Enhancing the Impact Attenuation Capacity of a Car Bumper with a Friction Damper using Simulation

A. Agyei-Agyemang, S. P. Owusu-Ofori, J. Antonio

Abstract— Crash phenomena involving road vehicles were investigated to develop an impact attenuation design that can withstand speeds higher than the current specified range of up to 4 km/h for a bumper. A passive friction element was introduced into the bumper system to improve on the attenuation capacity and the energy absorption. A mathematical model of the bumper-damper system was formulated and used to simulate impact phenomena for a 1900 kg mass moving at speeds up to 50 km/h (13.9 m/s).

The results showed that the addition of a friction element to a bumper-damper system with the new design parameters could improve its energy absorption capacity by about 103.6 kJ, that is about 146 %. It was also observed that the addition of the friction element to a traditional vehicle bumper could increase the critical design speed from 4 km/h (1.11 m/s) to 14.9 km/h (4.1 m/s). It was concluded that a passive friction damper system could be used to attenuate road vehicle impact energy in collisions (of vehicles of mass similar to that of a typical sedan car) at speeds 3 times higher than the speed for which current conventional bumpers are designed to attenuate (i.e. 4 km/h).

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Index Terms— Impact attenuation; friction damper; crash dynamics; car bumper; mathematical model; spring constant; damping coefficient; damping ratio, simulation.

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1 INTRODUCTION

Road crashes have serious impact on the world's economy. Road traffic injuries are ranked ninth globally among the leading causes of disease burden, in terms of Disability Adjusted Life Years (DALYs) lost (Odero, 2006). According to the American Automobile Association, road traffic accidents claim a life every thirteen minutes in the United States (Zheng, 2006) and four 4 lives daily in Ghana (Appiah, 2009).

The estimated direct economic cost of global road crashes is about US$ 518 billion (Peden et al., 2004). Over a million people die worldwide every year as a result of road traffic crashes. The loss in terms of human and material resources are huge and could be saved and used in development programs and projects to improve the quality of life. This is a cause for concern that needs to be addressed.

Friction Dampers have been used in seismic applications installed on special braces between adjacent floors in buildings to reduce seismic effects (Ruiz et al., 2005). In another application bracing system and the forces of friction developed at the interface of steel plates and friction pads tend to resist motion and thus protect against seismic effects of vibration (Mualla and Belev, 2002).

During a major earthquake, the friction dampers slip at a predetermined optimum load before yielding begins in other structural members, and they dissipate a good portion of the seismic energy to protect the buildings (Malhotra et al., 2004).

Friction dampers have been used in turbomachinery applications to provide mechanical damping to reduce resonance stresses (Sanliturk et al., 2001). In such applications dissipation of vibration energy into thermal energy starts when blade displacements reach a certain level (Petrov and Ewins, 2007). Relative displacements between the blade platforms and the friction damper generate friction forces to dissipate energy as desired (Panning et al., 2003). In yet another design, a blade-to-ground design, dissipation of energy is realized by placement of dry friction dampers between the blades and the cover plate (Ciğeroğlu and Özgüven, 2006).

To protect the occupant of a vehicle in a crash the vehicle must be crashworthy. Crashworthiness is a measure of the occupant protection offered by a vehicle (Brideson et al., 2001). Vehicle components like front side rails, rear rails, door structure and

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- *Dr. Anthony Agyei-Agyemang, Mechanical Engineering Department, Kwame Nkrumah University of Science and Technology Engineering St. Block 1, Kumasi, Ghana E-mail: tonyagyemang@yahoo.com; tonyagyemang@knust.edu.gh Tel: +233-24-4375816*
- *Prof. Samuel P. Owusu-Ofori, Department of Mechanical Engineering North Carolina Agricultural and Technical State University, 1601 E. Market Street, Greensboro, NC 27411, USA Tel: +1 3363347620 E-mail: ofori@ncat.edu*
- *Dr. Jerome Antonio, Department of Mechanical Engineering North Carolina Agricultural and Technical State University, 1601 E. Market Street, Greensboro, NC 27411, USA E-mail: koklovi2001@yahoo.co.uk*

pillars undergo considerable amounts of deformation to assist in mitigating the effects of impact in a crash (Nripen, 1993). Witteman proposed a concept for energy absorption to mitigate effect of vehicle collision by axial friction through an applied normal force (Witteman, 2005). One of the major components of good bumper design is effective energy absorption (Aylor et al., 2005).

