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STATISTICAL MODELING OF CARDIOVASCULAR MORTALITY TRENDS IN INDIA

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Abstract : Cardiovascular diseases (CVDs) remain the leading cause of mortality worldwide, with India bearing a disproportionately high burden relative to global averages. Understanding long-term mortality patterns is crucial for informed public health planning. This study analyzes overall and gender-specific CVD mortality rates in India from 2000 to 2021 using exponential and logistic growth models. Model performance was assessed through the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), root mean square error (RMSE), and coefficient of determination (R^2). Results revealed a steady increase in CVD death rates across both genders, with male mortality rising more sharply than female mortality. While both models closely aligned with observed data, the logistic growth model consistently outperformed the exponential model, demonstrating lower error values and higher goodness-of-fit, particularly for total and male datasets. The logistic model's plateauing dynamic also makes it more suitable for long-term forecasting. These findings provide valuable insights into the trajectory of CVD mortality in India and highlight the importance of adopting robust statistical modeling approaches to inform targeted prevention strategies, healthcare planning, and resource allocation.

Keywords - Cardiovascular diseases, Mortality, Growth model, AIC, BIC, RMSE.

I. INTRODUCTION

CVDs are a group of disorders of the heart and blood vessels, including coronary artery disease, cerebrovascular disease, rheumatic heart disease, and other related conditions (WHO, 2025). Globally, they represent the leading cause of mortality, accounting for approximately 19.8 million deaths each year and nearly one-third of all deaths worldwide (BHF, 2025). The World Health Organization emphasizes that over three-quarters of these deaths occur in low- and middle-income countries, underscoring the role of social, economic, and health system disparities in shaping CVD outcomes (Roth et al., 2020).

In India, the burden of CVD has reached alarming proportions. The age-standardized death rate from CVD stands at 272 per 100,000 population, which is substantially higher than the global average of 235 per 100,000 (Prabhakaran et al., 2016). In India, the prevalence of CVD among adults has been estimated in a recent systematic review and meta-analysis .CVDs now account for more than a quarter of total deaths, surpassing infectious diseases and other non-communicable diseases as the dominant cause of mortality (Ghaffar et al., 2014). The rapid epidemiological transition characterized by declining communicable diseases and rising lifestyle-related conditions has placed CVD at the forefront of India's public health challenges (Gaziano et al., 2010).

Several factors contribute to this rising trend, including high prevalence of hypertension, diabetes, tobacco use, obesity, and dietary risk factors, coupled with sedentary lifestyles and increasing urbanization (Mohan et al., 2013). These determinants not only increase the overall disease burden but also lower the age of onset, with a significant share of CVD deaths in India occurring before the age of 70 years (Patel et al., 2016). This premature mortality poses significant social and economic challenges.

Analyzing long-term trends in CVD mortality is crucial for public health planning and policy in India. Statistical models such as exponential and logistic growth functions provide valuable tools for assessing and forecasting mortality rates. The exponential model assumes continuous growth, whereas the logistic model accounts for potential plateau effects, making it especially useful for long-term projections where improvements in healthcare or demographic shifts may slow the pace of increase. The present study examines male, female, and total CVD death rates in India between 2000 and 2021, and evaluates the performance of exponential and logistic growth models. By applying these approaches, the study seeks to provide robust insights into the trajectory of CVD mortality, offering evidence to guide prevention strategies, resource allocation, and national health policies.

II. MATERIALS AND METHODS

Data Source

Data on mortality rates from cardiovascular diseases (CVDs) in India for the period 2000–2021 were obtained from the Global Burden of Disease (GBD) Study conducted by the Institute for Health Metrics and Evaluation (IHME). Mortality rates were reported per 100,000 population and disaggregated by gender (male, female) as well as for the total population.

Study Design

Death rates were examined separately for males, females, and the total population to identify gender-specific variations in CVD mortality. The analysis further compared observed mortality rates with values estimated by statistical growth models to evaluate model accuracy and forecasting potential.

