Balakrishnan, C., & M, B. (2023). Testing CO_2 Emissions Data During Covid-19 Pandemic Using Benford's Law. *Energy RESEARCH LETTERS*, *4*(2). https://doi.org/10.46557/001c.38783

Peer-reviewed research

Testing CO_2 Emissions Data During Covid-19 Pandemic Using Benford's Law

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Keywords: CO_2 Emissions, Benford's Law, COVID-19 pandemic, JEL: I18 K32 Q5

https://doi.org/10.46557/001c.38783

Energy RESEARCH LETTERS

Vol. 4, Issue 2, 2023

The Covid-19 pandemic disrupted economic activities, which led to the reduction of carbon dioxide (CO_2) emissions due to lockdowns and restrictions. Using Benford's Law, we tested for anomalies in the world's daily CO_2 emissions data for different sectors from January 2020 to December 2021. We found that the CO_2 emissions data were under the category of "conformity" in 2020 and "non-conformity" in 2021.

I. Introduction

On 30th January 2020, WHO declared novel coronavirus 2019 (Covid-19) as a public health emergency of international concern (Andrews et al., 2020). Following the Covid-19 outbreak, China declared a lockdown on 23rd January 2020, and later all countries moved to lockdown in different phases (Andrews et al., 2020; Charumathi & Mangaiyarkarasi, 2022; Koh, 2020).

The lockdowns forced people to stay at home, restricted movements in and out of countries, companies to halt production, and schools to close, which led to a halt in economic activities and, in turn, a reduction in CO_2 emissions from different sectors around the world.

Studies, such as Adhikari et al. (2021), Charumathi and Mangaiyarkarasi (2022), Le et al. (2020), Ray et al. (2022), Saadat et al. (2020), and Weir et al. (2021), have explored different countries globally and found that, though there was a huge reduction in CO_2 emissions during Covid-19, emissions increased post lockdown and restrictions. This may lead to the manipulation of daily data during the restrictions and post-Covid-19 to show a sustainable emissions report. Studies, such as Auffhammer and Carson (2008), Cole et al. (2020), and Coracioni and Danescu (2020), have applied Benford's Law to check the authenticity of the emissions reduction data reported on the CDM project, greenhouse gas and CO_2 emissions. In line with these studies, we test whether the first, second, and first two digits of the daily CO_2 emissions data conform to Benford's Law by taking the published global data during 2020 and 2021. In doing so, we add to the literature by examining whether the pandemic-induced government restrictions influenced the reporting of the emissions data. Our empirical investigation revealed that the CO_2 emissions data were under the category of "conformity" in 2020 and "non-conformity" in 2021. Thus, the pandemic-induced government restrictions influenced the reporting of the emissions data.

II. Method

Benford's Law is a popular mathematical tool for identifying the patterns and anomalies of numbers. It is a concept to check the digit frequencies of the natural numbers, introduced by US astronomer Simon Newcomb (1881). After 57 years, Frank Benford (1938) identified a pattern, which follows logarithmic frequency distribution on the position of digits. This tool has been successfully applied to detect accounting and financial fraud, and tax evasion by Carslaw (1988), and Nigrini (1999). Benford's Law can be checked through the tests of goodness of fit, such as chi-square, Kolmogorov-Smirnov test (KS), Joenssen's JP-square, Freedman-Watson U-square, Chebyshev distance, and Z-statistics. Nigrini (2012) introduced Mean Absolute Deviation (MAD) as a method to check the conformity of data with Benford's Law. This method is not influenced by the size of the sample compared to other methods Sadaf (2017).

