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Evaluating Road Network Complexity of Hyderabad's Regional Ring Road Using Fractal Dimension

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Abstract: Urban growth in Hyderabad has accelerated the demand for efficient transport corridors, leading to the development of the Regional Ring Road (RRR). This study evaluates the northern section of the RRR (160 km) using Fractal Dimension (FD) analysis to understand its effect on road network complexity and connectivity. The box-counting method was applied in ArcGIS at multiple grid scales to compute FD in two scenarios: with and without the RRR's Northern corridor. Results at the metropolitan scale show a measurable rise in FD after integrating the RRR, reflecting enhanced spatial coverage and improved connectivity.At the micro level, six representative zones (J1–J6) were analysed using combined FD and road density metrics to classify network typologies as Saturated, Fragmented, Emerging, and Inefficient. Zones such as Sangareddy (J1) and Bhongir (J5) showed high road density but low FD, classified as Inefficient, indicating unstructured layouts, while othersexhibited low density and poor integration. The findings highlight FD's value as a diagnostic tool to guide infrastructure planning, ensuring balanced growth and better accessibility in rapidly expanding metropolitan regions.
Keywords: Fractal analysis, road network efficiency, urban connectivity, Hyderabad RRR, GIS-based planning.

I. INTRODUCTION

Rapid urban expansion in Hyderabad has placed increasing demands on its transport infrastructure, creating the need for strategic, region-wide interventions to maintain connectivity and reduce congestion. The proposed 330 km Regional Ring Road (RRR) is designed to redistribute traffic loads, connect major growth nodes, and facilitate balanced urban development. Understanding how such large-scale road infrastructure influences network structure requires analytical tools capable of describing both spatial complexity and connectivity in quantitative terms. Fractal Dimension (FD), a geometric measure derived from fractal theory, has emerged as an effective metric for evaluating road networks beyond traditional measures of length and density [1], [3], [7], [8].

This study applies FD analysis to assess the impact of the northern segment of the RRR at two levels. At the macro scale, the road network of Hyderabad is examined with and without the RRR alignment to measure how the corridor alters the overall spatial organization of roads. At the micro scale, six representative zones (J1 to J6) along the northern corridor are evaluated using both FD and road density, enabling typological classification into fragmented, inefficient, emerging, or saturated patterns. Similar approaches in cities such as Karimnagar [3] and Amman [1] have shown how FD can highlight subtle variations in connectivity that conventional metrics fail to capture.

Fractal Dimension (FD) originates from the field of fractal geometry, introduced by Benoît Mandelbrot in the late 20th century. A fractal is a structure that exhibits self-similarity across different scales, meaning its pattern or form remains consistent regardless of the level of magnification. FD serves as a numerical indicator of how completely a fractal object fills space. Unlike conventional dimensions (1D for lines, 2D for surfaces), FD can take non-integer values and reflects the degree of spatial complexity.

Urban road networks can be analysed not only in terms of length or density but also in terms of their spatial complexity. Higher FD values generally indicate more intricate and connected road patterns, whereas lower values suggest sparser, less interconnected networks.

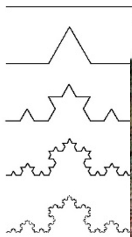

Fig1(a): Shape

Fig 1(b): Roots

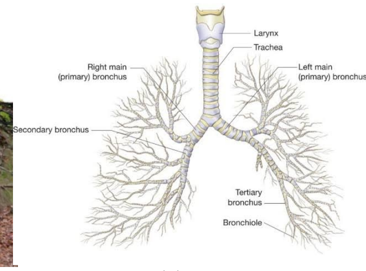

Fig1(c): Lungs

Among various methods available to calculate FD, the Box-Counting Method has proven to be practical for geographic datasets, especially when using Geographic Information Systems (GIS). This method overlays a grid of varying sizes over the road network and counts the number of grid cells intersected by roads, allowing researchers to quantify changes in network complexity at multiple scales.

The methodology combines ArcGIS-based spatial tools with the box-counting technique to generate FD values across varying grid resolutions, improving accuracy and consistency in measurement [6], [9]. By comparing results across scales, the analysis identifies how regional infrastructure interventions like the RRR influence local development patterns, reveal connectivity deficits, and expose risks of unplanned sprawl. Previous studies [7], [8] emphasize that even small increases in FD can signal meaningful structural change in an urban road network, underscoring the importance of tracking these variations over time.

