CRUSH VS ENERGY RELATIONSHIP FOR YUGO GV – CASE STUDY

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ABSTRACT

Due to extremly different vehicle structural performanse it is required to individualy analyze vehicle stiffness in any situation where acurate results of calculating crash speed are needed. From the begginings of vehicle stiffness modeling, by Emori, Campbell or any of there successors, methods of establishing equations are constantly improved. Nowdays, it is well known that normalized crush energy (known as EAF-Energy of Approach Factor) vs deformation can be succesfuly approximated with linear relationship using results from NHTSA 30 m/h frontal crash test speed. For higher speeds, bi-linear appeared to be accurate enough in most cases. But, there are certain cases where different relationship could give better results. Some researchers showed that nonlinear relationships could be also succesfuly used.

In this work, all known attempt from previous researchers where exercized on a YUGO GV vehicle. For this vehicle there are three NHTSA full frontal tests available. Using those results, it was concluded that, altough bi-linar relationship could be succesfuly used, best performanse was achived by combined approximation. Linear up to speed of 30 m/h and quadratic above that speed. This approximation gives best results in upper register of speeds, thus it is usefull for very deep crash deformations. Using computer for analysis eliminate complicated calculations, so establishing such relationships is no more hard job. It is important to notice that this kind of approximation can't be aplied in situation where only one crash test point is known. So, field of application is very limited.

УВОД

For a long period YUGO GV has been a national car in republic of Serbia (SE Europe). It's been widely used as a common vehicle for transportation and thus very often participant in crashes. That's why this case study is conducted for YUGO GV. This vehicle was selled in USA during 80s and it was subject to NHTSA Compliance and NCAP tests. Results of these tests are freely available and for the purpose of this analysis they were downloaded from internet adress: http://www-nrd.nhtsa.dot.gov/database/nrd-11/veh_db.html. In this analysis NHTSA database and detailed reports in PDF format were used to analyse and select appropriate dataset from YUGO GV frontal test.

METHOD OF ANALYSIS

Many researches about establishing equation between depth of deformation (deflection) and vehicle speed during crashes, or some other physical measure which is speed dependent, based upon crash test data, has been published.

Erliest pioneer work of Emori from 1968. [1] has brought into relationship depth of deformation and speed during crash testing, but it's been improved and Campbell (1974) [1] has established relationship between depth of deformation and force, and also analyzed crush energy per vehicle weight.

It's appear to be that it is useful, in order to take into account difference between masses of different vehicles or different test for same vehicle and various width of deformations, to analyze some sort of normalized energy. An appropriate measure for analysis would be Energy of Approach Factor (EAF) which was given by Strother [5] and which was extensively used after [5]. In fact, EAF take into account energy calculated from crash speed during testing, so it doesn't include energy of restitution, but only energy absorbed by the residual deformation. Thus, Energy of Crush Factor (ECF), which also takes into account energy of residual deformation, would be better for analysis, since it calculates energy in more comprehensive way, but it is more demanding for data that are often not available [2].

Strother [5] defined EAF as:

$$EAF = \sqrt{\frac{2E}{L}}$$

where
L -length of deformation
E -absorbed energy (J)

This equation can be written as

$$EAF = \sqrt{B} \cdot C$$

C -depth (amount) of deflection (m)
B -represents coefficient of stiffness, per width unit

B is defined as

$$B = \frac{k}{L_C}$$

Adding initial energy before residual deformations occure, described as EAF_0 (known also as Onset Energy Factor), tipicaly comprehended as speed of starting deformations, in EAF equation, we have

$$EAF = EAF_0 + \sqrt{B} \cdot C$$

Since Δv data from tests are not available for all tests of YUGO GV, EAF will be used in this case study.

SOME PREVIOUS RESEARCHES

Using least squares method, Strother [5] approximated EAF and crush depth using linear (and bi-linear) and nonlinear (quadratic) relationships. They have found that, for GM Citation 1980-1982, bi-linear relationship is more appropriate (Figure 1) while for Plymouth Satellite 1974 (Figure 2), data shows quadratic trend.

Jiang [1] called upon Sakurias work which describes that "two-stage constant force-crush relationship with a transition as the deformation reaches the engine, could be used to represent vehicles' frontal crush characteristics", and which was confirmed by Futamata and Toyama.

