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Application of Mathematical Principles in Analysis of Impact Energy as a Basis of Crush Severity in Vehicle Accidents

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Abstract— Vehicle speed and mass play crucial role on energy transferred during vehicle accidents. This energy is exhibited as kinetic energy (KE) and is significant in determining the crush severity (vehicle damage) during accident reconstruction analysis. However, conventional road vehicle safety systems play little role in regulation of this energy. Thereby leaving a gap when road safety and impact energy are mentioned with regards to changes in vehicle structures and road safety. Understanding the role of KE in relation to vehicle damage will help come up with effective measures towards the generation, transfer and controlling effects of impact energy during vehicle road accidents. This study suggests a mathematical modelling approach towards regulation of impact energy as a basis of crush severity. A focus is made on full frontal impact tests as applied in vehicle accident reconstruction. Crash tests are simulated based on Kudlich-Slibar model of car crash analysis using virtual CRASH® v4.0 simulation software. The software provides an interface to simulate and analyse full frontal vehicle collisions. At first, barriers and sample vehicles were modelled then crash dynamic parameters were adjusted to fit momentum-based impact model of car crash analysis. Data was collected from vCRASH® data panel, tabulated and analysed based on vehicle speed, deformation (crush severity), impact energy and impulse using Minitab 17.0 and SigmaPlot 14.0 data analysis tools. Using the data, mathematical models were developed upon analysis of transferred energy. Final results were presented in graphs and mathematical models. The findings clearly indicate the need to adapt vehicle speeds with a focus on impact energy based on monitored vehicle weights.

Index Terms— Impact energy, Speed, Vehicle accidents, Vehicle weight, Crush severity, Kinetic energy, Vehicle damage

1 Introduction

Classical mechanics qualifies mass and speed to have a significant role in energy transferred during car crash. This energy is exhibited as K.E whose overall magnitude influences vehicle damage. It is expressed from first principles as one half of the body mass multiplied by the square of the object speed. So as to meet the road transport safety limits put in place, vehicle safety should be focused on regulation of impact energy through vehicle specific speed adaptation rather than static speed limits. This can be achieved through understanding the role of K.E in vehicle frontal damage, measures to reduce the generation, distribution and effects of energy absorbed by vehicle structure will be easily realized [6].

In 2001, Fleming [5], affirms that vehicle safety is an important consideration in vehicle road transport. So as to achieve this, he suggest the need for both active and passive safety systems employment. Where active systems prevent accidents from happening while passive systems are inbuilt with the vehicle to protect occupants in a crash event. Furthermore active systems are seen to reduce the level of injury severity by placing focus on overall vehicle damage and fatalities in accidents. For example vehicle speed governor. This is a device in vehicles used to limit the top speed to a predetermined level by country policies [1].

This project presents an objective approach towards analysis of impact energy absorbed in vehicle accidents; by placing a focus on generated crush severity and force deflection properties of energy absorbed so as do develop descriptive math models for vehicle specific speed profiles adaptation systems. In 2014, McHenry [8] findings indicate that impact energy can be considered as a measure of estimation the level of injury severity in vehicles collisions. The underlying principle being that the energy transferred in vehicle accidents if a function of both speed and mass.

In concept, the vehicle damage and dynamic force-deflection characteristics of the body structure are the available estimate of the energy transferred during inelastic effects in vehicle damage [3]. In 1974, Campbell [3] proposes a crash model restricted to frontal damage as having a total force per unit width equivalent to kinetic energy transferred. His development of the concept was restricted to frontal damege besides the technique being generally applied to either rear or side impacts vehicle damage analysis.

Studies have shown that during a vehicle accidents, the K.E from the bullet vehicle is transferred into crush severity (also vehicle damage or deformation). Therefore, from accident re-

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construction science, there is need to assess the severity of crush pattern resulting so as to come with possible safety measures in improvement of vehicle safety. With accident reconstruction, an analysis on vehicle damage based on crush severity measured can be done and scientifically integrate vehicle crash dynamic parameters like crush coefficients to achieve accurate inequalities towards improvements of road vehicle safety. All this with a focus on impact energy absorbed as a basis of crush severity in full frontal vehicle accidents.