The findings from this dual-scale approach not only quantify the immediate structural impact of the RRR but also provide a framework that can guide road design priorities and planning strategies for rapidly urbanizing metropolitan regions. This research aligns with global applications of FD in transport planning [1], [4], [6], demonstrating its value as a diagnostic tool to support sustainable and efficient infrastructure development.

A. OBJECTIVES

1) To calculate the Fractal Dimension (FD) of the road network with proposed Regional Ring Road(RRR) [northern corridor] of Hyderabad city using ArcGIS to analyze road connectivity.
2) To compute and compare the Fractal Dimension of the existing road network of Hyderabad city before and after inclusion of Regional Ring Road (RRR) [northern corridor]
3) To assess six selected RRR [northern corridor] zones and determine their typologies based on Fractal Dimension and Road Density.

II. LITERATURE REVIEW

The study of urban growth and transportation networks has evolved from traditional traffic-based evaluations to more spatially oriented approaches. Early research highlighted how road infrastructure influences regional development, emphasizing the need for methods that capture structural and spatial changes rather than relying solely on traffic flow or economic indicators [1], [2].

Spatial metrics such as road density and connectivity have been widely used to assess the extent and distribution of transportation infrastructure [3]. These measures provide insight into whether growth patterns are uniform, fragmented, or underdeveloped. However, they alone may not fully describe the geometric complexity of urban networks.

Fractal geometry has emerged as a powerful tool for analyzing urban form. Batty and Longley [4] introduced the concept of fractal dimension (FD) to quantify how road systems fill space, and subsequent studies have demonstrated its usefulness in evaluating network hierarchy and self-organizing properties [5], [6]. Research integrating FD with road density has allowed classification of urban growth into typologies such as saturated, emerging, fragmented, and inefficient [7].

With the development of Geographic Information Systems (GIS), these methods have become more precise and scalable. Jiang and Yao [8] illustrated how techniques such as the box-counting method enable FD calculations at both macro and micro levels, improving assessments of regional infrastructure. These advancements provide a robust analytical framework for evaluating large-scale road projects such as the Regional Ring Road, ensuring that infrastructure planning supports balanced and sustainable urban expansion [9].

III. METHODOLOGY

A. STUDY AREA AND DATA PREPARATION

This study focuses on the Hyderabad Metropolitan Region (~6,789 km²), where the proposed Regional Ring Road (RRR)[northern corridor] traverses areas of varying urban intensity — from dense urban nodes to semi-rural peripheriesThe spatial dataset for this analysis was obtained from the BBBike Extract service (https://extract.bbbike.org), an open-source platform that provides geospatial vector data derived from OpenStreetMap (OSM)..The dataset included primary, secondary, and tertiary roads, which were cleaned to remove duplicates, correct topological errors, and standardized into a single projection for accurate spatial measurements.

All processing was performed using ArcGIS Pro. The road network was digitized and segmented to reflect functional hierarchies. A fishnet grid was generated to divide the study area into uniform cells at multiple resolutions (30×30, 50×50, 100×100, and 200×200 no of grid). This multi-scale grid design allowed both macro-level (city-wide) and micro-level (corridor zone) analysis. For local evaluation, the RRR northern corridor alignment was subdivided into six zones of each 200 km² (J1–J6).

B. ANALYTICAL FRAMEWORK

The road network was evaluated using Fractal Dimension (FD) and road density to understand spatial complexity and infrastructure intensity.

Fractal Dimension using Box-Counting:

The box-counting method overlays grids of varying sizes over the road network and counts the number of cells intersecting roads. Traditionally, FD is derived from:

$$FD = \log(N) / \log(1/r)$$

Where:

- N = number of boxes(grids) intersecting the road network
- r = side length of each box (grid cell size)
- 1/r = the scale factor

By plotting log(N) vs log(1/r), the slope of the resulting line represents the FD.

- This formula works when the length of grid size is known. As in this the study area remains same but the grid levels are varying (30×30, 50×50,100×100 and 200×200). Then in this case we will use is:

Let:

- T = total number of grid cells at a given grid resolution
- N = number of grid cells that intersect the road network

Compute:

$$X=1/2\log(T)$$

Since,

$$Y=\log(N)$$

$T \propto 1/r^2$ in 2D

Then run a simple linear regression:

$$Y=a+bX$$

Fractal Dimension (FD) = slope 'b'

In this study, the method was modified by using the total grid count in place of grid size. A log–log plot of occupied cells versus total grid count was generated, and the slope (b) of the regression line was used as the fractal dimension.

