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Analysis of Impact Energy as a Basis of Collision Severity in Vehicle Accidents

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Abstract— Vehicle speed and mass play a major role on energy transferred during vehicle accidents. This energy is exhibited as kinetic energy (KE) and is significant in analysing the collision severity (deformation) during accident reconstruction. However, conventional road vehicle safety systems play little role in monitoring this energy. This leaves a gap when road safety and frontal impact energy are mentioned with regards to changes in vehicle structure dynamics and safety systems. Understanding the role of KE in relation to deformation will help come up with effective measures towards the generation, transfer and controlling effects of impact energy during vehicle road accidents. This study applies first principles to analyse impact energy in full frontal collisions. A focus is made on collision severity resulting from each crash test by applying vehicle accident reconstruction methods. Crash tests were simulated based on Kudlich-Slibar model of car crash analysis using Virtual CRASH® v4.0 suite. The software provides an interface to simulate and investigate full frontal, rear-end and side vehicle collisions. At first, impact barriers and vehicle samples were modelled. Thereafter, 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 (as a measure of collision severity), impact energy and impulse. Relationship between deformation magnitude versus impact energy, speed and impact force was established. Results were presented through graphs and equations models defined from physics first principles. The findings indicate the need to monitor vehicle speeds with a focus on impact energy factor based on monitored vehicle weights.

Index Terms— Impact energy, Speed adaptation, Vehicle accidents, axle load, Collision severity, Kinetic energy, Vehicle damage

1. INTRODUCTION

Classical mechanics qualifies mass and speed to have a significant role on the energy transferred during car collisions. This energy is exhibited as KE 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 only be achieved through understanding the role of KE in vehicle deformation, measures taken to reduce the generation, distribution and effects of energy absorbed on vehicle structure [6].

In 2001, Fleming [5] affirms that vehicle safety is an important consideration in vehicle road transport. So as to achieve this, he suggests to incorporate both active and passive safety systems in vehicles. 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 [1].

This project presents a simulated procedure towards analysis of impact energy absorbed in vehicle accidents; by placing a focus on generated collision severity and force deflection properties of energy absorbed. This is used to review descriptive relating inequality for vehicle specific speed profile adaptation. 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, vehicle deformation and the dynamic force-deflection characteristics of the body structure are the only available estimates of the energy transferred during inelastic effects in vehicle accidents [3]; [9]. 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.

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Studies have shown that during vehicle accidents, the KE from the bullet vehicle is transferred to the bodies involved to inflict collision severity taken as the deformation index. Therefore, from accident reconstruction science, there is need to assess the severity of crush pattern resulting to help come with possible safety measures in improvement of vehicle safety. With accident reconstruction, an analysis of collision severity based on measured deformation can be done and scientifically integrate vehicle crash dynamic parameters like crush coefficients to achieve accurate descriptive algorithms towards advancement of active safety systems. All this with a focus on impact energy absorbed as a basis of collision 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 deformation 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 mentioned by Campbell [3]; Berg *et al* [2].

This research aimed at developing a descriptive analysis of impact energy absorbed and KE gained by a moving vehicle for further research works in advancement of vehicle transport safety systems. The study acknowledges the relationship between impact speed and impact force on vehicle deformation. The findings are used in analysing impact energy factor as a basis of collision severity from crash dynamic parameters based on work-energy theorem and other first principles of physics as mentioned in the study.

1.1 Problem Statement and Objectives

Advancements in vehicle technologies have caused a tremendous decrease in structural worthiness of vehicles. In return, it has affected vehicle safety when impact energy and collision severity in frontal impacts 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 collision severities due to the limitations of existing methods used in vehicle transport safety. Besides, it has been noted that deformation during collisions is greatly influenced by the initial amount of impact energy before a collision. Hence at elevated vehicle speeds, kinetic energy is generated at high levels which results in high degree of collision severity at impact.

This study aimed at applying first principles in analysis of impact energy as a basis of collision severity in full frontal impacts. This includes work-energy theorem and impulse momentum principle which are reviewed towards decisive and conclusive results. The study forms a preliminary review on further work in this field.

2. THEORETICAL CONSIDERATIONS

vCRASH® suite 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 $-1 \leq e \leq 1$, 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 deformation and force deflection characteristics to estimate the energy absorbed during frontal impacts. 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.

