Methodology for Determining the Initial Speed of Vehicle Collisions Based on Deformation Energy Analysis

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Abstract: Determining the initial speed of motor vehicle collisions is critical in accurately identifying the causes and circumstances of traffic accidents. This study develops a methodology for estimating the initial speed of vehicle collisions in Mongolia, based on the energy expended on deformation. Traditional methods, such as analyzing skid marks, road surface friction, and kinetic energy changes, were examined alongside advanced approaches like the finite element method and the Energy Equivalent Speed (EES) concept. The research aimed to enhance accuracy in estimating the initial collision speed by considering the structural deformation, stiffness properties, and material characteristics of vehicles. This methodology provides a robust framework for analyzing accident conditions in Mongolia's transport sector, contributing significantly to traffic accident prevention and improving road safety.

Keywords: Vehicle Collision Analysis, Initial Speed Estimation, Deformation Energy, Energy Equivalent Speed (EES), Traffic Accident Reconstruction

1. INTRODUCTION

The global vehicle fleet continues to witness a rapid increase in the proportion of high-speed and powerful automobiles, leading to challenges in maintaining safe traffic conditions on urban and rural roads. To address these issues, speed limits have been introduced to ensure safe participation in traffic. However, setting these limits requires a thorough analysis of the factors defining the reliability of the Driver-Vehicle-Road-Environment (DVRE) system. The DVRE system consists of various quantitative and qualitative parameters that must be comprehensively evaluated.

The influence of human factors on speed selection is assessed based on psychological and physiological capacities, individual behavior, mental states, and the preparedness of drivers. One of the key physiological constraints is the level of collision energy that the human body can withstand without severe injury or fatal consequences.

Previous studies (Brach, 2011; Lay, 1992, The Automobile: A Century of Progress, 1997; Campbell, 1974) have analyzed acceptable speed limits for different road environments, such as pedestrian crossings, focusing on reducing the risk of fatalities among pedestrians (Figure 1), vehicle passengers (Table 1), and drivers in the event of traffic accidents. These findings are used to pre-calculate and establish permissible vehicle speeds aimed at minimizing fatalities and enhancing traffic safety.

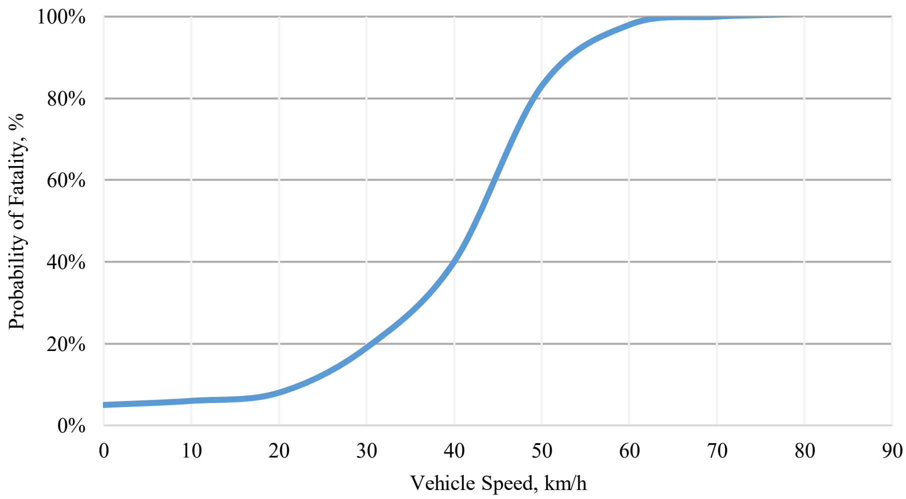

Figure 1. The Impact of Vehicle Speed on the Probability of Fatality When a Pedestrian is Hit by a Vehicle

Table 1. Consequences of Traffic Accidents and Speed Limits

Type of Collision	Vehicle Safety Design Features	Estimated Speed Limit for Fatality Risk
Frontal Collision	Seatbelt, airbags, energy-absorbing structural elements, safe distance for drivers and passengers	70 km/h
Side Collision		50 km/h
Collision with a Pedestrian	--------	30 km/h

On non-urban roads, the speed limit is set at 80 km/h according to traffic regulations. However, this speed limit significantly reduces the survival probability of accident victims in cases where vehicles fail to brake effectively and collide with unexpected obstacles, such as side impacts from intersecting roads. During a collision, reducing vehicle speed requires a certain amount of time, and a significant portion of the vehicle's kinetic energy is not fully absorbed by the braking mechanism. The probability of such scenarios increases with higher speeds, as greater speeds lead to longer reaction times for drivers and extended braking distances.