Kerkhoff [2] showed, based on repeated crash tests data for Ford Escort, that relationship between ECF or EAF and deflection, can be considered as linear between 15 and 40 m/h.

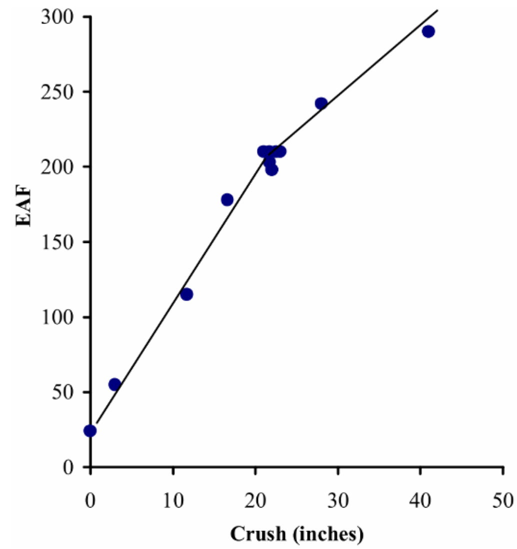

Figure 1. *EAF* vs crush for Citation 1980-1982.

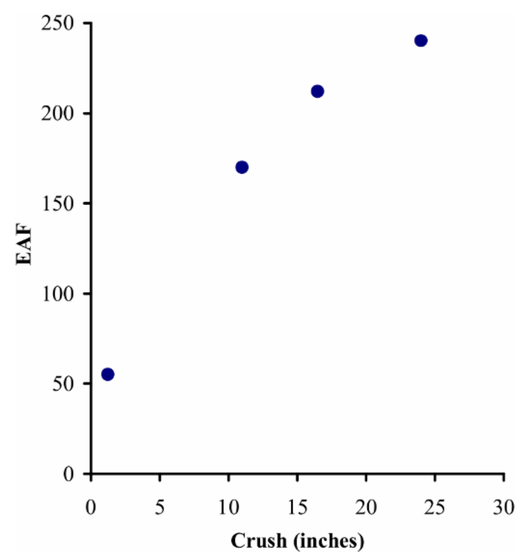

Figure 2. *EAF* vs crush for Plymouth Satellites 1974.

Varat [5] analyzed EAF and found that there two trends of frontal stiffness (relationship between EAF and deflection): linear and non-linear. Non-linear takes into account some softening of vehicle structure with deeper deflections. Some vehicles, as Ford Anglia, showed linear trend (Figure 3) up to 35 m/h and non-linear (Figure 4) for higher speeds (up to 50 m/h). They have also analyzed application to accident reconstruction using available tests data, for speeds of 30 and 35 m/h, and not knowing whether appropriate relationship between EAF and crush would be linear or non-linear.

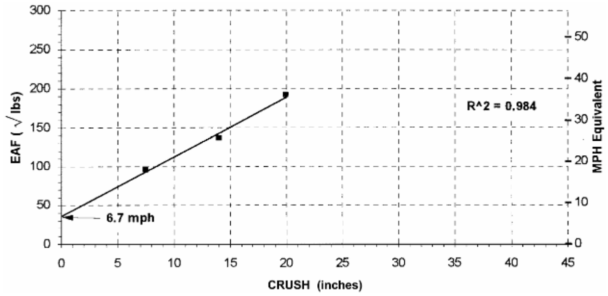

Figure 3. Anglia up to 35 m/h.

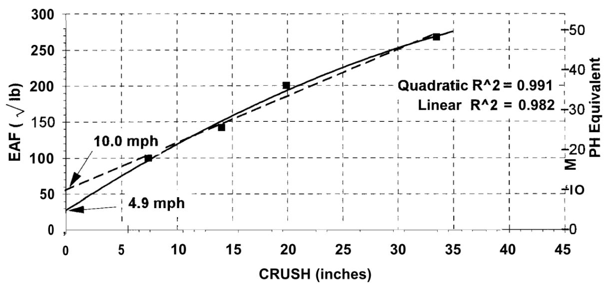

Figure 4. Anglia up to 50 m/h.

Bi-linear relationship by Strother [1] was used to describe EAF vs crush. Bi-linear relationship is presented as one linear relation for speeds up to 30 m/h and second linear for speeds from 30 to 50 m/h (Figure 5). They share the common 30 m/h data point.

