1$ for DMU k . We can then decompose the MPI into efficiency change and technological change as

$$MPI_k^{t,t+1} = EC_k^{t,t+1} \times TC_k^{t,t+1} = \frac{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^t(x^t, y^t, b^t)} \times \left[\frac{\rho_k^t(x^t, y^t, b^t)}{\rho_k^{t+1}(x^t, y^t, b^t)} \times \frac{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \right]^{1/2} \quad (4)$$

where the first term, $\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})/\rho_k^t(x^t, y^t, b^t)$, denotes the change of relative efficiency for the k th DMU from period t to $t+1$, representing the effect of catching up. The second term between brackets reflects the technological change or the effect of the shift in the technology frontier, as represented by $\left[\frac{\rho_k^t(x^t, y^t, b^t)}{\rho_k^{t+1}(x^t, y^t, b^t)} \times \frac{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \right]^{1/2}$.

Moreover, $EC_k^{t,t+1} > 1$ (< 1) indicates an improvement (degradation) of relative efficiency during the period from t to $t+1$, while a value of $TC_k^{t,t+1}$ greater (less) than one indicates progress (deterioration) of technology between periods t and $t+1$.

3.3 The measure and direction of the biased technological change

Based on the decomposition above, following Färe et al. [45], TC can be initially decomposed into a magnitude index (the magnitude of technological change, MTC) and a technical bias index (the bias of technological change, BTC). The latter is further decomposed into an input bias index (the input-biased technological change, IBTC) and an output bias index (the output-biased technological change, OBTC), taking the forms as follows.

$$\begin{aligned} TC_k^{t,t+1} &= \left[\frac{\rho_k^t(x^t, y^t, b^t)}{\rho_k^{t+1}(x^t, y^t, b^t)} \times \frac{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \right]^{1/2} \\ &= \frac{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \times \left[\frac{\rho_k^t(x^t, y^t, b^t)}{\rho_k^{t+1}(x^t, y^t, b^t)} \times \frac{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})} \right]^{1/2} \\ &= MTC_k^{t,t+1} \times BTC_k^{t,t+1} \end{aligned} \quad (5)$$

and

$$\begin{aligned}
BTC_k^{t,t+1} &= \left[\frac{\rho_k^t(x^t, y^t, b^t)}{\rho_k^{t+1}(x^t, y^t, b^t)} \times \frac{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})} \right]^{1/2} \\
&= \left[\frac{\rho_k^{t+1}(x^t, y^t, b^t)}{\rho_k^t(x^t, y^t, b^t)} \times \frac{\rho_k^t(x^{t+1}, y^t, b^t)}{\rho_k^{t+1}(x^{t+1}, y^t, b^t)} \right]^{1/2} \times \left[\frac{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \times \frac{\rho_k^{t+1}(x^{t+1}, y^t, b^t)}{\rho_k^t(x^{t+1}, y^t, b^t)} \right]^{1/2} \\
&= IBTC_k^{t,t+1} \times OBTC_k^{t,t+1}
\end{aligned} \tag{6}$$

where $TC_k^{t,t+1} = MTC_k^{t,t+1} \times IBTC_k^{t,t+1} \times OBTC_k^{t,t+1}$. $\rho_k^t(x^{t+1}, y^t, b^t)$ and $\rho_k^{t+1}(x^{t+1}, y^t, b^t)$ is the efficiency values based on period $t+1$ inputs, period t desirable and undesirable outputs for the production technology at period t and $t+1$, respectively. MTC indicates the Hicks-neutral technological change, as represented by the ratio in Equation (5), referring to the “homothetic” or “neutral” shift of the technology frontier. The second term of Equation (5) denotes the bias of technological change, indicating the effect of the “non-homothetic” or “non-neutral” shift in the technology frontier. Moreover, the two geometric means shown in Equation (6) denote the IBTC and the OBTC, respectively, reflecting the effect of change of the MRS of inputs and outputs caused by the technological change. If IBTC (OBTC) is greater (less) than 1, there exists progress (deterioration) in input-biased (output-biased) technology. When the IBTC and OBTC are equal to 1, then the technological change is Hicks-neutral.