A critical psychological factor for drivers is the ability to accurately assess speed and time intervals. Studies (Brach, 2011; Lay, 1992, The Automobile: A Century of Progress, 1997; Campbell, 1974) show that at least 15% of drivers tend to travel faster than the flow of traffic, while up to 40% make errors in reducing their speed. Researchers (McHenry, 1997; McHenry, 1986; María and Christian 2023) conclude that the safest speed is equal to the average traffic flow speed. Deviating by 30 km/h above or below the traffic flow speed increases the probability of an accident by 10 times. Additionally, variations in the technical capabilities of vehicles participating in traffic (e.g., a speed difference of 60 km/h) significantly increase the likelihood of accidents. Studies indicate that reducing speed by 10 km/h on non-urban roads or by 5 km/h in urban areas can halve the risk of traffic accidents.

From a technical perspective, factors influencing road safety include vehicle energy efficiency, structural sophistication, technical condition, fleet composition, and age. The modern global vehicle fleet exhibits diverse technical and structural characteristics. Road and environmental factors affecting safe speed choices include road surface conditions, the quality of transportation infrastructure, and the level of traffic management.

Effective traffic management focuses on creating homogeneous traffic flow, setting safe speed limits, optimizing lane use, and designing intersections to minimize conflicts. Another crucial goal is improving accountability for speeding drivers by enhancing accident reconstruction models and refining mathematical interpretations of accidents. The precision of mathematical models and the estimation of vehicle speed parameters during accidents play a vital role in determining the culpability of those involved.

The primary parameter defining all characteristics of subsequent accident stages is the initial speed of the vehicle before the collision. Despite the diverse and expansive scope of recent research, several contentious issues remain regarding methodologies for estimating initial vehicle speed and reconstructing traffic accidents. Therefore, evaluating methods for determining vehicle speed during accident investigations remains critical.

2. METHODS FOR DETERMINING THE INITIAL SPEED OF VEHICLES IN TRAFFIC COLLISIONS

Technical experts categorize the methods for determining the speed of vehicles involved in traffic collisions into four main groups. The simplest method is based on road conditions, particularly the vehicle's trajectory, visibility, and environmental factors. The second method calculates the speed using skid marks left on the road or the length of tire drag marks at the collision site. The third method involves estimating the speed using the displacement (momentum transfer) parameters of the vehicles post-collision, based on the law of conservation of momentum. The fourth and final method determines speed by analyzing the deformation of the vehicles caused by the collision. This approach calculates the kinetic energy absorbed by the deformed surfaces of the vehicles during the impact.

3. DETERMINING SPEED BASED ON DEFORMATION FROM TRAFFIC COLLISIONS

This method has not yet been fully incorporated into expert analyses. While it is evident that higher vehicle speeds increase the likelihood of severe damage during traffic collisions, there are no sufficiently validated and widely accepted methods to accurately address this issue.

Specialists who use finite element methods to estimate speed based on deformation achieve high levels of accuracy, but their conclusions often face skepticism. Vehicle speed is influenced by numerous factors, and the extent of damage is affected by even more variables. These include braking efficiency, tire conditions (e.g., pressure, tread pattern, wear, studded tires), vehicle structure, load weight and distribution, road surface adhesion coefficients, braking system functionality, brake drum condition, anti-lock braking system (ABS) presence, vehicle age, wind direction, and other external forces. Many of these factors are not considered in existing calculation methods, and in some cases, they cannot be accounted for.

Our proposed method involves using detailed information about the stiffness properties of vehicle components that have deformed during a collision, specific to the type and model of the vehicle. However, manufacturers typically do not disclose such information. Although the method relies on stiffness data specific to vehicle models, in practice, we acknowledge the limited availability of such data. Therefore, we validated our assumptions through controlled simulations using typical spring characteristics of commonly used passenger vehicles in Mongolia, as presented in Section 5. These results provide a feasible estimate under standard conditions, while recognizing that actual vehicle-to-vehicle variability remains a limitation of the study.