This streamlined approach fits seamlessly within ArcGIS workflows while retaining the mathematical integrity of the box-counting technique. FD values closer to 2 indicate well-connected, space-filling networks, while lower values suggest sparse or fragmented development.

Road density was computed as the total length of roads per unit area (km/km²) for each corridor zone, The road length of each zone is calculated using ArcGIS. This metric quantified infrastructure intensity and, when combined with FD, provided deeper insight into whether dense networks were efficiently organized or poorly structured. Further Typology Classification is done based on FD and road density values were jointly analyzed to classify each corridor zone. To capture both regional and local variations, FD and density calculations were performed at multiple scales.

Visualization was carried out using ArcGIS Pro. FD and density results were visualized by using graphs. Validation was performed by testing multiple grid scales to confirm stability in log–log regression slopes and by cross-checking road lengths and grid occupancy counts to avoid computational errors.

IV. RESULTS AND DISCUSSION

A. FRACTAL DIMENSION OF THE HYDERABAD ROAD NETWORK (MACRO ANALYSIS)

This section evaluates how the Regional Ring Road (RRR) [northern corridor) alters the overall spatial complexity of Hyderabad's Road network. Fractal Dimension (FD) was computed using the box-counting approach across multiple grid resolutions (30×30, 50×50, 100×100, 200×200) for two scenarios: (i) without the RRR and (ii) with the RRR integrated. Results are presented for the entire metropolitan network and then separately for the North corridor.

TABLE 1: FD values for different grid resolution of RRR (Northern Corridor) [Macro Analysis].

			Without RRR			With RRR		
Grid Resolution	Total Grids	X	Y	Intersecting Grids	FD	Y	Intersecting Grids	FD
30×30	900	1.477121	2.942504	876	1.703	2.944483	880	1.707
50×50	2500	1.69897	3.349666	2237	1.659	3.353916	2259	1.661
100×100	10000	2	3.863025	7295	1.614	3.868527	7388	1.613
200×200	40000	2.30103	4.348908	22331	-	4.354301	22610	-

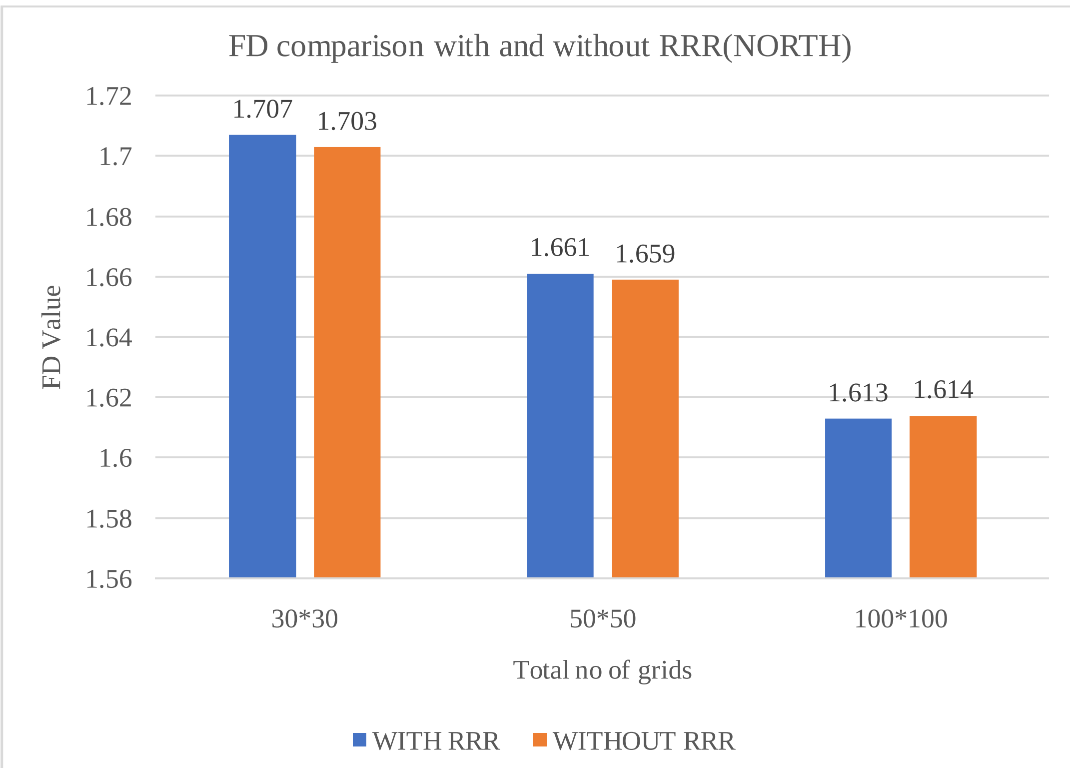

Fig 2 : Comparison of FD with and without RRR (north part).