In 2017, Kodsi [7] developed a review of impact force crush coefficients. Form his review it is clear that the crush severity is proportionate to energy equivalent speed (EES) at the time of crush. That both the impact force and EES have an influence on the work done in vehicle dame as evident from work-energy principle. This work done can be equated by characterization of dynamic force deflection properties earlier mention by Campbell [3].

This research aimed at developing a mathematical model based upon analysis of impact energy absorbed and K.E gained by a moving vehicle for further research work in advancement of road vehicle transport safety. The study shows the relationship between impact speed and force on vehicle damage and use the findings to analysis impact energy as a basis of crush severity based on vehicle crash dynamic parameters discussed in Kudlich-Slibar model.

1.1 Problem Statement and Objectives

Advancements in vehicle technologies has caused a tremendous decrease in structural worthiness of vehicles. In return, it has affected vehicle safety when impact energy and crush severity in frontal impact collisions is considered. This is regardless of new vehicle technologies employing crush zones and vehicle bumpers to improve occupant safety. Furthermore, accidents are prone to occur over a broad range of crush severities due to the limitations of existing methods in vehicle transport safety. Besides, it has been noted that crush severity during collisions is greatly influenced by the initial amount of impact energy before an impact. Hence at elevated vehicle speeds, large amounts of kinetics energy is generated which results in high degree of crush severity in frontal impacts vehicle collisions.

This study aims at applying mathematical principles in analysis of impact energy as a basis of crush severity in full frontal impact accidents. Work-energy theorem and impulse momentum theorem will be reviewed towards decisive modelling and conclusive results.

2 Literature Review

Crush severity during collisions has been scientifically related to the amount of energy absorbed and EES in inelastic effects [2]. Through technical research and crash tests experiments, there is a linear relationship between speed and deformation magnitude. The degree of deformation is thought to be crush severity inflicted during vehicle damage [3].

Campbell [3] findings of 1974, gave a series of results on frontal and rear impacts. The summary of his findings concluded on two crush coefficients b_0 and b_1. His approach has since then been exploited using crash algorithms like Simulation Model of Automobile Crash (SMAC) and Computer Reconstruction of Automobile Speeds on the Highways (CRASH) amongst others to further discussions on accident reconstruction.

According to Neptune [9], car crash test experiments have shown that vehicle collisions occur in any imaginable combination of parameters namely: speed, impact angle, vehicle structure, motion sequence and other vehicle dynamics. These variables contribute to scientific analysis of vehicle crashes.

Furthermore, for effective analysis of impact energy as a basis of crush severity, the focus should be on the impact speed, related to the crush coefficients as proposed by Campbell [3].

In 2009, Vangi [12] argues out that the best approach to analyse impact energy is to conduct several crash tests simulating real world events. From which crush severity can be profiled. He further conclude that the available evidence for determining the crush magnitude is the collision severity resulting from energy absorbed. This energy is an equivalent of K.E with respect to car crash dynamics of Kudlich-Slibar model.

Several authors have suggested the desirable manner in which to rate the vehicle damage to an existing test condition e.g. barrier impact approach Vangi [12]. The barrier impact tests involves vehicle having same EES subjected to several crash tests. Assuming same energy per unit width is absorbed. This energy is then analysed based upon the dynamic force-deflection characteristics of the vehicle body structure in inelastic deformation to establish a viable judgement.

In 2001, Fay [4] proposes that the absorbed energy can be described with respect to restitution, and energy per unit width formulation so as to equate the energy to vehicle specific crush constants.

2.1 Automobile Crash Tests

In its simplest for, crash test can be simulated using computer crash algorithms or using real world experiments. Where a bullet vehicle is propelled on a barrier (either fixed or deformable) at a known speed and measuring the crush severity suffered by the vehicle body structure. This is illustrated in Fig. 1 of crash test experiment by National Highway and Transport Safety Authority (NHTSA) of the United States of America. This is an Authority which focuses on improvement of vehicle transport safety among other highway regulations through crash tests experiments and simulations.

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Fig. 1. Full frontal impact test (NHTSA-USA, 2018)

The findings from these tests indicate a speed band of between 40 kmh^{-1} to 65 kmh^{-1} to have serious crush severity. This calls for a need to estimate an average crush profile in accidents towards a viable proposed safety measure.