Furthermore, over time, metal fatigue and changes in material properties alter the stiffness of vehicle components. Accurately accounting for these factors would require extensive data, much of which is currently inaccessible (Ganjargal and Bayarsaikhan, 2023).

Analyzing all existing methods for determining the initial speed of vehicles during collisions reveals that the accuracy of results depends heavily on the correct selection of initial parameters, such as sudden deceleration during emergency braking, rolling resistance, and adhesion coefficients.

Textbooks and reference materials (Brach, 2011; McHenry, 1986; María and Christian 2023; Żuchowski, 2015) show that these initial parameters often vary significantly. The greater the variability in these parameters, the greater their impact on the final accuracy of speed estimations. Therefore, this variability must be carefully addressed when calculating vehicle speeds in collision analyses.

4. METHODOLOGY FOR CALCULATING ENERGY ABSORBED BY VEHICLE DEFORMATION DURING COLLISIONS

There are numerous methods for calculating the energy absorbed by elastic deformation of vehicle components in traffic accident analyses. The most commonly used group of methods is based on calculating the Energy Equivalent Speed (EES). In various studies (Brach, 2011; Campbell, 1974; McHenry, 1997; McHenry, 1986; María and Christian 2023; Żuchowski, 2015), EES is used as a measure of the energy expended on deformation.

EES, or Energy Equivalent Speed, represents the speed at which a vehicle, upon colliding with a rigid stationary object, would expend an equivalent amount of energy on deformation. In other words, EES serves as a metric for the energy consumed by deformation. The kinetic energy acquired by any object can be expressed in a simplified form as follows:

$$W = 0.5mV^2 \tag{1}$$

Where W is the kinetic energy, m is the mass of the object, and V is the velocity.
This relationship forms the foundation for determining the equivalent energy consumed by deformation during vehicle collisions. From this,

$$W = 0.5m(EES)^2 \tag{2}$$

Thus, determining this parameter becomes necessary. In some cases, the EES value is referred to as EEV (Energy Equivalent Velocity) or EBS (Energy Barrier Speed). Several approaches can be considered for calculating energy expenditure through elastic deformation:

- **Comparison Method** (Nikonov, 2007): This method uses pre-prepared reference data representing actual vehicle deformation scenarios. The expert focuses on the type and model of the vehicle and selects the EES value from data corresponding to a vehicle with similar technical specifications. This approach is simple, relatively accurate, time-efficient, and commonly used in traffic accident analysis software.

- **Analytical Method** (Nikonov, 2007): This method determines the EES value using a formula that incorporates two variables: ETD (Equivalent Test Deformation) and EOD (Equivalent Overlap Degree). These variables define the geometric characteristics of the damaged area of the vehicle involved in the collision (Figure 2).

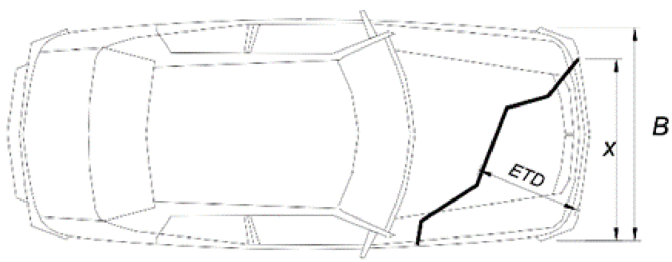

Figure 2. Geometric Shape of the Damaged Area of the Vehicle

The variable EOD is expressed as follows:

$$EOD = xB^{-1} \cdot 100\% \tag{3}$$

Where,

x: The width of the dented or damaged area, in meters.

B: The total width of the vehicle, in meters.