For the North corridor, FD shows a modest but consistent increase when the RRR is included—rising from approximately ~1.6 (without RRR) to ~1.7 (with RRR) at different grid resolutions.

This pattern suggests the North corridor is already served by several high-capacity links; the RRR adds structure and redundancy, but the corridor's baseline connectivity means the uplift is naturally smaller. In planning terms, the North is moving from moderate to stronger spatial order, with the ring enabling better circumferential flow and relieving central bottlenecks.

Across northern corridor, the FD uplift is strongest at finer scales (100×100 and 200×200) because small cells are sensitive to new local links and junctions created by the ring. Coarser grids (300×30 and 50×50) still show improvement but compress the detail, reflecting the ring's influence more as a corridor-level backbone than as local branching. Together, the scale-consistent rise confirms that the RRR is not just adding length—it is adding structural connectivity that shows up from local detail to corridor form.

B. ZONAL-LEVEL FD AND ROAD DENSITY ANALYSIS (MICRO ANALYSIS)

While Macro Analysis showed how the Regional Ring Road (RRR) [northern corridor] improves connectivity at the metropolitan scale, this Micro level analysis evaluates local variations along the corridor. The study area was divided into six zones (J1–J6) of each 200km^2, and Fractal Dimension (FD) as well as road density were calculated for each zone using grid resolutions of 100×100 and 200×200 only. These scales were selected because they provide more stable and reliable FD values, consistent with macro-level findings.

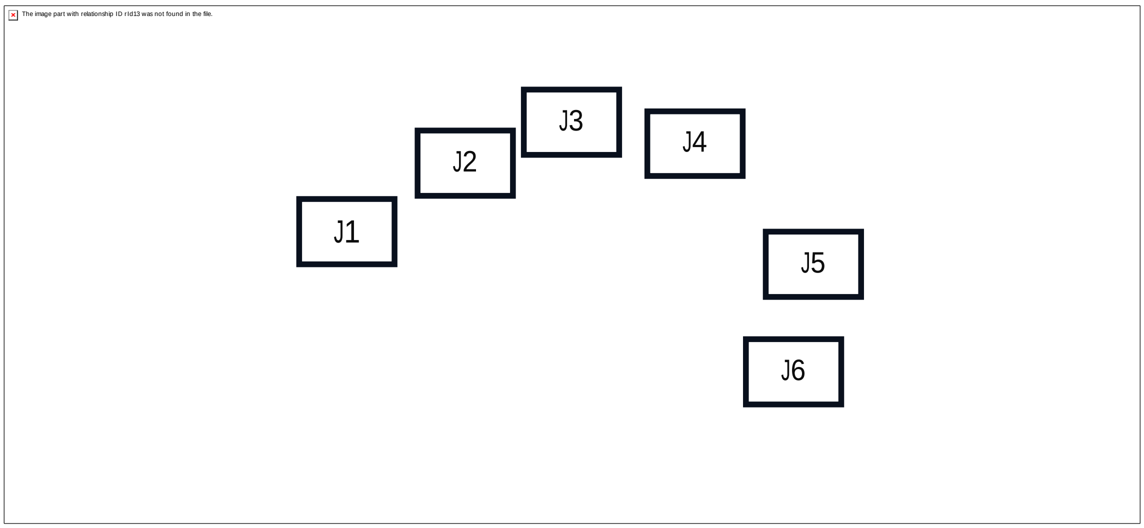

Fig 3: Regional Ring Road (RRR) [northern corridor] alignment with junctions J1–J6 (west to east).

TABLE 2: FD - Road Density (km/km^2) calculation of six zones (J1 to J6) across northern corridor of RRR[Micro Analysis].

T (Total grids)	X = 0.5·LOG10(T)	J1 (N)	J1(Y1)	J2 (N)	J2(Y2)	J3 (N)	J3(Y3)	J4 (N)	J4(Y4)	J5 (N)	J5(Y5)	J6 (N)	J6(Y6)
10000	2	3114	3.493	1532	3.185	2263	3.354	1989	3.298	2740	3.437	2285	3.358
40000	2.301029996	7919	3.898	3316	3.520	4970	3.696	4629	3.665	6941	3.841	5371	3.730
FD		1.346549		1.114028		1.135009		1.218657		1.340968		1.232997	
Road Length (km)		722.8561		216.9482		339.3744		393.3744		634.9405		439.2858	
Road Density (km/km^2)		3.6142		1.084		1.696		1.968		3.174		2.196	

VALUE

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Fig4 : FD-Road Density values for the zones J1 to J10 along the RRR.