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

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

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

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

Where: θ is the impact angle, s is displacement, m is vehicle mass and a as the acceleration (motion sequence).

3. METHODOLOGY AND DATA

Using vCRASH® suite, 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 as provided in Table 1.

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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® suite set up panel of Fig. 1. This included pre-impact speed, yaw angle, motion sequence and steering input. These parameters influence the crash simulation sequence as described by Schram [11].

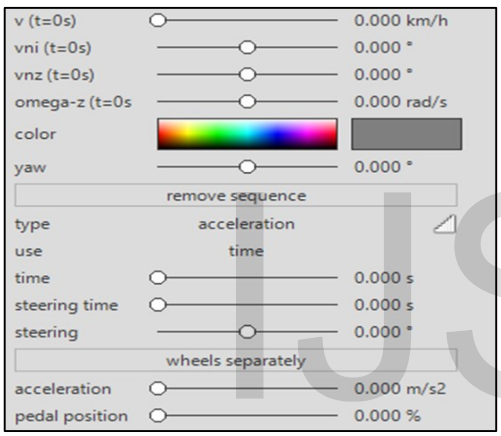

Fig. 1. vCRASH® suite parameters setup panel

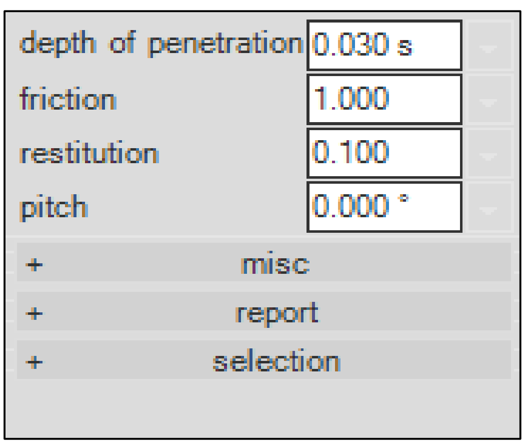

Fig. 2. vCRASH® suite crash analysis constants

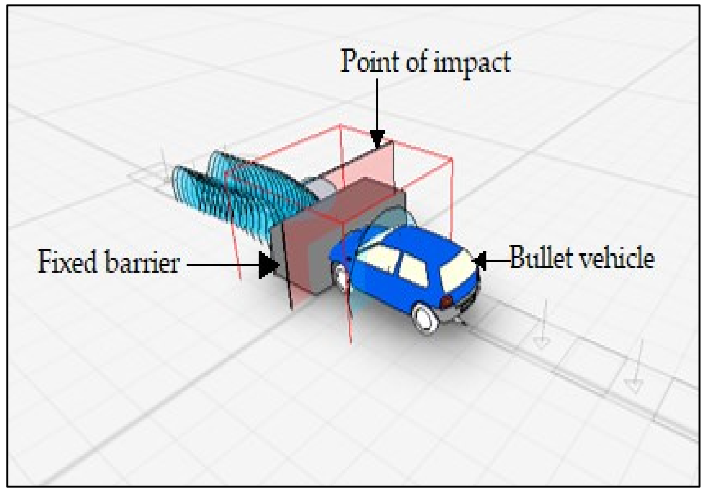

Fig. 3. Simulated Car crash using vCRASH® suite

So as to configure with Kudlich-Slibar model, the simulation sequence set the value of restitution, *e* and friction coefficient, μ as provided in Fig. 2. The values describe the momentum-based impact model of car crash analysis using computer algorithms. The depth of penetration, Δt, is taken as the contact time for a given collision phase.

Simultaneous crash tests were conducted for each vehicle model as in Fig. 3 using vCRASH® suite. Data was collected from vCRASH® data panel for analysis and discussion as presented in tables (Table 2 - Table 10).