Based on Benford's law, the naturally occurring number's first digit will be 1 or 2 compared to 8 or 9. The general logarithmic pattern of Benford's law is

$$P\left(D1 = d1\right) = \log\left(1 + \frac{1}{d1}\right) for\ d1 \in \{1, \ldots, 9\} \tag{1}$$

$$P\left(D2 = d2\right) = \sum 9d1 = 1 \log\left(1 + \frac{1}{d1d2}\right) for\ d2 \in \{1, \ldots, 9\} \tag{2}$$

$$P\left(D1D2 = d1d2\right) = log(1 + \frac{1}{d1\ d2})\ for\ d1\ d2 \in \{1, \ldots, 9\} \tag{3}$$

where $D1,\ D2 \ldots D9$ denote the expected and $d1,\ d2 \ldots d9$ denote the actual first digit, second digit, ..., ninth digit of the naturally occurring numbers, respectively.

Based on Benford's Law (see Appendix 1), digit 1 appears 30% as the first digit in a number, and digit 9 appears only 5% as the first digit. This study applied MAD to check the

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conformity of the numbers to Benford's law. MAD can be calculated by

$$MAD = \sum Ki = 1|AP - EP| / K \tag{4}$$

Here, AP and EP are actual and expected proportions.[1]

III. Data and Results

This study used the world's daily CO_2 emissions data for various sectors, *viz.* power, residential, industry, domestic aviation, international aviation, and ground transport from January 2020 to December 2021. The data is taken from the website https://carbonmonitor.org/. The group of countries cover in our study are Brazil, Russia, India and China (BRIC), the US, EU27 countries and UK, and the rest of the world (ROW).

First, we analysed whether the CO_2 emissions data follow the requirements of Benford's Law considering the following assumptions:

- Data should be from natural events or naturally occurring numbers (not predefined numbers like invoice number, serial number, etc.) (see Nigrini, 2012).
- Data set or observations should be fairly large; the sample should be between 50 to 100 (see Tošić & Vičič, 2021).
- The mean of the data should be greater than the median (or the data should be right-skewed); the data should not be symmetric (see Tošić & Vičič, 2021).

Table 1 summarises the descriptive statistics of the global CO_2 emissions for 2020 and 2021. The global CO_2 emissions, CO_2 emissions by BRIC countries, sector-wise global CO_2 emissions (except ground transport), and sector-wise CO_2 emissions by BRIC countries (except international aviation in 2021) have skewness greater than 1 and, hence, these data are right-skewed (i.e. mean is greater than the median). The number of observations is greater than 100, and the daily emissions data comes under the category of naturally-occurring numbers. Hence, these data follow the basic requirements of Benford's Law and are fit for the test.

Table 2 explains the test results of the first digit, second digit, and first two-digit frequency of the global CO_2 emissions data (only right-skewed) from January 2020 to December 2021. For 2020, the first digit frequency of CO_2 emissions has a MAD value of 0.0138, which ranges from 0.015 to 0.012 and comes under "marginally acceptable conformity". The second digit frequency has a MAD value of 0.0050, which falls under the category of "close conformity" with the range of 0.000 to 0.008, and finally, the first two digits fall under the category of "marginally acceptable conformity" with a MAD value of 0.0020. Likewise, for 2021, the MAD value of the first digit is 0.0199 ("nonconformity"), the second digit is 0.0071 ("close conformity"), and the MAD value of the first two digits is 0.0025 ("nonconformity"). Therefore, the global CO_2 emissions data for 2021 is not conforming, and 2020 conforms with Benford's Law.

For CO_2 emissions data of the BRIC countries, the MAD values for 2020 and 2021 for the first digit fall under "nonconformity", the second digit under "acceptable conformity", and the first two digits under "nonconformity" categories. For sector-wise global CO_2 emissions data, the MAD values of the first digit of all the sectors fall under the category of "nonconformity"; the second digit of the industry (2021), international aviation (2021), and residential (both 2020 and 2021) fall under the category of "nonconformity", and the first two digits of all the sectors fall under "nonconformity". For sector-wise emissions by BRIC countries, the first, second, and first two digits are under "nonconformity", except for the second digit of the international aviation sector in 2020.