2.2 Estimation of Crush profile

In 2001, Fay [4] suggests that the best approach to estimate the average crush is using mathematical formulae for non-uniform area geometry. In his approach, individual crush zones are summed up to give the average crush profile that can be used to estimate the impact energy absorbed in inelastic effects. Knowledge of this will assist in modelling constitutive equations towards relating the energies involved in vehicle damage for full frontal impact tests.

3 Theoretical Considerations

Virtual CRASH (vCRASH) software uses momentum-based impact model that relies on restitution instead of vehicle stiffness coefficients. This model is adopted for most crash simulation algorithms and was first described in Kudlich-Slibar model [11]. In this model, the user can calculate full impacts and sliding impacts. The model defines impact in two phases namely: compression phase and the restitution phase. At the end of compression phase, the velocities of vehicles at the impulse point are said to be identical for full impacts. The vehicles separate due to elasticity of the vehicle structures, this is called restitution, e. The value of restitution from Kudlich-Slibar model is explained as the ratio between the restitution impulse and compression impulse, Prochowski [10]. This is called Poisson-restitution, which allows the restitution to be defined between $-1 \le e \le 1$, in vehicle crash simulations software. A positive value defines fully elastic effect, a negative value defines a state of no common velocity and a zero value defines fully inelastic effect.

The study further employs the work energy principle in the analysis of full frontal vehicle damage. The dynamic force deflection characteristics of the vehicle structure are analysed so as to estimate the energy absorbed. Using classical mechanics definitions of work and energy; it is seen that work done is a function of energy expressed in terms of force acting on an object in a given displacement. Equation (1) expresses this relationship.

$$w = Fs\cos\theta \qquad (1)$$

In vehicle damage, this energy is investigated as crush energy inflicting crush severity. The force, F can be defined from Newton's second law, this yields (2).

$$w = ma \cdot s\cos\theta \qquad (2)$$

$$F = ma \qquad (3)$$

Where: θ is the impact angle, s is displacement, m is vehicle mass and a is vehicle acceleration.

4 Methodology and Data

Using vCRASH software, fixed barriers were modelled with dimension 5 m x 2.5 m x 3 m. Vehicle models were designed based on sampled data of Campbell [3] experiments for validation. The selected vehicle models are provided in Table 1.

TABLE 1
SAMPLED VEHICLE MODELS

	Chevrolet crew cab silverdo 2003-7	Chevrolet blazer LS 2000	Chevrolet corvette C6-Z06
Curb weight (kg)	2485	1825	1420
Gross weight (kg)	4173	2426	1598
Payload (kg)	1687	601	169
Width (m)	2	1.71	1.84

Initial crash parameters were input from the vCRASH set up panel of Fig. 2. This included pre-impact speed, yaw angle, motion sequence and steering input. These parameters are described in details scope of vehicle crash dynamics.

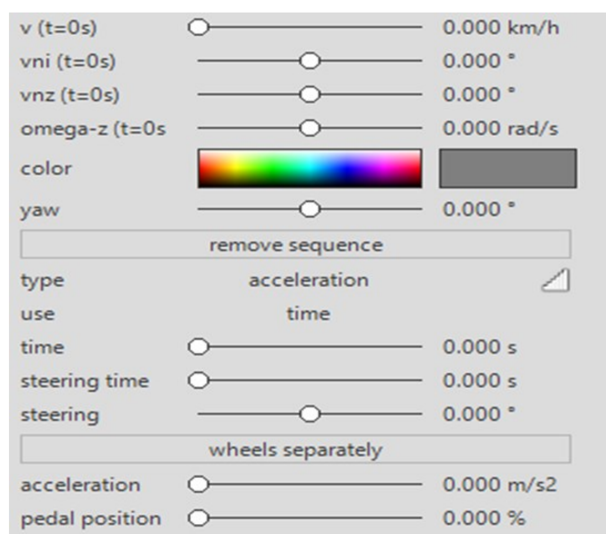

Fig. 2. vCRASH crash setup panel

So as to configure with Kudlich-Slibar model, the simulation sequence set the value of restitution and friction coefficient as provided in Fig. 3. The values describe the momentum-based impact model of car crash analysis using computer algorithms.