TABLE 2
IMPACT SPEED DATA FOR CHEVROLET BLAZER LS 2000

Crash test	Impact speed (ms^{-1})	Deformation (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})	Deformation (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})	Deformation (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)	Deformation (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)	Deformation (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
CRUSH ENERGY DATA FOR CHEVROLET CREW CAB SILVERDO 2003-7

Crash test	Crush energy (Joules)	Deformation (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)	Deformation (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)	Deformation (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)	Deformation (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

4. DATA ANALYSIS AND DISCUSSIONS

The study acknowledged an overall relationship between impact speed and collision severity (deformation) to be linear as given in (4) and the graph of Fig. 4 from the simulated crash tests data. The graph is in clear agreement with the studies by McHenry [8] and Campbell [3]. Further analysis compared the crush coefficients for the different vehicle models used as provided in Table 11. It is a clear indication from the findings that deformation (a measure of collision severity) increases with increase in vehicle speeds depending on the vehicle body structure defined by the coefficients.

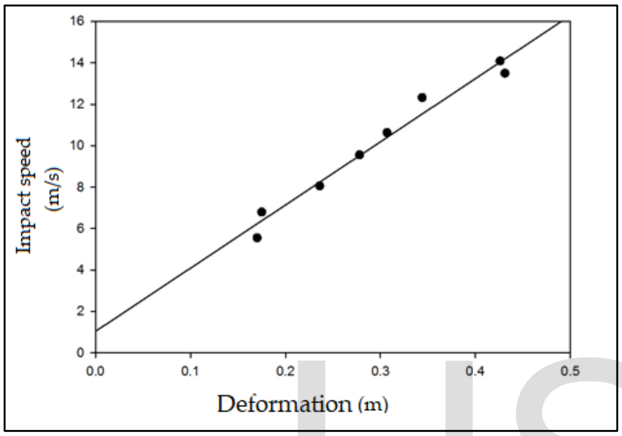

Fig. 4. Impact speed versus deformation for Chevrolet Blazer LS 2000

From Fig.3 a conclusive summary was made for all vehicle models in terms of impact speed, collision 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 deformation (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 deformation. 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	
Chevrolet Corvette C6-Z06	1.36	28.90	Varies with Impact speed
Chevrolet Crew cab- Silverdo 2003-7	0.48	26.62	

Using (5), the study investigated crush energy per unit width for each vehicle model based on (6) which illustrates a linear model given in Fig. 5.

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

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

Where v is the impact velocity in (4), e is restitution ($e = 0$), m is the vehicle mass, E_C is gain in kinetic energy which is transferred to impact energy at time of crush, E^* is the crush energy per unit width, w_0. The coefficients d_0 and d_1 are vehicle specific crush stiffness values which experimentally defines crush dynamics of the vehicle [12].

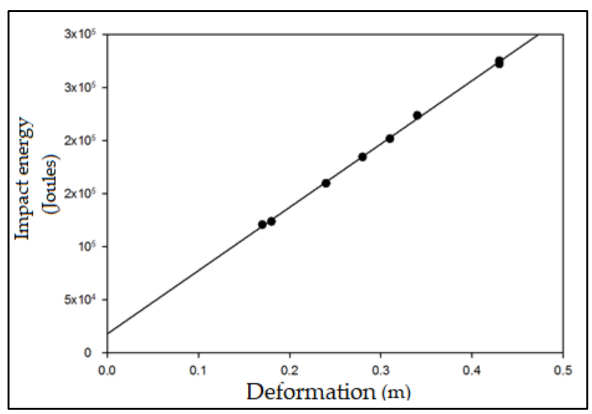

Fig. 5. Crush energy versus deformation for Chevrolet Blazer LS 2000

From Fig. 5, a conclusive summary was made for all vehicle models in terms of crush energy, collision severity and crush coefficients as given in (6).

Applying differential calculus we redefined acceleration as stated in (3) to (7).

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

Substituting (4) into crush constant b_1 we get (8). Which defines a derivative of *EES* with respect to deformation (Collision severity).

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

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

$$\begin{aligned} E_a &= m\left[(b_0 + b_1 C) b_1\right] \cdot s\cos\theta \\ E_a &= \left[m b_0 b_1 + m b_1^2 C\right] \cdot s\cos\theta \end{aligned} \quad (9)$$

Where E_a is absorbed energy in vehicle damage, s is the displacement of impact force which is taken as the deformation depth, C. θ is taken as the steering input angle during crash test simulations. Where ($\theta = 0°$) for this study, and it defines the angle of impact.

$$F = m b_0 b_1 + m b_1^2 C \quad (10)$$

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

$$\begin{aligned} F &= \frac{m}{w_0}\left[b_0 b_1 + b_1^2 C\right] \\ k_0 &= \frac{m}{w_0} b_0 b_1 \\ k_1 &= \frac{m}{w_0} b_1^2 \\ G &= \frac{k_0^{\,2}}{2k_1} \end{aligned} \quad (11)$$

The k_0 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 k_1 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 deformation.