The use of impact sensors and exterior airbags to reduce effects of road traffic crashes (Schuster, 2004) has been investigated. A more reliable way of checking this effect is the use of attenuation systems that require no external energy. They are considered as passive systems (Lametrie, 2001). In this study the use of a passive friction damper is considered

2 OBJECTIVES

The mission of this road safety research is to minimize the effects of road crashes when they happen. The aim is to reduce the effect of crash impact on both the vehicle and the passengers in collision of vehicles traveling at medium speeds (40 km/h to 50 km/h).

Automobile bumpers are designed to withstand impacts at about 4 km/h. This corresponds to rolling impact and it would be beneficial to improve upon this design criterion. Three major components of good bumper design that are lacking on many current passenger vehicles are compatible geometry, stability during impacts, and effective energy absorption (Aylor et al., 2005). This study aims at improving the effective energy absorption capacity of the bumper.

The specific objectives are to:

i. Improve automobile bumpers to enable them withstand impact energy of vehicles traveling at several times the speeds conventional bumpers are designed for.
ii. Model and simulate impact phenomenon in order to study crash dynamics.
iii. Use information from the simulation to generate design parameters for better impact attenuation bumpers.

3 METHOD

In an effort to absorb and dissipate as much energy as possible with the bumper in crash at elevated speed, the use of coulomb friction damper is proposed. The Kelvin model (Fung and Tong, 2001) was modified by adding a friction element to aid in more energy dissipation. Figure 1 shows a diagram of the proposed model. The applied friction from the friction element in this model is done by controlling the normal force applied on the friction damper.

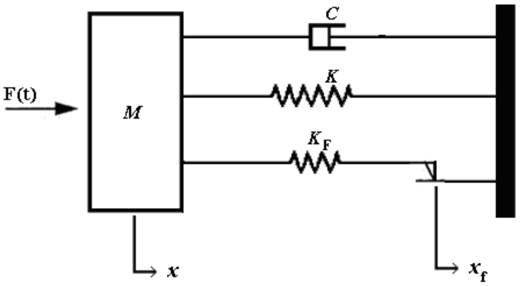

Fig. 1. Schematic of the Bumper with Friction Damper Model

The mathematical model of the bumper-damper system is

$$M\ddot{x} + c\dot{x} + kx + f_f = F(t) ----1$$

where f_f

is the force due to the friction damper and can be written as

$$f_f = k_F(x - x_f) --------2$$

or as

$$\mu_f F_N = k_F(x - x_f) -----3$$

where F_N is the normal force on the friction damper and μ_f is the coefficient of friction of the friction surface of the friction damper.

In this model the external excitation force *F(t)*, which is the impact force, is the input in the system and the vibration amplitude is the output of the system. The aim is to reduce this output response amplitude to a minimum through energy dissipation. The amount of energy dissipated can be controlled by an appropriate choice of the normal force or coefficient of friction acting on the friction surfaces. Damping in this model occurs when there is no relative displacement and there is sticking friction.

The Kelvin model (Fung and Tong, 2001) was modified and used to model and simulate the behavior of a road vehicle bumper. Equation 1, which is an equation of a modified Kelvin's model, had to be solved to give the displacement, velocity and acceleration information for further analysis. The solution of the displacement, velocity, and acceleration responses were found numerically using VisSim™ software, an easy-to-use dynamic simulation and model-based system development software (VSI, 2012). MATLAB™ software was used for the post processing of the simulation results.

The effect of a friction element on the displacement of the 1900 kg moving mass was studied. Different friction elements were introduced, and simulations performed using a bumper-damper system with material stiffness k of 542.7 kN/m, and damping coefficient c of 11.5 kN.s/m. Starting with friction force of 0 kN and increasing it steadily up to 228 kN, simulation was performed to record the displacement responses using different impact velocities.

4 RESULTS AND DISCUSSION

4.1 Deformation and Velocity

The results of the simulation for deformation are shown in Figure 2.