Statistical Models

To analyze long-term trends and project future mortality, two mathematical growth models Exponential and Logistic were applied. Growth models are commonly used in epidemiology to describe and forecast changes in mortality over time.

1. **Exponential Growth Model:** The exponential model assumes continuous, unrestricted growth in mortality rates over time:

$$y(t) = a\, e^{bt}$$

where,

- $y(t)$= mortality rate at time t
- a= initial value or scale parameter
- b= growth rate
- e = Euler's number (~2.718).

This model captures long-term trends where mortality increases continuously without a limit.

2. **Logistic Growth Model**: The logistic model accounts for potential saturation effects, where growth slows as it approaches a maximum limit:

$$y(t) = \frac{k}{1 + ae^{-bt}}$$

where,

- $y(t)$= mortality rate at time t
- k= carrying capacity (maximum possible mortality rate)
- a= constant determined by initial conditions
- b= growth rate
- e = Euler's number (~2.718), base of natural logarithms

This model is particularly useful for long-term projections where healthcare improvements or demographic changes may limit further increases in mortality rates.

Both models were fitted separately for **males, females, and the total population** to evaluate their accuracy in capturing trends and forecasting future CVD mortality.

Further, model performance was assessed using AIC, BIC, RMSE and Coefficient of determination R^2. These metrics collectively measure goodness-of-fit, predictive accuracy, and model parsimony.

III. RESULTS AND DISCUSSION

In this section, we have discussed the CVDs mortality rates in India (2000–2021) for males, females, and the total population. The focus was on evaluating the performance of Exponential and Logistic growth models in capturing long-term trends and projecting future death rates. Model performance metrics were applied to compare the models to identify the best fit for each gender group.

Table 1 : Estimated values of death rate of CVDs for Males

YEAR	OBSERVED	EXPONENTIAL	LOGISTIC
2000	163.112	167.1489	159.1818
2001	165.7954	169.3872	163.6154
2002	170.4198	171.6556	167.8694
2003	172.3123	173.9544	171.9367
2004	169.2108	176.2839	175.8125
2005	169.9017	178.6446	179.4938
2006	180.1154	181.0369	182.9798
2007	185.3705	183.4613	186.2713
2008	185.0283	185.9181	189.3706
2009	197.1799	188.4079	192.2816
2010	205.4806	190.931	195.0089
2011	191.0022	193.4878	197.5585
2012	199.4108	196.0789	199.9369
2013	211.2871	198.7047	202.1511
2014	207.2444	201.3657	204.2087
2015	216.5052	204.0623	206.1176
2016	207.0266	206.795	207.8857
2017	209.4589	209.5643	209.5209
2018	221.7751	212.3707	211.0313
2019	165.7809	215.2147	212.4245
2020	225.4305	218.0968	213.7082
2021	224.4649	221.0175	214.8897

Table 1 shows the observed and model-estimated male death rates due to CVDs .Both models closely follow the general upward trend in mortality rates, with fluctuations in observed values across years. The observed rates rise from 163.11 per 100,000 in 2000 to a peak of 225.43 in 2020, followed by a slight decrease to 224.46 in 2021. The exponential and logistic models estimate similar values throughout the period, with logistic estimates typically slightly lower than exponential ones in later years.

The data indicate a gradual increase in male CVDs mortality over the two decades, with notable spikes in 2006–2010 and again post-2016. While both models capture the long-term trend well, discrepancies appear in certain years (e.g., 2004, 2019), where observed values deviate substantially from model projections. This suggests that while growth models are effective for capturing overall patterns, real-world mortality trends may be influenced by sudden shifts in health risks, healthcare access, or other socio-environmental factors not accounted for in the models.