IV. Concluding Remarks

The reduction of CO_2 emissions is more important in this highly polluted era, and the Covid-19 restrictions led to its reduction, but it was not sustainable. Our digit analysis of the global CO_2 emissions data revealed that the emissions for 2020 conforms to Benford's Law, whereas the emissions for 2021 do not. This may be attributed to reporting dynamics in light of the regulatory pressures to show a sustainable emission report by the countries. Our results can be used to establish whether any particular government policy during the pandemic influenced the reported data. This can be done by comparing our results with couple of years before and after the pandemic. For the sectoral analysis, we found that the second digit conforms to Benford's law and the first and first two digits do not. Even though the calculation of daily CO_2 emissions data is difficult, reporting true and fair data is important. Normally, analysts, researchers, and regulators use Benford's Law to identify the red flags for further investigations. Similarly, the anomalies in the global CO_2 emission data can be considered red flags, and more serious investigation can be done with the help of big data analytical tools than ever before.

Acknowledgement

Authors would also like to thank the anonymous referee and the editorial team of the journal for their valuable comments in improving this study.

Submitted: July 21, 2022 AEST, Accepted: October 04, 2022 AEST

1 See the critical MAD values for conforming the data with Benford's Law in Appendix 2.

Table 1. Descriptive Statistics

Category	Year	Obs.	Mean	Median	SD	Skewness	SE Skewness
Global CO_2 Emissions	2020	17568	1.896	0.593	3.052	2.399*	0.018
	2021	17520	2.025	0.609	3.228	2.381*	0.019
Country group-wise CO_2 Emissions							
BRIC Countries	2020	8784	1.661	0.356	3.315	2.787*	0.026
	2021	8760	1.792	0.399	.540	2.757*	0.026
US	2020	2196	2.094	2.394	.663	0.185	0.052
	2021	2190	2.229	2.530	.756	0.214	0.052
EU27&UK	2020	2196	1.329	1.475	.003	0.002	0.052
	2021	2190	1.451	1.706	.073	-0.04	0.052
ROW	2020	2196	5.100	4.593	.511	0.304	0.052
	2021	2190	5.115	4.637	4.503	0.289	0.052
Sector-wise Global CO_2 Emissions							
Power	2020	2928	4.441	2.729	4.237	1.098*	0.45
	2021	2920	4.799	3.034	.563	1.132*	0.45
Industry	2020	2928	3.584	1.764	.141	1.242*	0.45
	2021	2920	3.759	1.958	.239	1.17*	0.45
Domestic Aviation	2020	2928	0.086	0.033	.112	1.933*	0.45
	2021	2920	0.108	0.041	.137	1.778*	0.45
International Aviation	2020	2928	0.095	0.030	.143	2.719*	0.45
	2021	2920	0.112	0.027	.141	1.302*	0.45
Ground Transport	2020	2928	1.981	0.862	.752	0.910	0.45
	2021	2920	2.160	1.074	.887	0.819	0.45
Residential	2020	2928	1.190	0.708	.158	1.178*	0.45
	2021	2920	1.215	0.714	1.194	1.184*	0.45
Sector-wise CO_2 Emissions by BRIC Countries							
Power	2020	1464	4.453	2.618	4.861	1.102*	0.45
	2021	1460	4.977	2.836	5.355	1.077*	0.45
Industry	2020	1464	3.638	0.945	4.758	1.232*	0.45
	2021	1460	3.800	1.304	4.813	1.163*	0.45
Domestic Aviation	2020	1464	0.051	0.028	0.059	1.443*	0.45
	2021	1460	0.062	0.034	0.061	1.252*	0.45
International Aviation	2020	1464	0.018	0.013	0.016	2.058*	0.45
	2021	1460	0.019	0.018	0.009	0.289	0.45
Ground Transport	2020	1464	0.980	0.682	0.765	1.200*	0.45
	2021	1460	1.076	0.691	0.829	1.061*	0.45
Residential	2020	1464	0.828	0.347	0.978	1.676*	0.45
	2021	1460	0.823	0.360	0.964	1.682*	0.45

This table describes the descriptive statistics (Year, Number of observations (Obs.), Mean, Median, Standard Deviation (SD), Skewness and Standard Error (SE) of skewness) of global CO_2 emissions data by categorising country group-wise and sector-wise. "*" denotes the right-skewed values.

