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Contributions to the Determination of Kinematic Parameters Specific to the Impact of the Car-Pedestrian, using the Pedestrian Body Mass Index

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Abstract: For analysing and reconstruction of vehicle-pedestrian collisions, many models have been developed and improved over the years and their level of complexity is different depending on hypothetical-deductive mathematical system used. The main purpose of this paper is to identify a series of factors that significantly influence the dynamics of vehicle-pedestrian impact and to determine a two-dimensional model of pedestrian distance assessment taking into account these parameters, including the pedestrian body mass index. Other parameters that influence the pedestrian throw distance, such as vehicle speed, vehicle mass, vehicle-to-ground friction coefficient and pedestrian-to-ground friction coefficient are taken into consideration.
Keywords: Accident reconstruction, body mass index, pedestrian, car collision, vehicle speed

I. OBJECTIVES OF THE PAPER

Determining the impact speed of the vehicle involved in a vehicle-pedestrian collision represents one of the main requirements in analyzing and reconstructing road accidents [14]. Establishing this kinematic parameter is very useful, so it represents an important objective in technical expertise activity of vehicle-pedestrian collision, because it has an extremely important role for the judicial body to establish the guilt of the parties involved in the event.

The occurrence of a vehicle-pedestrian accident is later materialized by the existence of material evidence means. Generally, in the reconstruction activity of vehicle-pedestrian collision, the projection distance of the pedestrian can be determined by putting together the material evidence means provided for the expertise by the investigation performed by the police on site, with the measurements performed by the police with this occasion. In this way, it is possible to assess the impact speed with the pedestrian, mainly knowing the projection distance of the pedestrian.

Starting with the 1960s and until present day, experimental studies and investigations were performed regarding the vehicle-pedestrian impact, by Searle, Wood, Batista, Han, Kuhnel, Rau etc.

Based on theoretical approaches and tests or experimental trials performed, different models and calculus relations were proposed, being presented in specialty literature [2; 3; 6; 7; 12; 13], to determine the impact speed of the vehicle based on the projection distance of the pedestrian. These models did not take into consideration the influence of all parameters that intervene in the kinematics and dynamics of the vehicle-pedestrian impact.

The reconstruction practice of this kind of accident shown the fact that the pedestrian's mass, and especially its' height sometimes influence the values of the kinematic and dynamic parameters, characteristic to the vehicle-pedestrian impact.

The present paper introduces for the first time a link factor between the pedestrian's mass and its' height. This factor, starting from the studied related to human anatomy [1; 5; 9; 10; 11], was named the body mass index and was defined as the ratio between the body mass, expressed in kilos and the square height, expressed in meters.

So, the body mass index is established with the relation:

$$i_{mc} = \frac{m_p}{h_p^2} \tag{1}$$

where m_p represents the pedestrian's mass [kg] and h_p its' height [m].

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Therefore, it's a necessity to establish a function like: $S_p = f(V, m_a, \varphi, \varphi_{ps}, i_{mc})$, where: S_p represents the pedestrian's projection distance after the impact with the vehicle, V represents the speed of the vehicle, m_a represents the vehicle's mass, φ represents the adhesion coefficient vehicle-ground, φ_{ps} represents the pedestrain-ground friction coefficient and i_{mc} represents the pedestrian's body mass index.

In this respect, two real accidents were investigated by computerized reconstruction with the help of the specialized program PC-Crash 10.1. Thus, it was intended to establish the expression of the function provided above and bring it to a form that would allow an easy use in practice of the vehicle-pedestrian accidents reconstruction. For this purpose, the five influential factors were varied and by operations with values intervals, it has been established the values for the projection distance of the pedestrian. The variation of each of the parameters mentioned above was performed in the program by multiple iterations, in successive series. For the two accidents 72 values (iterations) resulted for these parameters and the obtained results are presented in figure 1. In one iteration it has been modified a single parameter and kept the other ones constant, obtaining the variation of each parameter in this manner.