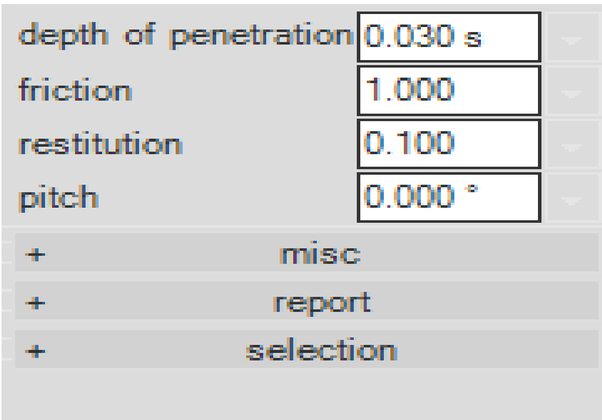

Fig. 3. vCRASH crash analysis constants

A series of crash tests was done for each vehicle model as in Fig. 4 and data was collected from vCRASH data panel for analysis and discussion as presented from tables (Table 2 to Table 10).

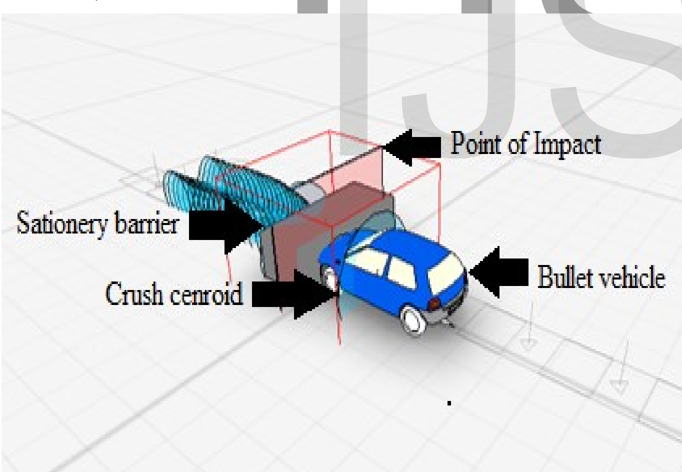

Fig. 4. Simulated Car crash using vCRASH suite

TABLE 2
IMPACT SPEED DATA FOR CHEVROLET BLAZER LS 2000

Crash test	Impact speed (ms^{-1})	Cush severity (m)
1.	5.510	0.170
2.	9.790	0.175
3.	8.063	0.236
4.	9.558	0.278
5.	10.633	0.307
6.	12.324	0.344
7.	13.497	0.426
8.	14.087	0.431

TABLE 3
IMPACT SPEED DATA FOR CHEVROLET CORVETTE C6 Z06

Crash test	Impact speed (ms^{-1})	Cush severity (m)
1.	6.153	0.174
2.	6.790	0.179
3.	8.060	0.240
4.	9.558	0.292
5.	10.632	0.311
6.	12.324	0.352
7.	13.495	0.435
8.	14.085	0.440

TABLE 4
IMPACT SPEED DATA FOR CHEVROLET CREW CAB SILVERDO 2003-7

Crash test	Impact speed (ms^{-1})	Cush severity (m)
1.	6.140	0.210
2.	6.788	0.250
3.	8.015	0.310
4.	9.544	0.311
5.	10.624	0.381
6.	12.316	0.422
7.	13.487	0.505
8.	14.077	0.510

TABLE 5
CRUSH ENERGY DATA FOR CHEVROLET BLAZER LS 2000

Crash test	Crush energy (Joules)	Cush severity (m)
1.	206.649	0.170
2.	253.013	0.175
3.	300.154	0.236
4.	355.750	0.278
5.	395.752	0.307
6.	458.714	0.344
7.	502.265	0.426
8.	525.224	0.431

TABLE 6
CRUSH ENERGY DATA FOR CHEVROLET CORVETTE C6 Z06

Crash test	Crush energy (Joules)	Cush severity (m)
1.	233.336	0.174
2.	257.779	0.179
3.	305.808	0.240
4.	362.452	0.292
5.	403.207	0.311
6.	467.356	0.352
7.	511.726	0.435
8.	543.105	0.440

TABLE 7

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CRUSH ENERGY DATA FOR CHEVROLET CREW CAB SILVERDO 2003-7

Crash test	Crush energy (Joules)	Cush severity (m)
1.	226.383	0.210
2.	250.240	0.250
3.	296.929	0.310
4.	357.764	0.311
5.	391.550	0.381
6.	453.868	0.422
7.	497.013	0.505
8.	518.750	0.510