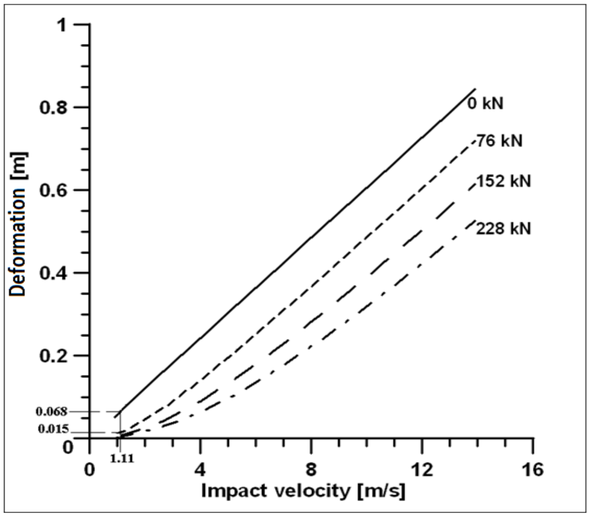

Fig. 2. Deformation for different Friction Elements.

It was observed that the deformation reduced with the introduction of the friction element. For example an impact velocity of 1.11 m/s results in a displacement of nearly 68 mm without a friction element, but 15 mm for an element introducing friction force of 76 kN, and no displacement at 228 kN or higher. For the friction damper to function properly, it is desirable for it to have no displacement. The displacement response can produce a design threshold criterion which, in this case, was 228 kN.

The impact forces, F_i for the moving mass were calculated using the impact velocities, V_i. That is $F_i = m.dV_i/dt$. The plot of the impact force against the deformation is shown in Figure 3. In the plot, F_d is the friction force from the friction damper. It is observed that the higher the impact force the higher the deformation, which must be the case. However, for the same impact force used, the higher the friction force from the friction element the lower the deformation.

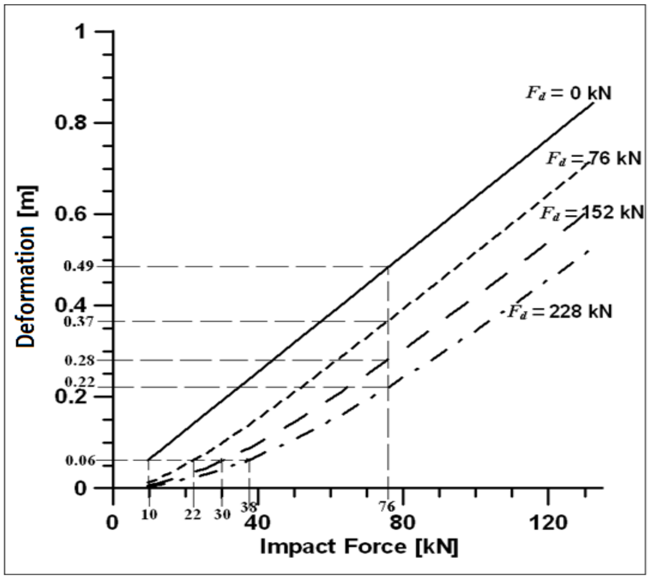

Fig. 3. Deformation of Bumper for different Impact Forces using Different Friction Elements.

The plot shows that without the friction damper the attenuation system will experience a deformation of 0.06 m (60 mm) at an impact force of 10 kN. With the introduction of a friction damper, the impact force that would cause the same deformation increases. This plot also confirms a threshold friction force of 228 kN at which no deformation results. It is desirable to obtain a relationship between the impact force and the deformation as a means to obtain the threshold impact force for a given set of system characteristics.

The threshold friction force of 228 kN was obtained using system parameter of k = 542.7 kN/m and c = 11.5 kN-s/m. It is of interest to study the effect of k and c (bumper properties) on the threshold impact velocities and how the threshold friction force improves the threshold of the impact velocity. Figure 4 shows the effect of the impact velocity on the threshold friction force. The plot shows that for a given set of material characteristics, the impact velocity greater than 4.13 m/s will cause the friction damper to fail. It is also observed that the threshold friction force of 228 kN introduced could improve the performance of the design material R from an impact velocity of 1.11 m/s (4 km/h) to 4.13 m/s (14.9 km/h).