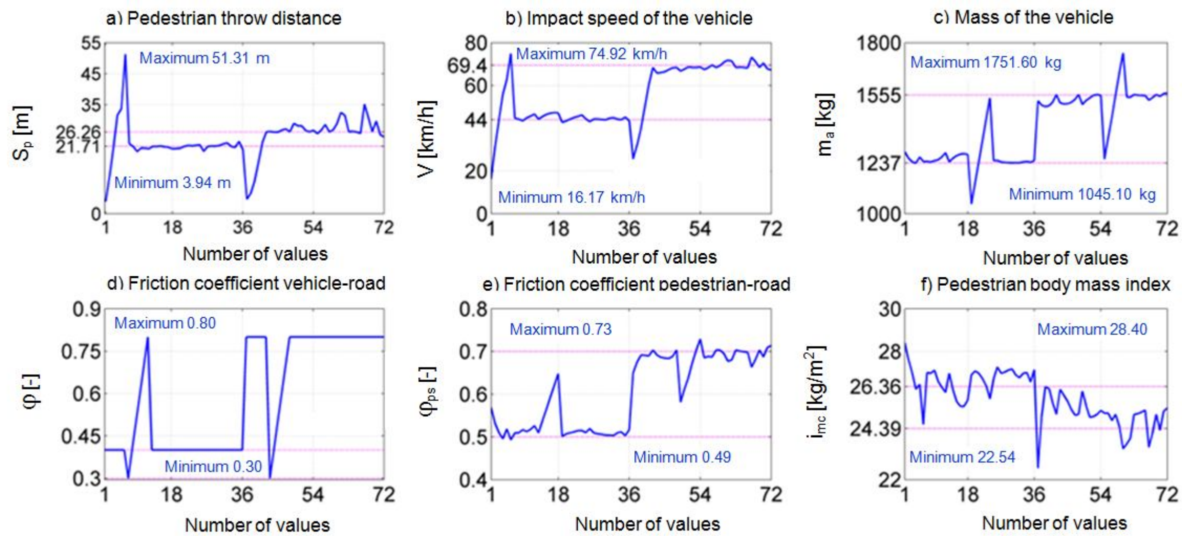

Figure 1. The variation intervals of the parameters characteristic to the vehicle-pedestrian impact and the values of the parameters for the analyzed accidents are shown.

In the graphics from figure 1 and the subsequent graphics the values of the two real accidents are also presented, that were investigated by computerized reconstruction with the help of the PC-Crash 10.1 program, specialized in this respect.

Using this data and using the analysis manner by operations with intervals of values, one can establish the mathematical model presented in figure 2, which is $S_p = f(V, m_a, \varphi, \varphi_{ps}, i_{mc})$.