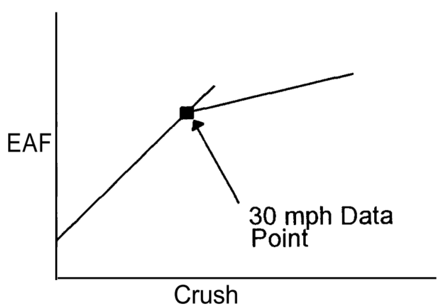

Figure 5. Bi-linear approximation.

In general case, bi-linear relationship is mathematicaly defined by next equations:

$$f(C) = \begin{cases} A_1 + B_1 C, & 0 \le C \le C_{30} \\ A_2 + B_2 C, & C_{30} \le C \end{cases}$$

where

C_{30} -crossover point, crush depth for 30 m/h test speed

For establishing relationship in first range (up to 30 m/h) datapoint for 30 m/h was used and EAF_0 was estimated for speed of 7.5 m/h (because they have found that average onset speed was 7.7 m/h for analyzed data).

For fitting in second range of bi-linear relationship (30 to 50 m/h), datapoint for 30 m/h was used and EAF_0 was estimated for speed of 15.2 m/h.

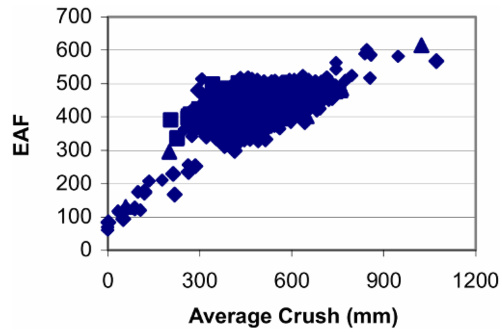

Figure 6. EAF **vs crush for passenger cars.**

Neptune [1999] also concluded that, in general, crush response characteristics of vehicle can be divided into two regions. First related to engine compartment deformation and second to passenger cage. Thus, vehicle can be modeled as bi-linear dissipator with second one not being compressed until first one "bottoms out". Both regions can be approximated with different linear functions.

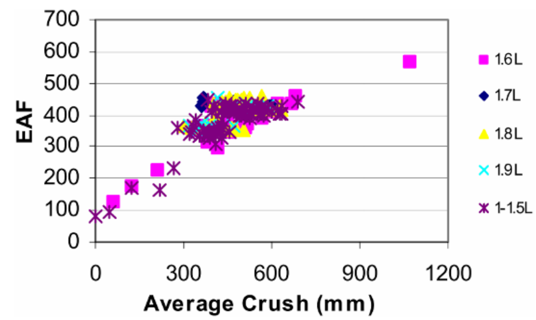

Figure 7. EAF **vs crush for cars with a 4cylinder transverse engine (1,0-1,9L).**

Jiang [1] analyzed EAF vs average crush depth for over 1000 vehicles tests from 1960. to 2002. Average crush depth was calculated based on at least 3, but mostly six (according to NHTSA vehicle test protocol) crush measurements. Figure 6 shows the results with bi-linear trend for analyzed passenger cars. They were further grouped according to engine configurations and for 4-cylinder transverse engine from 1000 ccm to 1900 ccm, and also showed bi-linear trend (Figure 7). For engines 1000 to 1500 ccm, bi-linear trend is also observed. Jiang also proposed a strategy for fitting. It is proposed that ECF should be used, unless rebound velocities are not available, when EAF should be used.

If only one test point is available, bi-linear relationship is recommended. The first stage for speeds up to 35 m/h