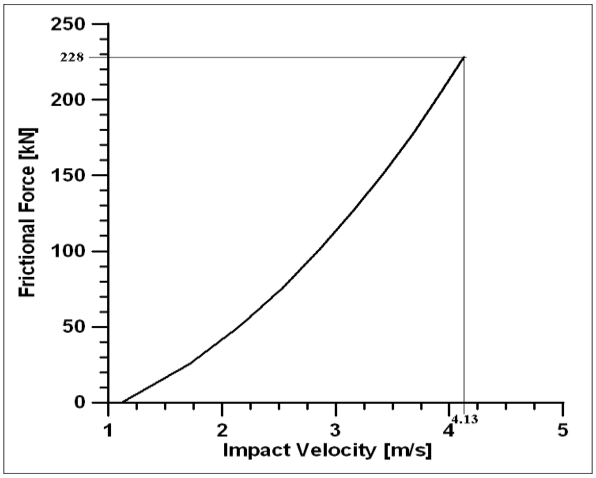

Fig. 4. Impact velocity and corresponding Friction Force necessary to produce a deformation of 68 mm for the Material *R*.

Simulations were performed for each of the remaining four design materials and the threshold impact velocities at the threshold friction force 228 kN recorded. Similar trend of results were obtained for the different design materials. Table 1 shows the threshold impact velocities and other information for different bumper material properties; referred to as new design material D1 through D4. The table gives the spring constants *k*, damping coefficients *c*, damping ratios ζ used and the threshold impact velocities v_t; ($\zeta = \frac{C}{2\sqrt{kM}}$, where *M is* the mass; *M* = 1900 kg). The results in Table 4.1 are plotted in the 3-D diagram in Figure 5.

TABLE 1
BUMPER DESIGN MATERIAL PARAMETERS (MASS = 1900 KG)

Bumper	Spring Constant, *k* [*kN*/*m*]	Damping Coefficient, *c* [*kN-s*/*m*]	Damping Factor, ζ	Threshold Impact velocity v_t [m/s]
Design Material R	542.7	11.5	0.1791	4.13
Design Material D1	750.0	13.5	0.1788	3.80
Design Material D2	850.0	14.0	0.1742	3.68
Design Material D3	400.0	6.5	0.1179	4.59
Design Material D4	300.0	6.0	0.1257	4.97

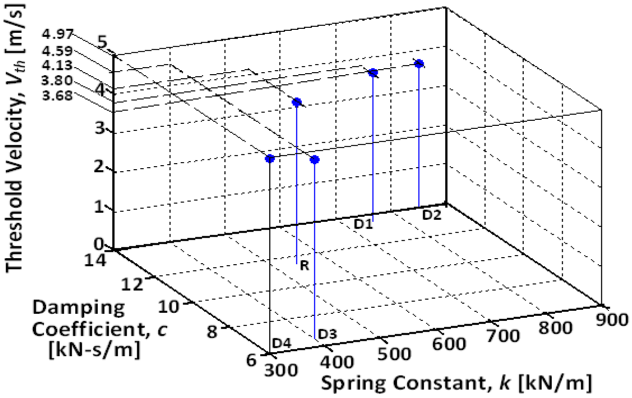

Fig. 5. Threshold Impact Velocities for various Bumper Material Characteristics

Intuitively, one would believe that the threshold impact velocity would increase as the bumper material stiffness (*k*) and damping coefficient (*c*) increase for the same mass. The design materials D1 and D2 represent increases in *k* and *c*. The simulation results shown in Fugure 5 and Table 1 indicate that the threshold impact velocity rather decreases from 4.13 m/s to 3.80 m/s and 3.68 m/s respectively. The design materials D3 and D4 were selected to study the effects of decreasing *k* and *c*. The responses show that the threshold impact velocity increases from 4.13 m/s to 4.59 and 4.97 m/s respectively, which is the desirable result. The results indicate that the friction element is more effective for materials with lower viscoelastic properties.