TABLE 8
IMPACT FORCE DATA FOR CHEVROLET BLAZER LS 2000

Crash test	Impact force (N)	Cush severity (m)
1.	120827.60	0.170
2.	123784.93	0.175
3.	159864.38	0.236
4.	184705.98	0.278
5.	201858.50	0.307
6.	223742.76	0.344
7.	275200.35	0.426
8.	272243.01	0.431

TABLE 9
IMPACT FORCE DATA FOR CHEVROLET CORVETTE C6 Z06

Crash test	Impact force (N)	Cush severity (m)
1.	147576.71	0.174
2.	150914.59	0.179
3.	191636.69	0.240
4.	226350.61	0.292
5.	239034.55	0.311
6.	266405.14	0.352
7.	321813.90	0.435
8.	325151.78	0.440

TABLE 10
IMPACT FORCE DATA FOR CHEVROLET CREW CAB SILVERDO 2003-7

Crash test	Impact force (N)	Cush severity (m)
1.	256884.64	0.210
2.	301945.88	0.250
3.	369537.75	0.310
4.	370664.28	0.311
5.	449521.46	0.381
6.	495709.23	0.422
7.	589211.31	0.505
8.	594843.97	0.510

5 DATA ANALYSIS AND DISCUSSIONS

The study concluded an overall relationship between impact speed and crush severity to be a linear form in (4). This is depicted from the graph of Fig. 5 using sampled test data for Chevrolet Blazer LS 2000. The graph is in clear agreement with the studies by McHenry [8] and Campbell [3]. Further analysis showed the comparison of the crush coefficients for the different vehicle models used as provided in Table 11. It is a clear indication from the findings that crush severity, which is a measure of vehicle damage increases with increase in vehicle speed. Depending on the vehicle body structure the energy absorbed was affected as per kinetic energy gained.

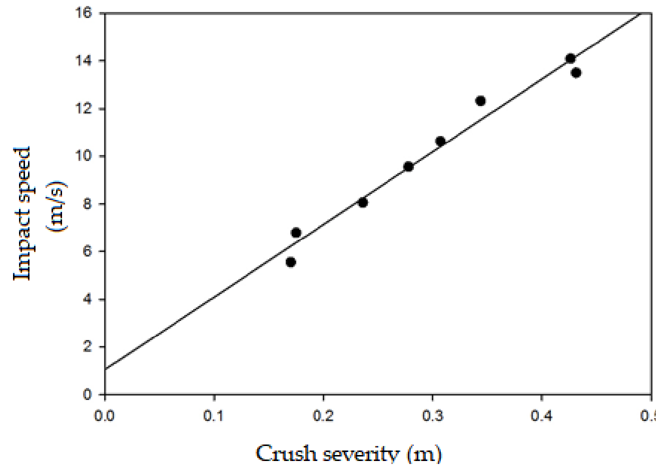

Fig. 5. Impact speed versus crush severity for Chevrolet Blazer LS 2000

From Fig. 5, a conclusive summary was made for all vehicle models in terms of impact speed, crush severity and crush coefficients as given in (4).

$$v = b_0 + b_1 C \quad (4)$$

Where v is impact speed (m/s), C is the crush severity (m), b_0 is the y-intercept in ms^{-1} and b_1 is the slope of the graphs in ms^{-1}/m. The intercept b_0 is taken as the vehicle speed which produces no crush severity. From the test conducted, there was no data included at speeds below the y-intercept point. The values are obtained using graph extrapolation feature of the analysis software used. The slope, b_1 is taken to represent the preciseness of sampled data.

TABLE 11
VEHICLE SPECIFIC CRUSH COEFFICIENTS

Vehicle model	b_0 (ms^{-1})	b_1 (ms-1/m)	Crush severity (m)
Chevrolet Blazer LS 2000	1.05	30.48	Varies with Impact speed magnitude
Chevrolet Corvette C6-Z06	1.36	28.90	
Chevrolet Crew cab- Silverdo 2003-7	0.48	26.62	

Using the stated model in (5), the study analysed crush energy per unit width from the impact energy absorbed. This yields a constitutive equation as in (6) for a linear graph model of Fig. 6.