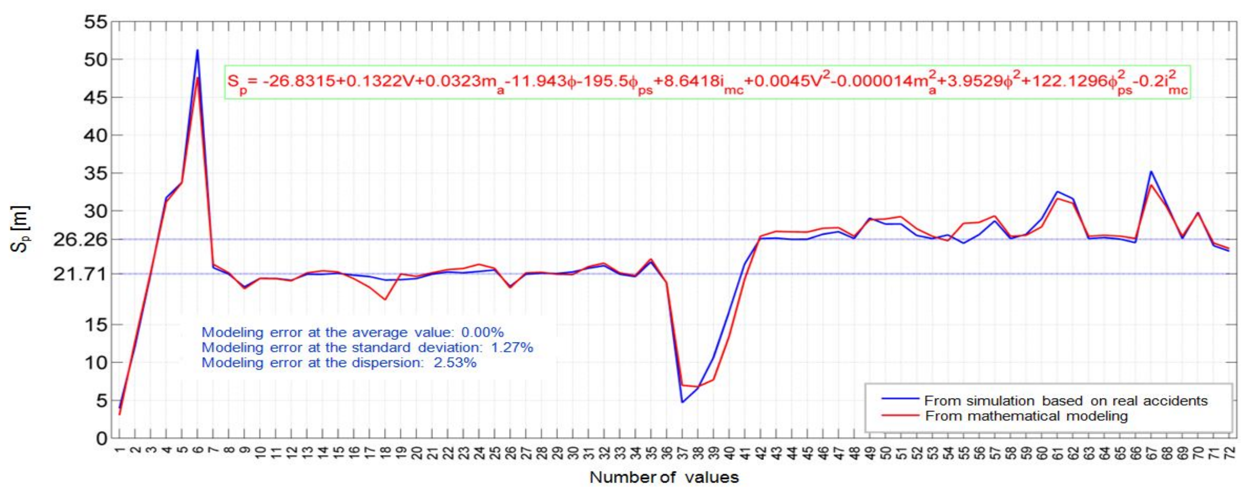

Figure 2. Car-pedestrian impact, the mathematical model has the form $S_p = f(V, m_a, \varphi, \varphi_{ps}, i_{mc})$.

The graphic in figure 2 presents the curve obtained by simulation, curve resulted by mathematical modeling and analytical expression of the mathematical model:

$$\begin{aligned}S_p &= -26{,}8315 + 0{,}1322V + 0{,}0323m_a - 11{,}943\varphi - 195{,}5\varphi_{ps} + 8{,}6418 i_{mc} + \\ &+ 0{,}0045V^2 - 0{,}000014m_a^2 + 3{,}9529\varphi^2 + 122{,}1296\varphi_{ps}^2 - 0{,}2i_{mc}^2\end{aligned} \tag{2}$$

The graphic also presents the errors obtained through modeling; because these values are below 4%, a frequently used limit, the conclusion is that the mathematical model (2) ensures a good precision.

It is important to study if the expression of the mathematical model (2) can be simplified, if an acceptable precision can be obtained, which is obviously possible only by reducing the number of the equation's term, meaning by neglecting one or several influential factors from the five factor concerned. In this respect, a sensitivity analysis will be performed, which offers the possibility to identify the factors with reduced influence that can be neglected.

II. SENSITIVITY ANALYSIS

In general, the sensitivity expresses the property of a resultative parameter (also called a dependent variable) to modify its' value under the influence of the factor variable (also called causal variable or independent variable).

The sensitivity constitutes a function that can be variable (case in which we are in the presence of a hetero-sensitivity) or it can be constant (iso-sensitivity). After the sense of the connection between the resultative and the factorial variable, the sensitivity can be direct or reverse.

From the aspects presented above it results that the sensitivity analysis also allows to study the influence of different factors (factorial values) over some resultative values.

In order to approach the sensitivity, we will consider a certain resultative variable *y* and a factorial value *x*. The sensitivity degree of the resultative variable according to the variation of the factorial value is measures with the sensitivity function *S*, defined by the report between the relative variation of the resultative value and the relative variation of the factorial value, in the considered case:

$$S_x^y = \frac{\mathrm{d}y}{y} : \frac{\mathrm{d}x}{x} \tag{3}$$

which shows that the function's sensitivity $y = \mathrm{f}(x)$ is equal to the rate of the relative variation of the resultative value *y* which returns to a relative variation unite of the factorial value *x*. Therefore, the sensitivity function shows with how much percentage the resultative value is modified, when the factorial value varies with 1%.

From the calculus relation (3) it results that the sensitivity is independent from the measurements units of the variables *x* and *y* (the sensitivity function is dimensionless); this expression can be written in the following form:

$$S_x^y = \frac{\mathrm{d}y}{\mathrm{d}x} : \frac{y}{x} \tag{4}$$

This leads to the second definition of the sensitivity function: the sensitivity of function *y* in relation to the variable *x* is equal to the report between the marginal value of the function and its' average value.