If these two parameters are known, the Energy Equivalent Speed (EES) can be expressed using the following equation:

$$EES = a^{*} \cdot ETD^{b} \cdot EOD^{c} \tag{4}$$

These parameters have specific values depending on the type and model of the vehicle. For instance, Mercedes-Benz manufacturers regularly publish and update this parameter information as needed. Some example data is provided in Table 2 below:

Table 2. Values of Parameters a, b, and c

Cabin Type	Model	Parameters		
		a	*b*	*c*
201	190 D/E	16.08	0.758	0.369
126	280SE-500SEL	11.42	0.973	0.423
123	200–280E	3.26	1.004	0.707
116	280E-450SEL	3.215	1.015	0.73

Other vehicle manufacturers do not publish this data. Therefore, an effort was made to develop a formula that meets the requirements of technical analysis for traffic accident reconstruction. The following preliminary assumptions were considered:

- The instantaneous value of the impact force and the extent of vehicle damage (depth of the dent) have a linear relationship.

- Elastic deformation is considered, while elastic recovery is excluded from the calculations.

The first condition can be expressed as follows:

$$F = c \cdot f \quad (5)$$

Where,

c : Stiffness, measured in $N \cdot м^{-1}$;

The second condition, representing the work done on elastic deformation, is expressed as follows:

$$W_{def} = 0.5cf^2 \quad (6)$$

Where,

f : Depth of the dent, in meters.

The stiffness parameter is represented by the following product:

$$c = bhk \quad (7)$$

Where,

b: Average width of the dent measured in the direction of the impact point, in meters.

h: Average height of the dent, in meters.

k: Unit stiffness, measured in $N \cdot м^{-3}$.

Finally, the work done on elastic deformation can be expressed as follows:

$$W = 0.5bkhf^2 \quad (8)$$

From the above expressions, determining the value of the unit stiffness k is a critical issue. This parameter depends not only on the type and model of the vehicle but also on the specific area of the vehicle that sustained damage. For instance, in the case of frontal or rear-end collisions of passenger vehicles with a dent depth of 0.4–0.5 m, $k=(13.5–22.6)\times10^5$ $N \cdot м^{-3}$ or $k=(9.1–13.5)\times10^5$ $N \cdot м^{-3}$, respectively. In contrast, for corner or side impacts (where the deformation area is relatively smaller), $k=(5.2–7.2)\times10^5$ $N \cdot м^{-3}$.

The graphical method by W. Rohrich (Brach, 2011; Campbell, 1974; McHenry, 1997) is worth mentioning here. This method is based on the use of schematic diagrams that illustrate the distribution of energy allocated to elastic deformation in different sections of the vehicle's surface. The schematic diagrams (Figure 3) are represented in a grid (or mesh) format.

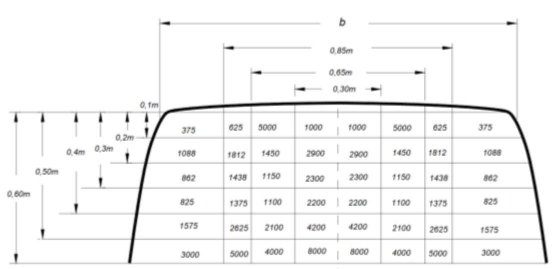

Figure 3. Deformation Grid

Each "window" in the grid diagram represents the amount of (work) energy expended on elastic deformation in the vehicle's cabin or other parts. To determine this energy value, the following steps are performed:

- Draw the grid diagram to the necessary scale.
- Overlay the grid with the schematic of the damaged section of the vehicle during the collision.
- Sum up the work values for all the "windows" in the grid to represent the total energy of elastic deformation.

This type of grid diagram allows energy calculations for different types of vehicles and various damaged areas.

In 1970, R.P. Mason and D.W. Whitcomb (Brach, 2011; Campbell, 1974; McHenry, 1997) introduced the first study on determining vehicle speed during collisions. In 1974, K.L. Campbell (Campbell, 1974) conducted experimental calculations of energy expenditure using a Chevrolet Vega, a compact car manufactured by GMC.

He hypothesized that the energy absorbed during elastic deformation is correlated with the total mass of the vehicle and observed a linear relationship between collision speed and the depth of residual deformation.

$$V = b_0 + b_1 c \tag{9}$$

Where,

V: Speed, in m/s.
b_0: Minimum speed required to initiate elastic deformation, in m/s.
b_1: Slope coefficient, in $\sec^{-1}$.
c: Depth of deformation, in meters.