Table 2. Benford's Law Conformity

Category	Year	First Digit MAD	Second Digit MAD	First Two-Digit MAD
Global CO_2 Emissions	2020	0.0138*	0.0050***	0.0020*
	2021	0.0199	0.0071***	0.0025
BRIC Countries Emissions	2020	0.0164	0.0082**	0.0033
	2021	0.0204	0.0095**	0.0034
Sector-wise Global CO_2 Emissions				
Power	2020	0.0609	0.0116*	0.0070
	2021	0.0510	0.0087**	0.0056
Industry	2020	0.0380	0.0083**	0.0048
	2021	0.0419	0.0123	0.0059
Domestic Aviation	2020	0.0270	0.0094**	0.0036
	2021	0.0482	0.0115*	0.0058
International Aviation	2020	0.0222	0.0045	0.0028
	2021	0.0450	0.0143	0.0053
Residential	2020	0.0285	0.0192	0.0048
	2021	0.0286	0.0204	0.0052
Sector-wise CO_2 Emissions by BRIC countries				
Power	2020	0.0760	0.0205	0.0092
	2021	0.0655	0.0187	0.0083
Industry	2020	0.0346	0.0243	0.0067
	2021	0.0430	0.0264	0.0087
Domestic Aviation	2020	0.0284	0.0129	0.0045
	2021	0.0421	0.0158	0.0060
International Aviation	2020	0.0244	0.0094**	0.0041
Ground Transport	2020	0.0751	0.0234	0.0094
	2021	0.0958	0.0430	0.0137
Residential	2020	0.0416	0.0428	0.0083
	2021	0.0461	0.0424	0.0087

This table presents the test results (MAD values) of the first digit, second digit and first two- digits of global CO_2 emissions and BRIC country emissions of 2020 and 2021; *** Close conformity, ** Acceptable conformity, * Marginally acceptable conformity.

References

Adhikari, A., Sengupta, J., & Hussain, C. M. (2021). Declining carbon emission/concentration during COVID-19: A critical review on temporary relief. *Carbon Trends*, *5*, 100131. https://doi.org/10.1016/j.cartre.2021.100131

Andrews, M., Areekal, B., Rajesh, K., Krishnan, J., Suryakala, R., Krishnan, B., Muraly, C., & Santhosh, P. (2020). First confirmed case of COVID-19 infection in india: A case report. *Indian Journal of Medical Research*, *151*(5), 490–492. https://doi.org/10.4103/ijmr.ijmr_2131_20

Auffhammer, M., & Carson, R. T. (2008). Forecasting the path of china's CO2 emissions using province-level information. *Journal of Environmental Economics and Management*, *55*(3), 229–247. https://doi.org/10.1016/j.jeem.2007.10.002

Benford, F. (1938). The law of anomalous numbers. *Proceedings of the American Philosophical Society*, 551–572.

Carslaw, C. A. P. N. (1988). Anomalies in Income Numbers: Evidence of Goal Oriented Behavior. *The Accounting Review*, *63*(2), 321–327.