Also, the calculus expression (3) can be written in the following form:

$$S_x^y = \frac{x}{y}\frac{\mathrm{d}y}{\mathrm{d}x} \tag{5}$$

Considering d*y* and d*x* as differential:

$$\int \frac{1}{y}\mathrm{d}y = \lg y;\ \int \frac{1}{x}\mathrm{d}x = \lg x \tag{6}$$

it results:

$$\int \frac{\mathrm{d}y}{y}\mathrm{d}(\lg y);\ \int \frac{\mathrm{d}x}{x}\mathrm{d}(\lg x) \tag{7}$$

and then the relation (5) becomes:

$$S_x^y = \frac{\mathrm{d}(\lg y)}{\mathrm{d}(\lg x)} \tag{8}$$

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The relation (8) leads to the third definition of the sensitivity function: the sensitivity of function *y* in relation to the variable *x* is equal to the relation between the logarithmic derivate of *y* and the logarithmic derivate of *x*. From here we can draw an important property of sensitivity: the sensitivity of a function at any point in the curve $y = f(x)$ is given by the inclination of the tangent to the curve in the respective point, when y and x are graphically represented in logarithmic scales.

Therefore, if we follow to establish the influence of the vehicle's speed *V* over the projection distance of the pedestrian S_p, the sensitivity function will be determined:

$$S_V^{S_p} = \frac{V}{S_p}\frac{\partial S_p}{\partial V} \tag{9}$$

where the values *V* and S_p are the ones from figure 1.a and figure 1.b; the partial derivate results from the analytical expression (2) of the mathematical model.

Thus the results presented in the figure 3 are obtained; the figure contains the instant values of the sensitivity function. As these graphics show, there is a hetero-sensitivity (all functions vary, they are not constant). Also, neither value can be annulled, so all five factors influence the projection distance of the pedestrian. Moreover, some functions are predominantly positive (so the connection is direct) and other predominantly negative (reverse connection).

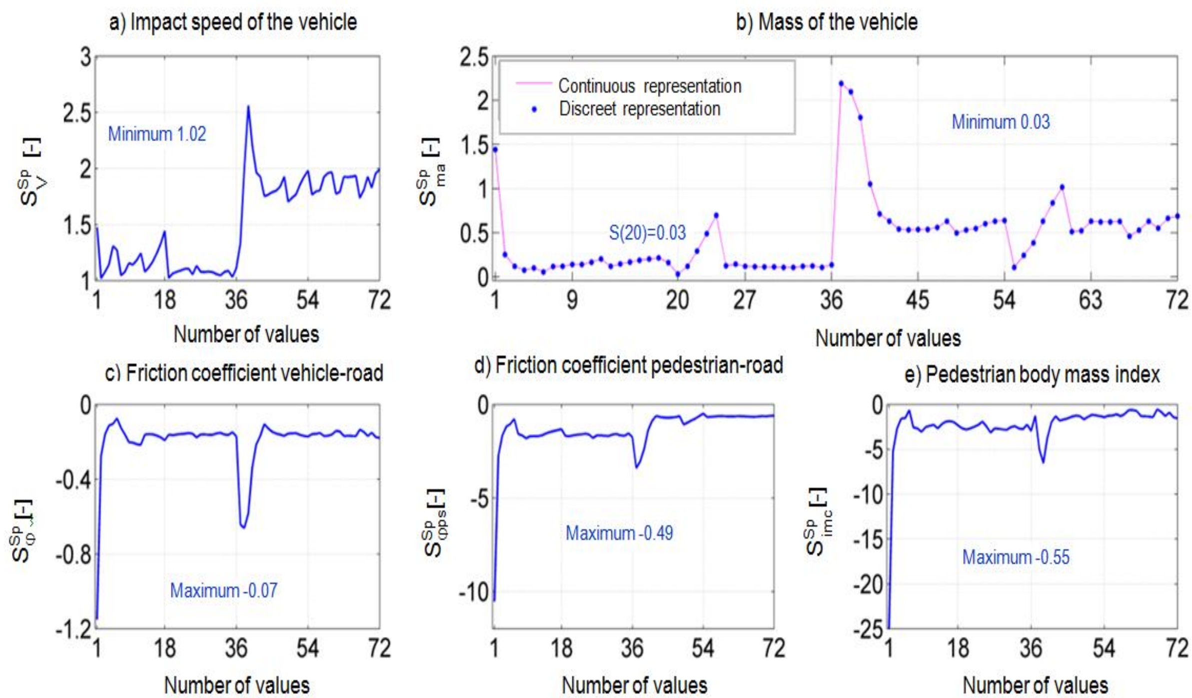

Figure 3. The instant values of the sensitivity function of the pedestrian's projection distance in relation to the five influential factors.