Interpreting FD and density together:
- Zones J3, J5 are saturated areas with space-filling road networks that need growth control and network optimization rather than more new construction.
- Zones J1remains a contradiction of high density with structural weakness.it gains only limited connectivity benefit from incremental improvements, underscoring the need for new feeder roads to unlock its full potential and alleviate congestion. Whereas Zones J2, J4, J6, J7 respond strongly to the RRR, confirming that the ring substantially improves connectivity in transitioning corridors.

C. TYPOLOGY CLASSIFICATION

To translate the quantitative findings into practical planning insights, Fractal Dimension (FD) and road density values from Micro Analysis were combined to classify the six RRR [northern corridor] zones (J1–J6) into four spatial typologies:

TABLE 3: Typology Classification

Type	FD	Density
Saturated	High FD	High Density
Fragmented	Low FD	Low Density
Emerging	High FD	Low Density
Inefficient	Low FD	High Density

TABLE 4: FD-Road Density Typology classification of zones.

Zone	FD	FD Class	Density (km/km²)	Density Class	Typology
J1 (Sangareddy)	1.346	VERY LOW	3.614	HIGH	INEFFICIENT
J2 (Narsapur)	1.114	VERY LOW	1.084	VERY LOW	FRAGMENTED
J3 (Chegunta)	1.135	VERY LOW	1.696	LOW	FRAGMENTED
J4 (Gajwel)	1.218	VERY LOW	1.968	LOW	FRAGMENTED
J5 (Bhongir)	1.340	VERY LOW	3.174	HIGH	INEFFICIENT
J6 (Choutuppal)	1.232	VERY LOW	2.196	MODERATE/LOW	FRAGMENTED

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TABLE5: Limits for the type of class for FD and Road Density.

FD Value Range	Class	Road Density (km/km²)	Class
< 1.6	Very Low	< 1.5	Very Low
1.6 – 1.9	Low	1.5 – 2.0	Low
1.9 – 2.2	Moderate	2.0 – 2.5	Moderate
> 2.2	High	> 2.5	High

Key observations:

The study shows fragmented zones (J2, J3, J4, J6) with sparse networks and low fractal dimension, reflecting poor connectivity. Inefficient zones (J1, J5) have denser roads but disorganized growth, indicating sprawl without structured planning. Western areas near Sangareddy and Bhongir are denser due to industrial and highway corridors but lack hierarchy, while density drops eastward. Overall, the north corridor forms a patchwork: J1 and J5 grow linearly, J2–J4 remain rural gaps, and J6 acts as a weakly structured transition.

Planning Implications:

This simplified two-class typology highlights that no part of the RRR corridor is yet mature or saturated. Instead:

- Fragmented zones (J2, J3, J4, J6) must be given top priority for new road links and integration with regional centers.
- Inefficient zones (J1,J5) require restructuring of existing roads and planning controls to prevent redundant or misaligned investments.

The combined FD and density framework ensures targeted development strategies, aligning infrastructure with urban form instead of simply adding road length.

V. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

This study assessed the spatial impact of the Regional Ring Road (RRR) on Hyderabad's Road network using Fractal Dimension (FD) and road density analysis. The methodology applied a box-counting approach at macro and micro scales to quantify structural connectivity, followed by typology classificationto guide planning decisions.

Key findings include:

1) The RRR improves overall spatial connectivity, with FD values rising in North corridor.

2) At the zonal level (J1–J6), no areas are fully "saturated." The corridor is dominated by:

- Fragmented zones (J2, J3, J4, J6): Low FD and low road density — minimal baseline connectivity.
- Inefficient zones (J1, J5): Higher density but poorly structured networks.

3) The combined FD and density framework provided a robust, scale-sensitive view of road development, demonstrating where the RRR alone is insufficient and where complementary upgrades are essential.

Overall, the RRR has the potential to transform Hyderabad's peripheral growth, but only if accompanied by systematic feeder-road development and stricter corridor planning controls.

B. RECOMMENDATIONS

1) Targeted Road Network Improvements

- Upgrade local connectors in fragmented zones (J2, J3, J4, J6) to fully integrate them with the RRR.
- Reorganize inefficient zones (J1, J5) through hierarchical road planning to avoid redundant or disordered development.