The amount of energy absorbed during elastic deformation can be expressed as follows:

$$E = Wg^{-1}\omega_0^{-1}\int_0^{\omega_0}(b_0 b_c + 0.5 b_1^2 c^2)d\omega + 0.5 w b_0^2 g^{-1} \tag{10}$$

K.L. Campbell also introduced the concept of Energy Barrier Speed (EBS), an energy equivalent measure.

$$E = 0.5Wg^{-1}(EBS)^2 \tag{11}$$

This parameter is equal to the amount of kinetic energy expended on the elastic deformation of the vehicle during a collision. It allows for determining the change in speed (ΔV) during the collision. Additionally, K.L. Campbell proposed that a certain portion of the energy is absorbed by elastic recovery, introducing a constant factor into the calculations.

$$E = \int_0^{w_0}\int_0^{c} F dc dw + const \tag{12}$$

Where,

F: The force acting on the deformed part of the vehicle.

This force can be expressed as follows through a linear relationship:

$$F = a_0 + a_1 c \quad (13)$$

After performing the appropriate transformations and substitutions, the relationships between the parameters and constants can be determined.

$$a_0 = W b_0 b_1/(d w_0); a_1 = W b_1/(g w_0); const = 0.5 W b_0^2/g \quad (14)$$

Where,

g : Acceleration due to gravity, in m/sec²;

w_0 : Width of the vehicle, in meters.

Finally, the force can be expressed as follows:

$$F = W(b_0 b_1 + b_1^2 c)/(g w_0) \quad (15)$$

Subsequently, researcher R.R. McHenry (McHenry, 1997; McHenry, 1986) refined K.L. Campbell's hypothesis and implemented it in the CRASH computer program. He expressed the magnitude of the impact force as a linear function.

$$F = A + BC \quad (16)$$

Where,

A: The force at which the initial elastic deformation occurs.

B: Stiffness of the vehicle's structure.

The parameters A, B, and F are compared per unit width of the deformed section of the vehicle.

In 1981, researcher D. Segal (María and Christian 2023; Żuchowski, 2015) compared R.R. MacHenry's conclusions and proposed the concept of an elastic-plastic element, which includes both elastic and plastic components. In this model:

A: Represents the initial load (stress) received by the spring.

B: Represents the energy expended on elastic deformation.

G: Represents the energy expended on elastic recovery.

$$G = 0.5 A^2/B \quad (17)$$

The amount of energy absorbed by the elastic deformation of vehicle components can be expressed as follows:

$$E = \int_0^{w_0} (AC + 0.5BC^2 + G)\, dw \quad (18)$$

Subsequently, researcher C.E. Strother (María and Christian 2023; Żuchowski, 2015) refuted the linear relationships proposed by R.R. MacHenry and K.L. Campbell. He modified K.L. Campbell's equation and derived the following relationship to determine the slope coefficient.

$$b_1 = (v - 5)/C \quad (19)$$

It was demonstrated that the parameters are related to K.L. Campbell's $\mathbf{b_0}$ and $\mathbf{b_1}$ through the following relationships.

$$F = mb_0b_1L^{-1};\ B = mb_1^2L^{-1};\ G = 0.5A^2B^{-1};\ b_0 = A(LB^{-1}m^{-1})^{0.5};\ b_1 = (BLm^{-1})^{0.5} \tag{20}$$

Researcher A.K. Prasad (María and Christian 2023; Żuchowski, 2015) analyzed the results of vehicle collision experiments and established that the parameter $(2E/W)^{0.5}$ has a linear relationship with the extent of vehicle deformation or dent depth.

$$(2E/W)^{0.5} = d_0 + d_1c \tag{21}$$

Where, Two new parameters, d_0 and d_1, are introduced, where W represents the width of the dent, as previously mentioned.

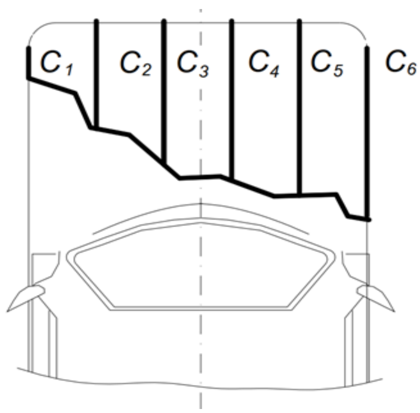

Figure 4. Depth of the Deformed Section of the Vehicle

This method provides an opportunity to develop another model for elastic deformation during vehicle collisions. The energy absorption can be expressed using the following equation:

$$E = \int_0^W 0.5(d_0 + d_1C)^2\,dW \tag{21}$$

If the numerical integration of the above expression is performed, it is sufficient to divide the width of the dent into 5–6 sections, representing the depth of the deformed area, labeled as C_1–C_6 (Figure 4).