In order to globally evaluate the sensitivity of the pedestrian's projection distance to the variation of all five influential factors, figure 4 presents the average values S_m of the sensitivity functions.

As shown by the graphic, the highest influence over the pedestrian's projection distance is held by the body mass index (S_m= -2,36) and the lowest – the adhesion coefficient vehicle-ground (S_m= -0,2).

Also, from figure 4 it results that the speed and mass of the vehicle are in direct connection with the projection distance, the sensitivity functions being positive. This aspect is obvious, with the increase of the speed and mass of the vehicle, the projection distance is also increased by the higher energetic transfer to the pedestrian.

Instead, the graphic shows that the body mass index, the adhesion coefficient vehicle-road and the friction coefficient pedestrian-road are in reverse connection with the projection distance, the sensitivity functions being negative. This aspect is also obvious, for example, with the increase of the friction coefficient pedestrian-road, the projection distance is reduced due to the higher energetic losses that appear with the friction.

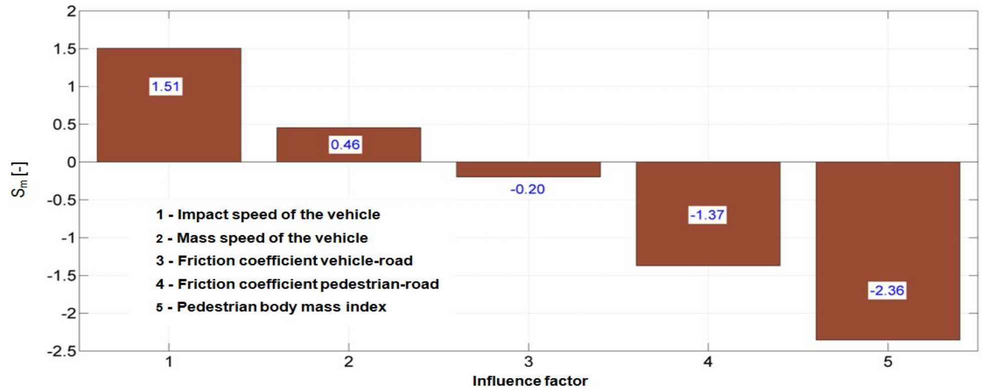

Figure 4. The average values of the sensitivity function of the pedestrian's projection distance in relation to the five influential factors.

From the aspects presented in figure 4 it results that, in order to establish a simplified mathematical model of type (2), we must verify the possibility to neglect the adhesion coefficient vehicle-ground and eventually the vehicle's mass.

III. ESTABLISH THE MATHEMATICAL MODEL

In this respect, figure 5 presents the establishment of a mathematical model like $S_p = f(V, m_a, \varphi_{ps}, i_{mc})$, respectively by neglecting the adhesion coefficient vehicle-ground, □.

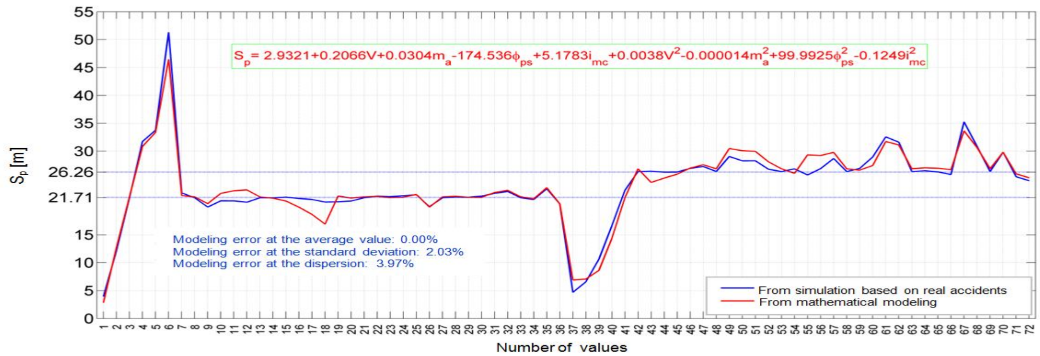

Figure 5. The mathematical modeling of the pedestrian's projection distance: $S_p = f(V, m_a, \varphi_{ps}, i_{mc})$.