2) Typology-Based Investment Planning

- Use FD and road density classification as a decision support framework for prioritizing road projects.
- Allocate higher funds to fragmented zones first, while regulating development pressure in inefficient zones.

3) Integrated Policy Measures
- Coordinate land use planning with infrastructure expansion to prevent uncontrolled growth.
- Establish monitoring systems using periodic FD analysis to assess whether new roads are genuinely improving connectivity.

4) Scope for Future Research
- Apply this methodology after the RRR becomes operational to track changes in FD over time.
- Extend the analysis to public transport networks and land use patterns for a more comprehensive urban growth model.

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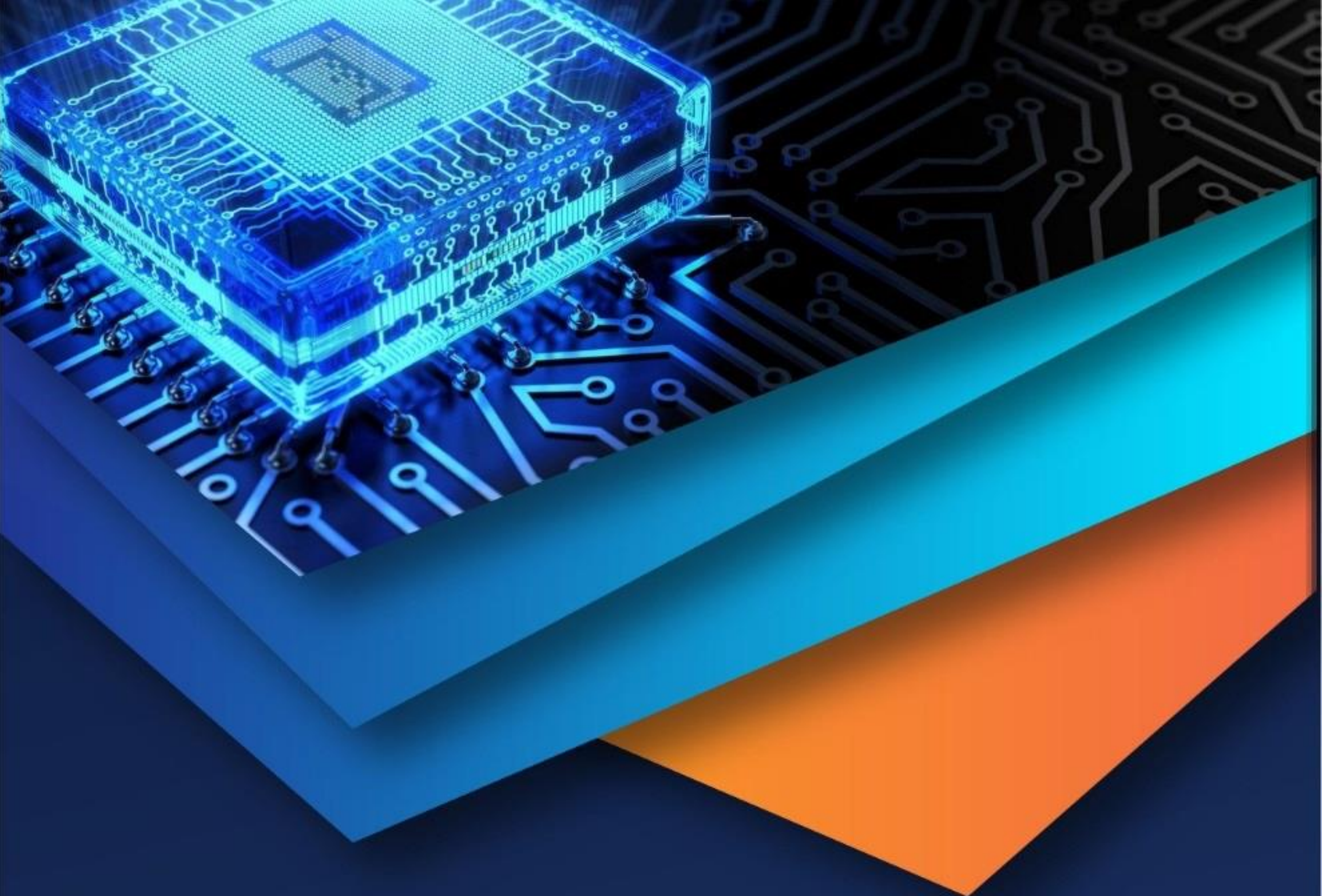

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