4.2 Work done

The work done by bumpers of different design materials studied were deduced from plots of impact force against the displacement for the bumpers for different friction elements. Figures 6 to 8 show plots of impact force against the displacement responses for the five design materials for different threshold friction forces. Figure 6 shows the displacement responses using no friction element, Figure 7 shows the responses using a friction element with 152 kN friction force and Figure 8 shows the responses using a 228 kN friction element. The work done by the bumper materials for the same amount of deformation was calculated for each case. A common deformation was used for all cases to compare the work done. A deformation of 0.3 m was used. The work done was found by calculating the relevant areas in the plot. For example, the work done by the bumper material D4 is given by the shaded area in Figure 6 and similarly in Figures 7 and 8.

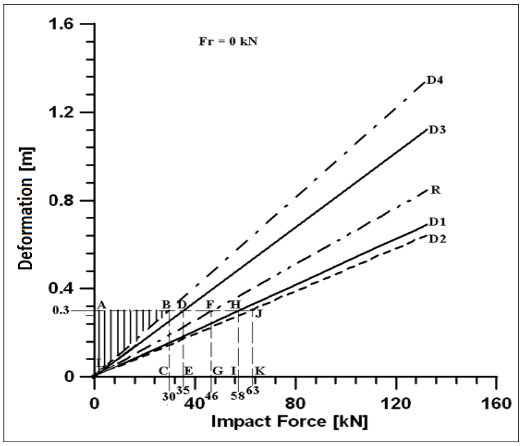

Fig.6. Maximum deformations of five Bumper materials at different Impact forces without a friction Element

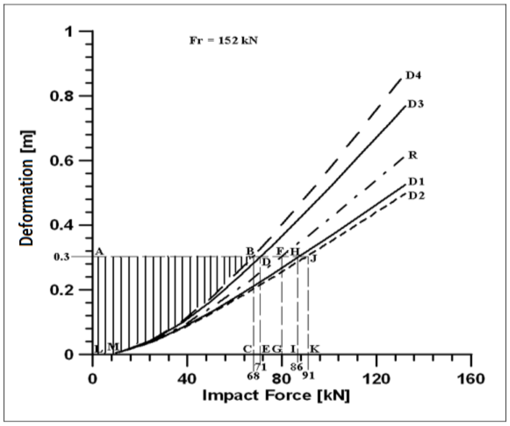

Fig. 7. Maximum deformation of five bumper materials at different Impact Forces with 152 kN Friction force from a Friction element

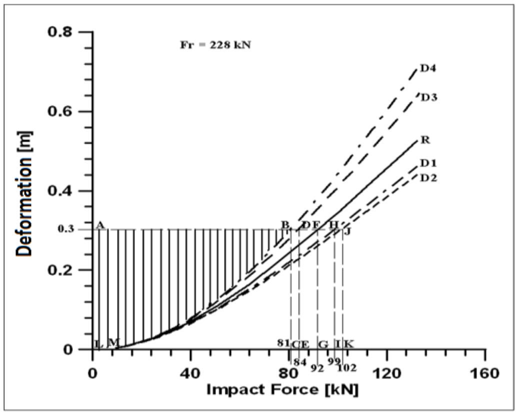

Fig. 8. Maximum deformation of five Bumper materials at different Impact Forces with 228 kN Friction Force from a Friction Element

The results of the calculations of the work done are given in Table 2.

TABLE 2

WORK DONE BY DIFFERENT BUMPER DESIGN MATERIALS

Friction Force from Friction Element [kN]	Work Done by Materials [Joules]				
	R	D1	D2	D3	D4
0.0	7050	8640	9260	5310	4430
152.0	14800	15750	16140	13680	13360
228.0	17410	18270	18610	16370	16100

The work done by materials D1, D2, D3 and D4 were compared with that done by material R. The work done by material R without a friction element was subtracted from those by all the other materials to determine how much more work was done by the other materials above that done by the material R with no friction element. The results of the comparison are given in Tables 3 and 4.