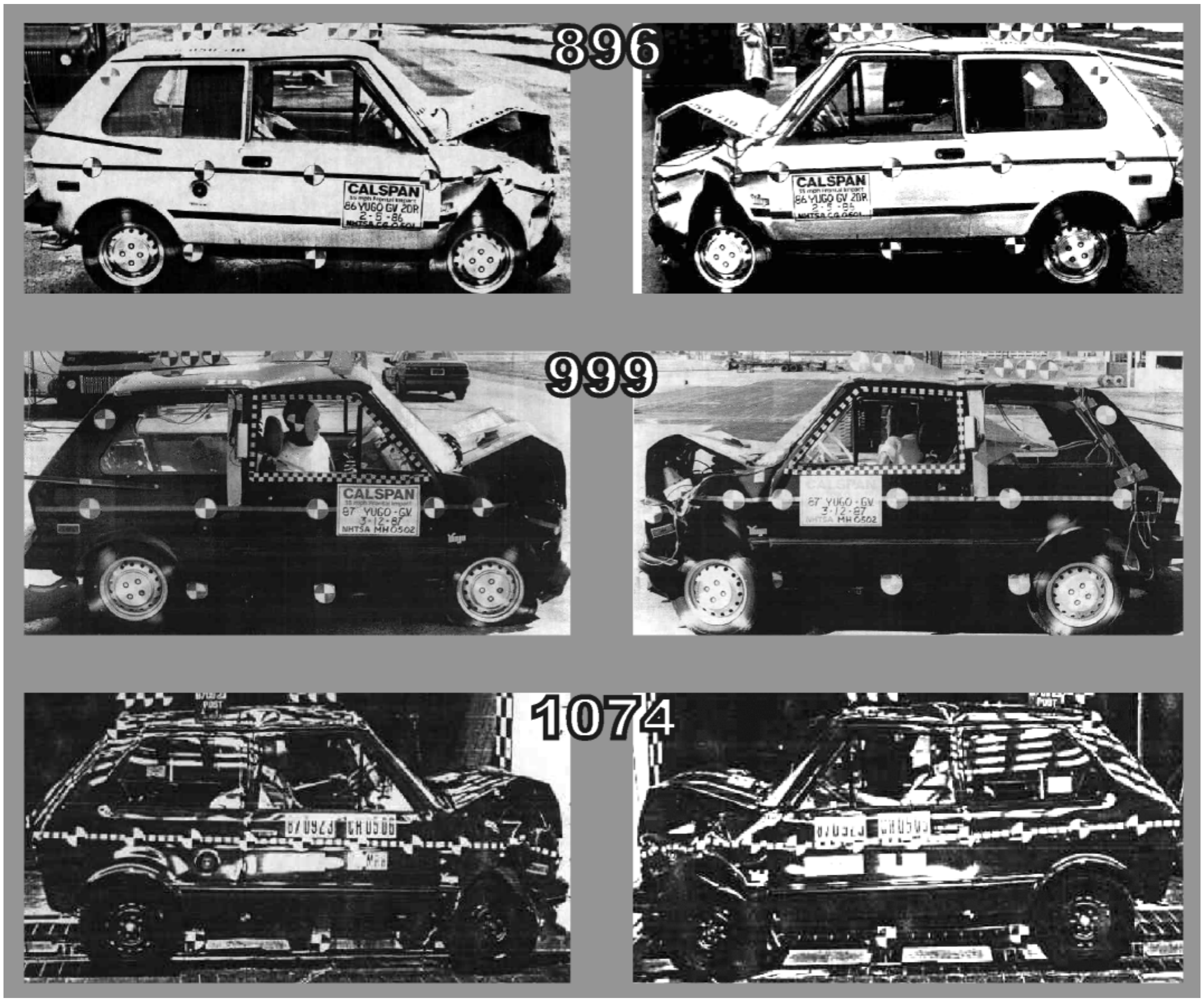

Figure 8. YUGO GV after testing.

(56 km/h) and with onset estimated at 5 m/h (2.2 m/s or 8 km/h). The second stage, for speeds 56-80 km/h, and with onset estimated at 15 m/h (6,7 m/s 24 km/h), as Varat [5] recommended.

DATA FOR CASE STUDY ANALYSIS

Four NHTSA crash tests has been conducted with YUGO GV. Three frontal and one side test. Results are available in NHTSA database, as separate detailed reports (in pdf form), and also as files containing digital data from accelerometers. Main data source for this analysis were NHTSA database and reports.

Three frontal crash tests are available for YUGO GV: no. 896, no. 999 and no. 1074. Considering recommendations about the test data from previous researchers (adjusting the gap during measuring from Neptune [3]) and fact that test reports present crush data in different manner, and that data from reports and database are sometimes different, all used data are logicaly checked and, if needed, corrected.

Relevant data

All crash test data for case study were summarized and shown in table 1. Vehicle photographs are shown in Figure 8. Vehicle width was corrected from obviously misspelled 1346 mm to 1546 mm.