It must be noted that the input-/output-biased technological change index cannot reflect the direction of the bias of technological change, such as in favor of using labor relative to capital. Following Fare et al. [53], if the ratio between Input 1 (x_1) and Input 2 (x_2) increases from period t to period $t+1$ ($x_2^{t+1}/x_1^{t+1} > x_2^t/x_1^t$), $IBTC > 1$ indicates an x_2 -using/ x_1 -saving technological bias and $IBTC < 1$ indicates an x_1 -using/ x_2 -saving technological bias. When $x_2^{t+1}/x_1^{t+1} < x_2^t/x_1^t$, $IBTC > 1$ indicates an x_1 -using/ x_2 -saving technological bias and $IBTC < 1$ indicates an x_2 -using/ x_1 -saving technological bias. Furthermore, the input-biased technological change is Hicks-neutral when $IBTC = 1$. The x_2 -using/ x_1 -saving technological bias implies that the input-biased technology is biased in favor of using more Input 2 relative to Input 1, while the x_1 -using/ x_2 -saving technological bias implies that the input-biased technology tends to use more Input 1 rather than Input 2.

Similarly to the input-biased technological change, when $OBTC > 1$, an increase in the marginal rate of transformation (MRT) between Output 1 (y_1) and Output 2 (y_2) ($y_2^{t+1}/y_1^{t+1} > y_2^t/y_1^t$) indicates a y_2 -producing technological bias, while a decrease in the MRT between the two outputs ($y_2^{t+1}/y_1^{t+1} < y_2^t/y_1^t$) indicates a y_1 -producing technological bias. If $OBTC < 1$, $y_2^{t+1}/y_1^{t+1} > y_2^t/y_1^t$ indicates a y_1 -producing technological bias and $y_2^{t+1}/y_1^{t+1} < y_2^t/y_1^t$ indicates a y_2 -producing technological bias. The technological change concerning output is Hicks-neutral when $OBTC = 1$. The y_1 -producing technological bias implies that output-biased technology tends to produce more y_1 relative to y_2 , while y_2 -producing technological bias is biased in favor of producing more y_2 relative to y_1 .

Point 2: I have the general question why the authors are only interested in the bias of technological change and not in the full technological change? It is true that they give figures about both changes, but the aim of the paper is limited to the bias.

Response 2: We agree with the reviewer that the major aim of this article is to analyze

the bias of technological change for 30 provinces in China. The bias of technological change, especially energy-saving technology and low-carbon technology, is the major influence factor on sustainable development in transportation, which is also regarded as a long-term approach to achieving sustainable development. Thus, given its importance, we focus on the bias of technological change instead of full technological change. There is no doubt that the full technological change is also important for the development of the transportation industry, which can be regarded as one of our research directions in the future.

Point 3: Line 63: “Green TFP implies” looks like the beginning of a definition of Green TFP. However, the remaining sentence does not define it but seems to describe what happens if Green TFP increases. Because of the central position of Green TFP in the paper, it is advisable to include a definition.

Response 3: Thanks for this suggestion, based on this, we add the definition of green TFP in this paper on line 65 and line 66 as follows.

“With respect to measures of sustainable development performance, green total factor productivity (TFP) is a popular indicator, which is the ratio of total outputs including pollution and total inputs.”

Point 4: In line 221 ‘x’ seems to relate to DMUs, ‘y’ to inputs and ‘b’ to undesirable outputs. But in line 228 and later in the paper the meaning of x and y changes: ‘x’ then relates to inputs and ‘y’ to desirable outputs. Is there a mistake in presumably line 221?

Response 4: We thank the reviewer for bringing this point to our notice. In fact, as the understanding of reviewer, ‘x’, ‘y’, and ‘b’ denotes the inputs, desirable outputs, and undesirable outputs, respectively. In the revision manuscript, we modify the subscript of the symbol to express more clearly in line 223. The corresponding selection is as follows.