Similar to this, figure 6 presents the establishment of a mathematical model like $S_p = f(V, \varphi_{ps}, i_{mc})$, respectively by neglecting the vehicle's mass and the adhesion coefficient vehicle-ground, □.

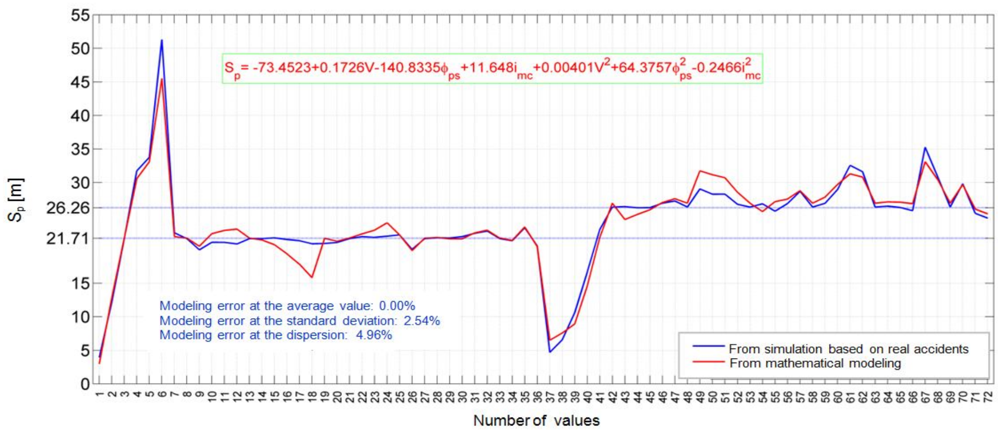

Figure 6. The mathematical modeling of the pedestrian's projection distance: $S_p = f(V, \varphi_{ps}, i_{mc})$.

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As provided in figure 6, it is not possible to use a mathematical model like $S_p = f(V, \varphi_{ps}, i_{mc})$, the dispersion error being almost 5%.

Instead, figure 5 shows that it can be used a mathematical model like $S_p = f(V, m_a, \varphi_{ps}, i_{mc})$, so by neglecting the adhesion coefficient vehicle-ground,□□. This model has the following analytical expression:

$$\begin{aligned} S_p &= 2{,}9321 + 0{,}2066V + 0{,}0304m_a - 174{,}536\varphi_{ps} + 5{,}1783i_{mc} + \\ &+ 0{,}0038V^2 - 0{,}000014m_a^2 + 99{,}9925\varphi_{ps}^2 - 0{,}1249i_{mc}^2 \end{aligned} \quad (10)$$

for which all these modeling errors presented in the graphic have reduced values, below the reference value indicated in the specialty literature [4; 8] of 4%.

IV. CONCLUSIONS

The body mass index of the pedestrian, as specific parameter for reconstruction of the vehicle-pedestrian collision is mentioned for the first time in the technical specialty literature.

The body mass index is a parameter with maximum sensitivity, which means that it has an important influence in the actual calculation of the vehicle-pedestrian impact dynamics. So it must be taken into consideration to determine the kinematic parameters of the vehicle-pedestrian collision, which are intended to be established in the technical expertise, respectively the connection between the pedestrian's projection distance and the vehicle's impact speed.

This calculus relation, $S_p = f(V, m_a, \varphi_{ps}, i_{mc})$, by using together with the analytical relations presented in the specialty literature, can contribute to individualizing, from an interval of values of the vehicle's impact speed, offering the specialist activating in the reconstruction of the vehicle-pedestrian accident a manner to precisely and accurately evaluate the kinematic parameters of the road conflict.