5. INVESTIGATION OF THE ENERGY ABSORPTION PROPERTIES OF VEHICLE SPRINGS DURING COLLISIONS

During vehicle collisions, numerous elements and components of the vehicle undergo deformation. This study focuses on determining the energy absorbed by the spring during deformation (compression and extension) to evaluate its elastic properties. Due to practical limitations, the sample used for modeling included typical rear and front springs from representative vehicle types. While the number of modeled scenarios is limited, they reflect commonly encountered configurations in Mongolian traffic accidents. Nonetheless, future work will aim to incorporate a broader sample and real crash test data to enhance generalizability. The geometric dimensions and material properties of the rear spring of a passenger vehicle are presented in Table 3.

Table 3. Geometric Dimensions and Material Properties of the Rear Spring

№	**Material**	**Stainless Steel ASTM-A313**
1	Total number of coils (n)	5
2	Number of active coils (n)	3
3	Coil diameter (d)	15.62 mm
4	Outer spring diameter (D0)	158.6 mm
5	Spring length (L)	304.8 mm
6	Pitch of active section (p1)	84.35 mm
7	Pitch of end section (p2)	25.875 mm
8	Density	7805.73 kg/m³
9	Young’s modulus	203.4 GPa
10	Poisson's ratio	0.27
11	Yield strength	767.39 MPa
12	Ultimate strength	2192.53 MPa

Using the geometric dimensions provided in the table, the rear spring was modeled using CAD software and converted into finite elements using the ANSYS program. The resulting finite element model is shown in Figure 5.

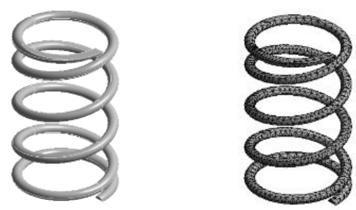

Figure 5. Rear Spring Modeled in CAD Software and Converted into Finite Elements in ANSYS

The material properties from the table were incorporated into the ANSYS program, and the spring was subjected to varying loads of 1600, 2700, 3850, 5000, 5900, and 6500 N. The resulting deformations for each load case are shown in Figure 6.

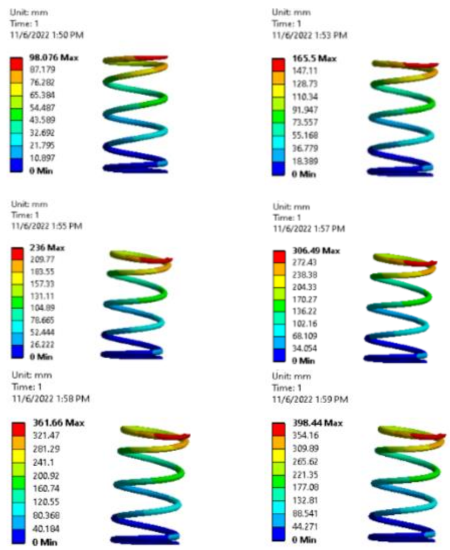

Figure 6. Deformation of the Rear Spring Under Loads of 1600 N, 2700 N, 3850 N, 5000 N, 5900 N, and 6500 N

Table 4 presents the changes in load applied to the rear spring and the corresponding results from the ANSYS simulations.

Table 4. Changes in Load Applied to the Rear Spring and Results

№	Load Applied to the Spring (N)	Spring Deformation (mm)
1	1600	98.076
2	2700	165.5
3	3850	236
4	5000	306.49
5	5900	361.66
6	6500	398.44

The geometric dimensions and material properties of the front spring are presented in Table 5.