Given their high accuracy and minimal differences, both models can be applied for forecasting male cardiovascular mortality rates. However, the logistic model may be more suitable for long-term projections due to its capacity to model potential saturation effects, whereas the exponential model may slightly overestimate future rates if current growth patterns plateau. For health policy and planning, model forecasts should be complemented with real-time epidemiological monitoring to capture short-term variations and sudden shifts in mortality trends.

Table 2: Estimated values of death rate of CVDs for females

YEAR	OBSERVED	EXPONENTIAL	LOGISTIC
2000	127.6487	123.8399	122.7839
2001	128.6166	126.3468	125.5294
2002	131.1805	128.9045	128.3133
2003	132.032	131.514	131.135
2004	129.5069	134.1763	133.9941
2005	131.5392	136.8924	136.8899
2006	137.5593	139.6636	139.8219
2007	142.6639	142.4909	142.7893
2008	144.9707	145.3754	145.7914
2009	143.8095	148.3183	148.8275
2010	144.9481	151.3207	151.8967
2011	150.7479	154.384	154.9981
2012	159.7066	157.5092	158.1308
2013	166.1526	160.6977	161.2939
2014	170.3452	163.9508	164.4863
2015	170.7567	167.2697	167.707
2016	175.2095	170.6558	170.9548
2017	177.4685	174.1105	174.2286
2018	181.3491	177.6351	177.5272
2019	182.7301	181.231	180.8494
2020	181.0877	184.8997	184.1939
2021	179.7322	188.6427	187.5594

Table 2 presents the observed and model-estimated female mortality rates from CVDs. Both the exponential and logistic growth models closely follow the observed values, with only minor deviations across most years. The data shows an overall upward trend in mortality rates, rising from 127.65 per 100,000 in 2000 to a peak of 182.73 in 2019, before a slight decline in 2020–2021. The exponential model slightly overestimates in the early years and underestimates around 2019, while the logistic model follows a similar pattern but shows marginally lower estimates toward the end, reflecting a possible plateauing effect.

The steady increase in female cardiovascular mortality rates over the two decades suggests a growing disease burden among women. The close alignment between observed data and both models indicates that these growth functions are reliable for trend estimation. The logistic model's slightly more conservative predictions in later years could be more realistic if mortality rates are approaching a natural limit due to healthcare improvements or demographic shifts. However, the dip after 2019 may reflect exceptional circumstances such as healthcare disruptions, competing mortality risks, or data artifacts that are not fully captured by either model.

Given their high agreement with observed data, both models can be considered effective for forecasting female cardiovascular mortality rates. However, for long-term projections, the logistic model may be preferable due to its capacity to model potential saturation effects. Public health planning should account for the persistent upward trend and focus on targeted interventions to curb female cardiovascular mortality

Table 3: Estimated values of death rates of CVDs for both gender

YEAR	OBSERVED	EXPONENTIAL	LOGISTIC
2000	146.0528	148.8383	141.462
2001	147.8971	151.0143	145.6094
2002	150.6749	153.2222	149.6141
2003	155.5119	155.4622	153.4674
2004	151.2836	157.7351	157.163
2005	151.3716	160.0412	160.6957
2006	161.9956	162.3809	164.0626
2007	165.228	164.7549	167.262
2008	165.6311	167.1636	170.2939
2009	174.638	169.6075	173.1595
2010	186.3608	172.0872	175.8612
2011	168.6628	174.6031	178.4024
2012	180.1206	177.1557	180.7875
2013	191.3705	179.7457	183.0213
2014	191.6453	182.3736	185.1095
2015	199.3741	185.0399	187.0579
2016	189.373	187.7451	188.8729
2017	193.8758	190.49	190.561
2018	202.7423	193.2749	192.1287
2019	149.1106	196.1005	193.5827
2020	203.1302	198.9675	194.9295
2021	203.3107	201.8764	196.1755

Table 3 presents the observed and model-estimated total death rates of cardiovascular disease for both genders from 2000 to 2021 using exponential and logistic growth models. The observed rates ranged from 146.05 per 100,000 in 2000 to 203.31 per 100,000 in 2021, with notable fluctuations, particularly a sharp dip in 2019 followed by an increase. Both the exponential and logistic models produced close estimates to the observed values, with gradual increases over time, although neither captured the sharp drop in 2019.