“ We assume that there are N decision-making units (DMUs) each having M inputs, S desirable outputs, and I undesirable outputs, as represented by $x \in R_M^+$, $y \in R_S^+$, and $b \in R_I^+$, respectively.”

Point 5: In equation 4 in the part that indicates the TC, the two denominators are identical. I suppose that in one denominator x_t , y_t , b_t should be x_{t+1} , y_{t+1} , b_{t+1} .

Response 5: Thanks for reminding us. By deducing the equation 4, we find that the ‘ x_t ’, ‘ y_t ’, and ‘ b_t ’ should be ‘ x_{t+1} ’, ‘ y_{t+1} ’, and ‘ b_{t+1} ’. In the revision manuscript, we thus change the ‘ x_t ’, ‘ y_t ’, and ‘ b_t ’ to ‘ x_{t+1} ’, ‘ y_{t+1} ’, and ‘ b_{t+1} ’ in equation 4, and also change the ‘ x_t ’, ‘ y_t ’, and ‘ b_t ’ to ‘ x_{t+1} ’, ‘ y_{t+1} ’, and ‘ b_{t+1} ’ in line 248. The corresponding results are

as follows.

$$“MPI_k^{t,t+1} = EC_k^{t,t+1} \times TC_k^{t,t+1} = \frac{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^t(x^t, y^t, b^t)} \times \left[\frac{\rho_k^t(x^t, y^t, b^t)}{\rho_k^{t+1}(x^t, y^t, b^t)} \times \frac{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \right]^{1/2} \quad (4)$$

where the first term, $S_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})/S_k^t(x^t, y^t, b^t)$, denotes the change of relative efficiency for the k th DMU from period t to $t+1$, representing the effect of catching up. The second term between brackets reflects the technological change or the effect of the shift in the technology frontier, as represented by $\left[\frac{\rho_k^t(x^t, y^t, b^t)}{\rho_k^{t+1}(x^t, y^t, b^t)} \times \frac{\rho_k^t(x^{t+1}, y^{t+1}, b^{t+1})}{\rho_k^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \right]^{1/2}$.

Point 6: Table 1: what do the minimum and maximum values mean? Are these the lowest and highest values of the provinces? What is the year(s) of the figures in the table?

Response 6: Thanks for this review. In fact, the minimum and maximum values are the lowest and highest values of 30 provinces in China during 2005–2017. At the same time, the years of the figures in the table are between 2005 and 2017.

This comment also makes us pay attention to the expression of the title of Table 1. We note that it is easy for readers to misunderstand or confuse the indicators in the table. Thus, we modify the title of Table 1 as “Table 1. The descriptive statistics of the input and output indicators for the transportation industry of 30 provinces in China during 2005–2017” in the revision manuscript.

Point 7: According to Table 2 the exogenous technological change (MTC) was below 1 in all provinces. Does it mean that the exogenous trend of technology was negative? This would be opposite to the general technological trend. Is there an explanation for this?

Response 7: Firstly, following the working of Weber and Domazlicky (1999), if the marginal output elasticity of each element is constant, the technology then is Hicks-neutral. The magnitude of technological change in Table 2 less than 1, indicates that the Hicks-neutral technology of these provinces decreases during the research period. As said in this paper, “we think this is consistent with the fact that the enterprises are often small and numerous in this sector, particularly for road freight transportation. Another important reason is the quantity- and supply-oriented economic development pattern, which has caused a serious oversupply problem in the transportation industry.”

Point 8: Figures 1 and 2: are these the averages for the Chinese provinces?

Response 8: As the understanding of the reviewer, Figures 1 and 2 are both the geometric mean of 30 provinces in China.

Point 9: Line 433-434: “divided by” can have the alternative meaning of taking the

ratio (BTC/IBTC and BTC/OBTC). To avoid confusion another wording is preferred (“split up by”, “broken down by”).

Response 9: We agree with the suggestion of the reviewer and thus adopt the wording of “split up by” instead of “divided by” in the revision manuscript.