Table 5. Geometric Dimensions and Material Properties of the Front Spring

№	Material	Stainless Steel ASTM-A313
1	Total number of coils (n)	7
2	Number of active coils (n)	5
3	Coil diameter (d)	15.62 mm
4	Outer spring diameter (D_0)	148.44 mm
5	Spring length (L)	304.8 mm
6	Pitch of active section (p_1)	50.61 mm
7	Pitch of end section (p_2)	25.875 mm

№	Material	Stainless Steel ASTM-A313
8	Density	7805.73 kg/m³
9	Young’s modulus	203.4 GPa
10	Poisson's ratio	0.27
11	Yield strength	767.39 MPa
12	Ultimate strength	2192.53 MPa

Using the geometric dimensions provided in the table, the front spring was modeled using CAD software and converted into finite elements in the ANSYS program. The resulting finite element model is shown in Figure 7.

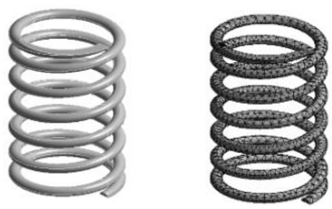

Figure 7. Front Spring Modeled in CAD Software and Converted into Finite Elements in ANSYS

The material properties from the table were incorporated into the ANSYS program, and the spring was subjected to varying loads of 2630, 3550, 4470, 5340, 5980, and 6700 N. The resulting deformations for each load case are shown in Figure 8.

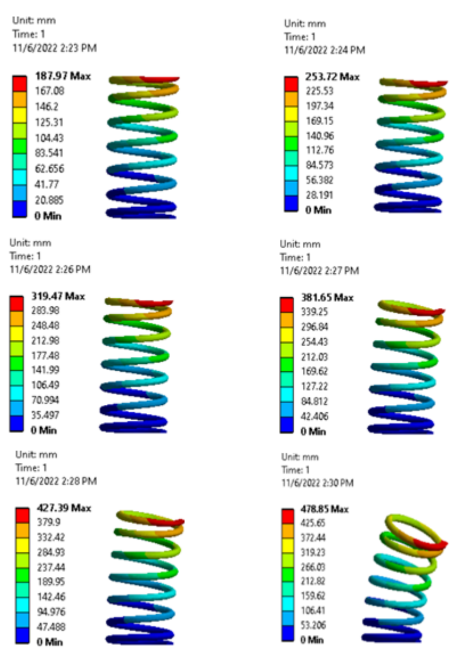

Figure 8. Deformation of the Front Spring Under Loads of 2630 N, 3550 N, 4470 N, 5340 N, 5980 N, and 6700 N

The changes in load applied to the front spring and the corresponding results from the ANSYS simulations are presented in Table 6.

Table 6. Changes in Load Applied to the Front Spring and Results

№	Load Applied to the Spring (N)	Spring Deformation (mm)
1	2630	187.97
2	3550	253.72
3	4470	319.47
4	5340	381.65
5	5980	427.39
6	6700	478.85

By continuing the calculations and determining the energy absorbed by the elastic deformation of the spring during a vehicle collision, it becomes possible to more accurately estimate the initial speed of the vehicle at the time of impact.

6. CONCLUSION

By analyzing the methods used to determine the energy absorbed by the elastic deformation of vehicles in traffic accident investigations, the following conclusions were drawn:

- Direct application of impact theory to traffic accident reconstruction presents several challenges. Impact theory assumes that the colliding bodies have simple shapes (e.g., spherical or flat), are homogeneous (isotropic), and possess uniform elastic and strength properties throughout. In contrast, a vehicle is a complex mechanical system with diverse structural and mechanical characteristics in its exterior and interior components. As a result, the actual consequences of collisions—particularly vehicle speed and displacement based on impact theory—may differ significantly from real-world traffic accident conditions.
- When a vehicle collides with vertical obstacles (e.g., poles, posts, or trees), only a few components come into contact, leading to unique damage characteristics. Each section of a vehicle's width exhibits different stiffness and strength properties. For instance, the longitudinal frame sections (longerons) are highly resistant to impact, whereas central areas are more prone to deformation. Therefore, collisions at the front corner or middle of a vehicle yield different outcomes.
- The most commonly used methods for determining the energy absorbed by elastic deformation in traffic accident analysis rely on the concept of Energy Equivalent Speed (EES). It is critical to have pre-prepared reference data that reflect actual deformation scenarios for vehicles. Such reference materials ensure more accurate and reliable assessments.

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