From (11), a new set of data for impact force for the respective crash tests performed on the three vehicle models was modelled. The data was recorded as shown in Table 8 to Table 10. These 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 k_0, k_1 and G. The study concluded a linear relationship between impact force and deformation as given in Fig. 6.

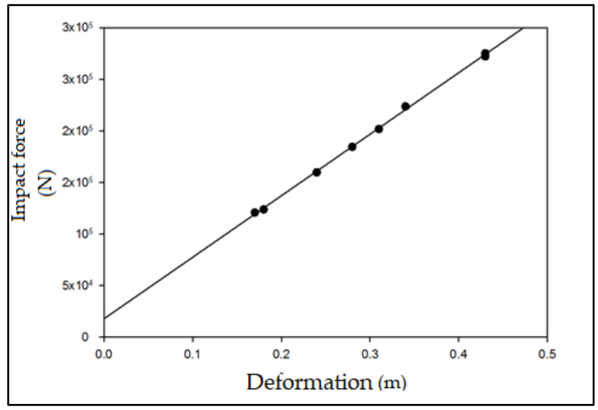

Fig. 6. Impact force versus deformation for Chevrolet Blazer LS 2000

From Fig. 6 a conclusive summary was made for all vehicle models in terms of impact force, deformation, C and crush coefficients as given in (12).

$$F = k_0 + k_1 C \quad (12)$$

The coefficients k_0 and k_1 are as discussed in the previous sections. The area under the graph of Fig. 6 gives the average impact energy absorbed over integral of width for full frontal impacts as given in (13).

$$E_a = w_0\left(k_0 C + \frac{k_1 C^2}{2} + \frac{k_0^{\,2}}{2k_1}\right) \quad (13)$$

E_a defines the average impact energy factor in full frontal impacts. It as a function of crush stiffness coefficients (stated as force-deflection characteristics), damage width, w_0 and collision 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 theoretical review and simulation analysis done, it was found that the energy transferred can be expressed as the total work done in an impact. Which is simply the total area under the force-characteristics curve. This energy is absorbed by the body structure during vehicle accidents and is equivalent to gain in kinetic energy given in (5).

From accident reconstruction analysis, deformation is the available measure of collision severity. Therefore, by regulating the energy transferred during impact, collision severity can be limited to admissible levels. The research suggest hence forth that, since kinetic energy is a function of EES (a dosage of collision severity); a proper relation of KE against the sustainable collision severity will at any time ensure that E_a is maintained to limits that ensures relative deformation 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 inequality given in (14) to be applied in development of speed adaptation algorithms. This will advance vehicle safety measures towards minimisation of collision severity during vehicle accidents.

$$KE \leq E_a \tag{14}$$

Equation (14) is justifiable in essence that vehicles come with different crash properties like vehicle weights, constants b_0, and b_1, k_0, k_1 and G. Hence under same speed, for different vehicles, different kinetic energy will be recorded which has varying collision severity. So, if a mechanism is put in place that will ensure equivalent energy speed for recommended impact energy factor is monitored across the board, then collision severity will reach the recommended threshold for each vehicle models categories.

5. CONCLUSION

Based on the findings it was concluded that:

1. Impact speed has a direct influence on the collision severity inflicted during full frontal impacts as given in [4].

2. Impact energy taken as a function of both vehicle speeds and vehicle weights monitored in real-time, directly influences the collision severity inflicted in full frontal impacts given in [6] and relates to gain in KE as shown in [5].

3. Impact energy can be estimated using force-deflection properties and deformation (collision severity) as defined in [14] for full frontal impacts.

4. Using the inequality given in [14], speed monitoring algorithms can be developed to ensure real time adaptation of vehicle speeds based on average impact energy factor, this will ensure admissible collision severity at impacts relative to vehicle models.

During the study, it was assumed that the crush damage profile was uniform across the vehicle width and has uniform depth. Though this scenario is not likely to occur and hence more research needs to be done to include the aspect of non-uniform crush magnitude.

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