Charumathi, B., & Mangaiyarkarasi, T. (2022). Effect of the COVID-19 pandemic on CO_2 emissions in India. *Energy RESEARCH LETTERS*, *3*(Early View). https://doi.org/10.46557/001c.32623

Cole, M. A., Maddison, D. J., & Zhang, L. (2020). Testing the emission reduction claims of CDM projects using the Benford's law. *Climatic Change*, *160*(3), 407–426. https://doi.org/10.1007/s10584-019-02593-5

Coracioni, A., & Danescu, T. (2020). Testing of published information on greenhouse gas emissions. Conformity analysis with the Benford's law method. *Audit Financiar*, *18*(160), 821–830. https://doi.org/10.20869/auditf/2020/160/029

Koh, D. (2020). COVID-19 lockdowns throughout the world. *Occupational Medicine*, *70*(5), 322–322. https://doi.org/10.1093/occmed/kqaa073

Le, T., Wang, Y., Liu, L., Yang, J., Yung, Y. L., Li, G., & Seinfeld, J. H. (2020). Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. *Science*, *369*(6504), 702–706. https://doi.org/10.1126/science.abb7431

Newcomb, S. (1881). Note on the Frequency of Use of the Different Digits in Natural Numbers. *American Journal of Mathematics*, *4*(1), 39–40. https://doi.org/10.2307/2369148

Nigrini, M. J. (1999). I've got your number. *Journal of Accountancy*, *187*(5), 79–83.

Nigrini, M. J. (2012). *Forensic Analytics: Methods and Techniques for Forensic Accounting Investigations*. Wiley. https://doi.org/10.1002/9781118386798

Ray, R. L., Singh, V. P., Singh, S. K., Acharya, B. S., & He, Y. (2022). What is the impact of COVID-19 pandemic on global carbon emissions? *Science of The Total Environment*, *816*, 151503. https://doi.org/10.1016/j.scitotenv.2021.151503

Saadat, S., Rawtani, D., & Hussain, C. M. (2020). Environmental perspective of COVID-19. *Science of The Total Environment*, *728*, 138870. https://doi.org/10.1016/j.scitotenv.2020.138870

Sadaf, R. (2017). Advanced Statistical Techniques for testing Benford's Law. *The Annals of the University of Oradea*, *2*, 229–238.

Tošić, A., & Vičič, J. (2021). Use of Benford's law on academic publishing networks. *Journal of Informetrics*, *15*(3), 101163. https://doi.org/10.1016/j.joi.2021.101163

Weir, B., Crisp, D., O'Dell, C. W., Basu, S., Chatterjee, A., Kolassa, J., Oda, T., Pawson, S., Poulter, B., Zhang, Z., Ciais, P., Davis, S. J., Liu, Z., & Ott, L. E. (2021). Regional impacts of COVID-19 on carbon dioxide detected worldwide from space. *Science Advances*, *7*(45). https://doi.org/10.1126/sciadv.abf9415

Appendix

Appendix 1. Benford's expected digit frequencies

Digit	First	Second	Third	Fourth
0		0.1197	0.1018	0.1002
1	0.3010	0.1139	0.1014	0.1001
2	0.1761	0.1088	0.1010	0.1001
3	0.1249	0.1043	0.1006	0.1001
4	0.0969	0.1003	0.1002	0.1000
5	0.0792	0.0967	0.0998	0.1000
6	0.0669	0.0934	0.0994	0.0999
7	0.0580	0.0904	0.0990	0.0999
8	0.0512	0.0876	0.0986	0.0999
9	0.0458	0.0850	0.0983	0.0998

This table shows Benford's expected digit frequencies. This is sourced from Nigrini (1999).

Appendix 2. Critical values of MAD to conform to Benford's Law

Digits	Range	Results
First digits	0.000 to 0.006	Close conformity
	0.006 to 0.012	Acceptable conformity
	0.012 to 0.015	Marginally acceptable conformity
	Above 0.015	Nonconformity
Second digits	0.000 to 0.008	Close conformity
	0.008 to 0.010	Acceptable conformity
	0.010 to 0.012	Marginally acceptable conformity
	Above 0.012	Nonconformity
First two digits	0.0000 to 0.0012	Close conformity
	0.0012 to 0.0018	Acceptable conformity
	0.0018 to 0.0022	Marginally acceptable conformity
	Above 0.0022	Nonconformity

This table reports the critical values of MAD to conform to Benford's Law. These are taken from Nigrini (2012).