Point 10: Table 4: what does mean “trans_added”? Is it identical to ‘value added’? And what is the meaning of the figures in the CO₂-producing column? If this is high (like in 2010), does it mean a high increase or a high decrease of the CO₂-emissions compared to the desired output?

Response 10: Just as the understanding of the reviewer, the “trans_added” denotes the value_added of transportation, which has been defined in Table 1. And the figures in the CO₂-producing column denotes the number of the provinces that experience the CO₂-producing technological bias. The greater value of these figures indicates that more provinces tend to experience CO₂-producing technological bias.

This comment reminds us that this paper does not introduce the meaning of the specific direction of technology, leading to the confusion of the reviewer. Thus, in the revision manuscript, we added the introduction of the meaning of the direction of technology in Section 3.3 as follows, and added the notes about the figures in Table 4 and Table 5 to make readers better understand the empirical results.

“It must be noted that the input-/output-biased technological change index cannot reflect the direction of the bias of technological change, such as in favor of using labor relative to capital. Following Fare et al. [53], if the ratio between Input 1 (x_1) and Input 2 (x_2) increases from period t to period $t+1$ ($x_2^{t+1}/x_1^{t+1} > x_2^t/x_1^t$), IBTC > 1 indicates an x_2 -using/ x_1 -saving technological bias and IBTC < 1 indicates an x_1 -using/ x_2 -saving technological bias. When $x_2^{t+1}/x_1^{t+1} < x_2^t/x_1^t$, IBTC > 1 indicates an x_1 -using/ x_2 -saving technological bias and IBTC < 1 indicates an x_2 -using/ x_1 -saving technological bias. Furthermore, the input-biased technological change is Hicks-neutral when IBTC = 1. The x_2 -using/ x_1 -saving technological bias implies that the input-biased technology is biased in favor of using more Input 2 relative to Input 1, while the x_1 -using/ x_2 -saving technological bias implies that the input-biased technology tends to use more Input 1 rather than Input 2.

Similarly to the input-biased technological change, when OBTC > 1 , an increase in the marginal rate of transformation (MRT) between Output 1 (y_1) and Output 2 (y_2) ($y_2^{t+1}/y_1^{t+1} > y_2^t/y_1^t$) indicates a y_2 -producing technological bias, while a decrease in the MRT between the two outputs ($y_2^{t+1}/y_1^{t+1} < y_2^t/y_1^t$) indicates a y_1 -producing technological bias. If OBTC < 1 , $y_2^{t+1}/y_1^{t+1} > y_2^t/y_1^t$ indicates a y_1 -producing technological bias and $y_2^{t+1}/y_1^{t+1} < y_2^t/y_1^t$ indicates a y_2 -producing technological bias. The technological change concerning output is Hicks-neutral when OBTC = 1. The y_1 -producing technological bias implies that output-biased technology tends to produce more y_1 relative to y_2 , while y_2 -producing technological bias is biased in favor of producing more y_2 relative to y_1 .”

Point 11: Lines 542-544: “in reality, these regions often increased emissions rather than producing more desirable output (trans_added) in 2005–2017, resulting in a negative influence on green productivity growth.” Can this be derived from Table 6, or is this information added by the authors?

Response 11: The conclusion mentioned above is derived from Table 6. Table 6 reveals the direction of technological change. We can note that the output-biased technological change of these provinces (7 out of 30 provinces) is less than 1 according to Table 6. The OBTC less than 1 indicates that the actual output structure of these provinces does not match the direction of the output-biased technological change. At the same time, the results shown in Table 6 reveal that output-biased technology is biased in favor of producing more value-added in transportation relative to CO₂ for these provinces. Thus, we can indirectly obtain the conclusion that “in reality, these regions often increased emissions rather than producing more desirable output (trans_added) in 2005–2017.” In other words, the inconsistency between production structure in reality and direction of output technology causes the value of OBTC less than 1, which then leads to green productivity deterioration.

Point 12: Line 591 and after: You talk about “transportation models” when you mean ‘transportation modes’.

Response 12: Thank the reviewer for this suggestion, we modify the express of “transportation models” to “transportation modes” in the revised manuscript.