TABLE 3

EXTRA WORK DONE BY DIFFERENT BUMPER DESIGN MATERIALS COMPARED WITH THAT DONE BY THE DESIGN MATERIAL R WITHOUT A FRICTION ELEMENT

Friction Force from Friction Element [kN]	Extra Work done by Bumper Design Materials [Joules]				
	R	D1	D2	D3	D4
0.0	0	1590	2210	-1740	-2620
152.0	7750	8700	9090	6630	6310
228.0	10360	11220	11560	9320	9050

TABLE 4

PERCENTAGE EXTRA WORK DONE BY DIFFERENT BUMPER DESIGN MATERIALS COMPARED WITH THAT DONE BY THE DESIGN MATERIAL R WITHOUT A FRICTION ELEMENT

Friction Force from Friction Element [kN]	Extra Work done by Bumper Design Materials [%]				
	R	D1	D2	D3	D4
0.0	0.00	22.55	31.35	-24.68	-37.16
152.0	109.93	123.40	128.94	94.04	89.50
228.0	146.95	159.15	163.97	132.20	128.37

Another comparison with work done by the materials with and without a friction element was made. The work done by the materials without a friction element was compared with that done by the same material with a 152 kN and 228 friction elements respectively. The results are given in Tables 5 and 6. Table 5 gives the difference in Joules while Table 6 gives the difference as a percentage of the work done without a friction element.

TABLE 5

EXTRA WORK DONE BY DIFFERENT BUMPER DESIGN MATERIALS AS RESULT OF THE INTRODUCTION OF FRICTION ELEMENT

Friction Force from Friction Element [kN]	Extra Work done by Bumper Design Materials [Joules]				
	R	D1	D2	D3	D4
152.0	7750.0	7110.0	6880.0	8370.0	8930.0
228.0	10360.0	9630.0	9350.0	11060.0	11670.0

TABLE 6

EXTRA WORK DONE BY DIFFERENT BUMPER DESIGN MATERIALS AS RESULT OF THE INTRODUCTION OF FRICTION ELEMENT AS A PERCENTAGE

Friction Force from Friction Element [kN]	Extra Work done by Bumper Design Materials [%]				
	R	D1	D2	D3	D4
152.0	109.93	82.29	74.30	157.63	201.58
228.0	146.95	111.46	100.97	208.29	263.43

It is desirable for the attenuation system to do less work during its operation. From the results, the amount of work done by D4 increased the most, followed by D3, R, D1 and D2, in that order. D4's work done, the maximum, was increased by 201.58% and 263.43% with the introduction of 152 kN and 228 kN friction elements respectively; while D2's work done, the minimum, increased by 74.30% and 100.97% with the introduction of 152 kN and 228 kN friction elements respectively. It can be observed that the lower the stiffness and damping coefficient, the greater the influence of a friction element on the work done.

It was observed that the addition of a 228 kN friction element to a bumper-damper system with the new design parameters (as in D2) can improve the work done by nearly 164 %, and the addition of a friction element to an ordinary bumper-damper system with the traditional design parameters (as in R) can improve the work done by nearly 147 %.

From the deformation results, it was observed that design D2 suffered the least deformation followed by D1, R, D3 and D4 in that order. Among the five bumper materials studied, material D2 recorded the highest work done after impact for the same amount of deformation, followed by designs D1, R, D3 and D4 in that order. It is observed that the higher the stiffness constant *k*, and coefficient of damping c, the better the bumper would be in terms of its capacity to do work and the resistance to deformation. However, the threshold impact velocity decreases.

Overall the design material D2 can be considered best among all the five design materials in terms of its ability to do more work. The design parameters selected are therefore those of D2, which are 850 kN/m for *k* and 14.0 kN-s/m for c. On the other hand in terms of high threshold impact velocity, D4 is better. The design parameters selected (for D4) are 300 kN/m for *k* and 6.0 kN-s/m for c.

5 CONCLUSION

The addition of a friction element to an ordinary bumper-damper system with the new design parameters can improve its energy absorption capacity by about 103.6 kJ, which is about 146 %. Additionally, the addition of the friction element to a traditional vehicle bumper could increase the critical design speed from 4 km/h (1.11 m/s) to 14.9 km/h (4.1 m/s).

It was concluded that a passive friction damper system could be used to attenuate road vehicle impact energy in collisions (of vehicles of mass similar to that of a typical sedan car) at speeds 3 times higher than the speed for which current conventional bumpers are designed to attenuate (i.e. 4 km/h).

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