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$$K.E = E_C = \frac{1}{2}(1-e^2)\cdot m \cdot v^2 \quad (5)$$

$$E^* = \sqrt{\frac{2E_C}{w_0}} = d_0 + d_1 C \quad (6)$$

Where v is the impact velocity in (4), e is restitution (e = 0), m is the vehicle mass, E_C is kinetic energy gained, which is converted to impact energy at time of crush (or crush energy), E^* is the crush energy per unit width, w_0. The coefficients d_0 and d_1 are vehicle specific crush stiffness values.

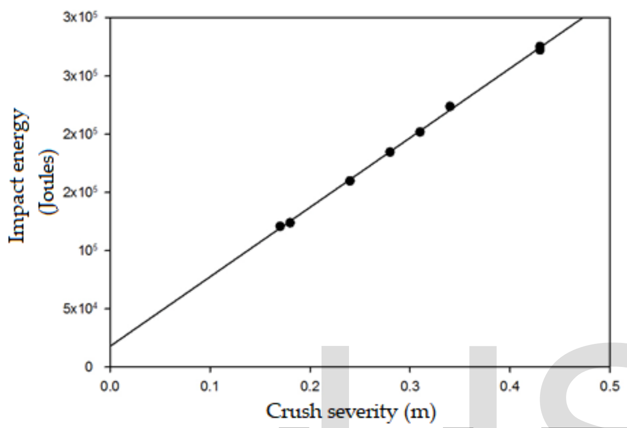

Fig. 6. Crush energy versus crush severity for Chevrolet Blazer LS 2000

From Fig. 6, a conclusive summary was made for all vehicle models in terms of crush energy, crush severity and crush coefficeints as given in (6).

Applying differential calculus we can redefine acceleration stated in (3) to be as shown in (7).

$$a = \frac{d}{dt}\cdot\frac{dx}{dt} = v\left[\frac{d}{dx}\cdot\frac{dx}{dt}\right] = v\cdot\frac{dv}{dx} \quad (7)$$

Taking model (4) and we can substitute b_1 as shown in (8).

$$b_1 = \frac{dv}{dx} = \frac{dv}{dC} \quad (8)$$

Assuming a uniform crush profile in a full frontal impact collision, the study estimated the total energy absorbed as given in (9) using work energy principle:

$$E_a = m[(b_0 + b_1 C)b_1]\cdot s\cos\theta$$
$$E_a = [mb_0 b_1 + mb_1^2 C]\cdot s\cos\theta \quad (9)$$

Where E_a is absorbed energy in vehicle damage, s is the displacement of impact force. Θ is taken as the steering input angle during crash test simulations. Where (Θ = 0°) in this study.

$$F = mb_0 b_1 + mb_1^2 C \quad (10)$$

From (9), the energy absorbed in vehicle damage is influenced by an impact force defined in terms of crush parameters b_0 and b_1 and vehicle mass in (10). Using the model in (10), force-deflection characteristics per unit width for full frontal impact collisions were analysed as given in (11).

$$F = \frac{m}{w_0}\left[b_0 b_1 + b_1^2 C\right]$$
$$A = \frac{m}{w_0} b_0 b_1$$
$$B = \frac{m}{w_0} b_1^2 \quad (11)$$
$$G = \frac{A^2}{2B}$$

The A stiffness coefficient represents the beginning of damage threshold i.e. the maximum force per unit width that can be sustained without producing any permanent crush. The B stiffness coefficient is the relatively linear relationship between the force and the amount of permanent crush. It is also the ratio of force per unit width of the contact area to the crush severity

Equation (11) was used to find a new set of data for impact force in the respective crash tests performed on the three vehicle models. The data was recorded as shown in Table 8 to Table 10. This data was analysed and graphs plotted using SigmaPlot® 14.0 data analysis tool. The graphs obtained were used to model the total impact energy profile absorbed by the vehicle structure with regards to crush stiffness coefficients A, B and G. The general finding was a linear model of graph in

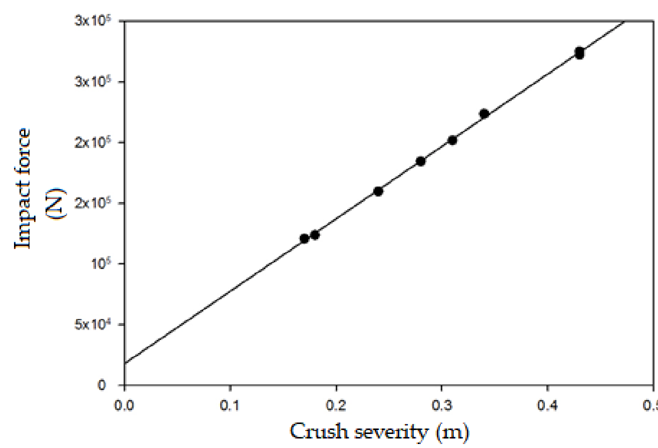

Fig. 7.