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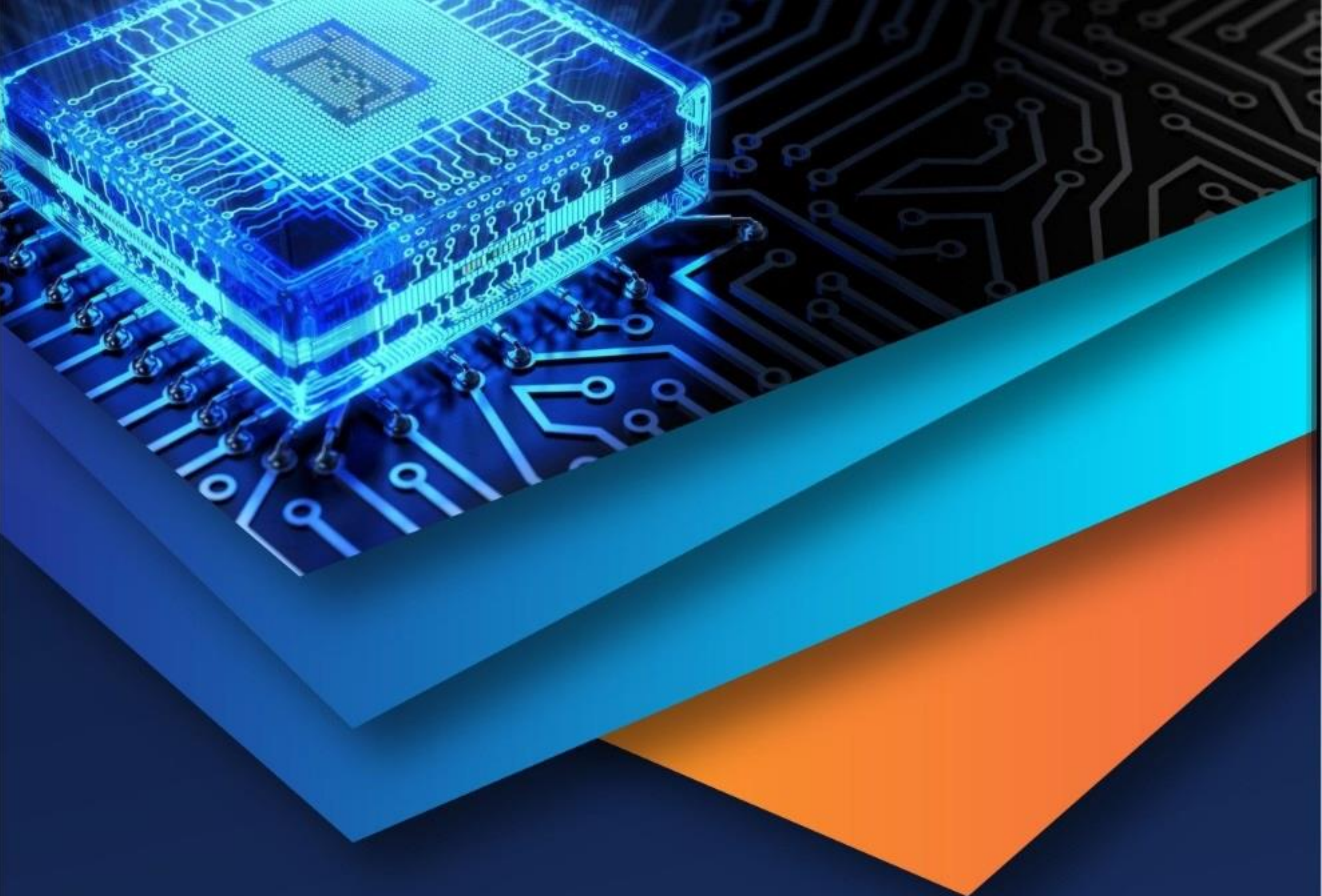

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