The results indicate an overall upward trend in total CVD mortality over the study period, suggesting a persistent public health concern. The exponential model tends to predict slightly higher values in later years compared to the logistic model, which levels off more, consistent with its saturation dynamics. The divergence between observed and predicted values in 2019 may reflect unusual external factors (e.g., data anomalies, health system changes, or reporting inconsistencies) that are not accounted for in the models.

Both models are suitable for forecasting future CVD mortality rates. However, the logistic model may be preferable when accounting for potential mortality rate stabilization over time, whereas the exponential model may be more appropriate if the trend continues to rise without plateau. Special consideration should be given to investigating and addressing the causes of the 2019 mortality drop, as this anomaly could impact model accuracy and public health strategy.

Table 4: Gender wise Model Performance Metrics for Death Rate

Metrics		AIC	BIC	RMSE	R^2
Exponential	**Male**	179.4316	182.7048	12.46207	0.6343684
	Female	131.3425	134.6156	4.17767	0.956472
	Total	177.8132	181.0863	12.01201	0.6444548
Logistic	**Male**	179.2115	183.5756	11.84885	0.6694662
	Female	132.8637	137.2279	4.13246	0.9574089
	Total	177.6337	181.9978	11.43149	0.6779903

Table 4 presents the performance metrics of exponential and logistic growth models in estimating CVDs death rates for males, females, and the total population. For males, the logistic model slightly outperforms the exponential model, exhibiting a lower RMSE (11.85 vs. 12.46) and marginally higher R^2 (0.669 vs. 0.634), along with lower AIC and BIC values, indicating better predictive accuracy and model parsimony. For females, both models demonstrate exceptionally high goodness-of-fit (R^2>0.95), with the logistic model again showing a slight edge, reflected in a marginally lower RMSE (4.13 vs. 4.18) and slightly higher R^2 (0.9574 vs. 0.9565). Similarly, for the total population, the logistic model outperforms the exponential model across all metrics, including lower RMSE (11.43 vs. 12.01) and higher R^2 (0.678 vs. 0.644). Overall, while both models provide robust fits to the data, the logistic model consistently yields better performance across genders, especially for the total and male datasets, with only minimal differences observed for females.

IV. CONCLUSIONS

The analysis of CVDs mortality in India from 2000 to 2021 demonstrates a persistent increase in death rates for males, females, and the total population. Both Exponential and Logistic growth models effectively captured the long-term trends, with the Logistic model showing slightly superior predictive performance, particularly in accounting for potential saturation in mortality rates. Male mortality consistently remained higher than female mortality, reflecting gender-specific risk patterns, while the combined population trends emphasize the overall public health burden of CVDs in India.

These findings underscore the urgent need for comprehensive public health strategies to address the rising burden of CVDs. Key preventive measures include early detection and management of hypertension, diabetes, and obesity; reduction of tobacco and alcohol use; promotion of physical activity; and encouraging balanced dietary practices rich in fruits, vegetables, and whole grains while limiting salt, sugar, and processed food intake. Urbanization, sedentary lifestyles, and changing dietary patterns are major contributing factors and require targeted awareness campaigns.

Policy interventions should focus on improving access to quality healthcare services, strengthening primary care for CVD prevention, and implementing population-level screening programs. Additionally, continuous monitoring of mortality trends using statistical models can guide resource allocation and help design evidence-based interventions.

In conclusion, integrating advanced statistical forecasting with preventive healthcare strategies and policy reforms is vital for reducing CVD mortality, preventing premature deaths, and improving cardiovascular health outcomes in India. Future efforts should also incorporate gender-sensitive approaches to address the higher risks observed among males and ensure equitable healthcare access across all segments of the population.

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