Fig. 7. Impact force versus crush severity for Chevrolet Blazer LS 2000

From Fig. 7 a conclusive summary was made for all vehicle models in terms of impact force, crush severity and crush coefficients as given in (12).

$$F = A + BC \quad (12)$$

The coefficients A and B are as discussed for the model in (11). The area under the graph of Fig. 7 gives the estimated energy absorbed over integral of width for full frontal impact vehicle damage. This is given as the model in (13).

$$E_a = w_0\left(AC + \frac{BC^2}{2} + \frac{A^2}{2B}\right) \qquad (13)$$

E_a defines the total crush energy absorbed. It as a function of crush stiffness coefficients (force-deflection characteristics), damage width, w_0 and crush severity, *C*. This is the reference equation without considering the angle of impact. It can be directly applied in computations provided the crush damage is assumed to be uniform along the whole damage width.

From the theory and models developed, it is found that the energy transferred can be expressed as the total work done in full frontal impact vehicle damage. Which is simply the total area under the force-characteristics curve. This energy is absorbed by the body structure during vehicle accidents. Where this energy is equated to kinetic energy gained as given in (5).

From accident reconstruction analysis, *C* is the only available measure of vehicle damage. Therefore, by regulating the energy transferred during impact, crush severity can be monitored to sustainable levels. The research suggest hence forth that, since kinetic energy is a function of EES (a dosage of crush severity); a proper relation of K.E against the sustainable crush severity magnitude will at any time ensure that E_a is maintained to limits that ensures relative vehicle damages during frontal impacts. This is achievable since crash tests are performed for vehicle model by different car manufactures during vehicle safety test prior to release to market. In which, data for vehicle specific safe speeds, crush coefficients constants and survival energy limits are recorded from these tests. Though not put into proper usage as far as road vehicle transport and safety is concerned.

The research incisively suggests the mathematical relation in (14) for regulation of energy transferred in frontal impacts accidents.

$$K.E \leq E_a \qquad (14)$$

Equation (14) is justifiable in essence that, vehicles come with different crash properties like vehicle weights, constants b_0, and b_1, A, B and G. Hence under same speed, for different vehicles, different kinetic energy will be recorded which has varying crush severity. So, if a mechanism is put in place that will ensure equivalent impact energy for recommended speeds is monitored across the board, then crush severity will reach the recommended threshold from the manufactures crash test database.

4 Conclusion

The need to advance vehicle safety has long been an important aspect in most studies. However, severe accidents are prone to occur due to the limitations of existing methods used to monitor road transport safety. Likewise the advancements in vehicle technologies has impacted structural compatibility of vehicle structures. Many variables exist in an event a car crashes e.g. impact energy, crush severity and EES. Vehicle caused during collisions is greatly influenced by the initial amount of kinetic energy before an impact occurs. This energy is transferred to the incident barrier by the bullet vehicle depending on the type of collision. It follows that for high impact velocity the greater the impact energy and this in return causes a high degree of crush severity or tissue trauma. Conventional road safety systems have limitations of monitoring the energy in a in a manner to limit speeds as evident from their operation principle which only relies on the set speed limit put in place by existing laws. The inability to monitor the impact energy implies a high degree of crush severity and hence great damage is caused during frontal impacts. The focus should be towards energy absorbed at time of crush as suggested from (14).

Assumption made during the study is that the crush damage is uniform across the width and has uniform depth. This scenario is not likely to occur and hence more research needs to be done to include the aspect of non-uniform crush magnitude C. The assumption was adopted for the purpose of deriving the possible theory and suggestions towards application of mathematical principles in the regulation of impact energy in full frontal impact vehicle accidents.

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