Onset speed is estimated as 8 km/h (5 m/h), in accordance with recommendations from Jiang [1].

Test No.	Vc [km/h] ±0,8 km/h	Vc [m/s]	Test mass [kg]	Model Year	DPD1 [mm]	DPD2 [mm]	DPD3 [mm]	DPD4 [mm]	DPD5 [mm]	DPD6 [mm]	C_{ave} [mm]	Max Deflection [mm]	Lc* [mm]	Vehicle Width [mm]	Δv [m/h]
0896	56,5	15,69	1052	1986	462	472	480	480	475	467	0,474	480	1387	1542	39,1
0999	56,2	15,61	1052	1987	381	414	434	445	447	450	0,431	450	1384	1546	/
1074	47,2	13,11	1035	1988	302	320	325	335	330	320	0,324	348	1410	1529	/
estimated	8	2,22	1035-1052		0	0	0	0	0	0	0	0	1410	1529	

Тбл. 1. Data for YUGO GV case study.

***Lc** (означено као LENCNT у NHTSA бази података) је укупна дужина контакта на возилу, односно ширина чеоне стране возила захваћена оштећењем. Ова дужина обухвата директно и индуковано оштећење.

Equivalent uniform deformation ($Cave$) for six measured distances of deformation profile was calculated according to recommendation from Neptune [3]. Same equation is used in German traffic accident analysis software, PC CRASH.

$$Cave = \frac{C_1 + 2\times\left(C_2 + C_3 + C_4 + C_5\right) + C_6}{10}$$

ESTABLISHING RELATIONSHIPS-APROXIMATION

Linear relationship

Since only one test has rebound velocity (896), EAF vs deflection was analyzed.

According to recommendations, for linear approximation EAF vs deflection through three crash test points, and estimated onset speed of 5 m/h (8 km/h or 2,2 m/s), EAF was calculated using next equation:

$$EAF = \sqrt{\frac{2E}{L_C}} = \sqrt{\frac{2\frac{m\cdot v^2}{2}}{L_C}} \qquad (\sqrt{N})$$

Using MS Excel, linear approximation was conducted with equation that is defined as:

$$EAF = EAF_0 + \sqrt{B}\cdot C = 61 + \sqrt{697058}\cdot C$$

EAF_0 was calculated with 1052 kg mass (like for tests 896 and 999) and 1410 mm crush lenght (like test no. 1074).

From established equation B, which represent individual characteristic of vehicle crash performance, here is 697058 $\sqrt{N}$.

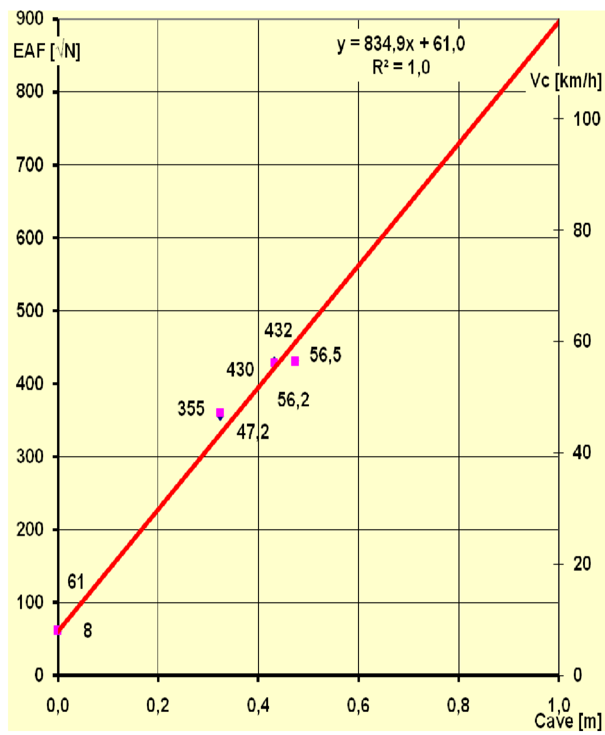

Figure 9. Linear EAF vs crush YUGO GV relationship.

For comparison, Figure 10 shows FORD Escort 1981-1985. linear approximation [5] for speed up to 35 m/h, where EAF is presented in $\sqrt{lb}$ and crush in inches.

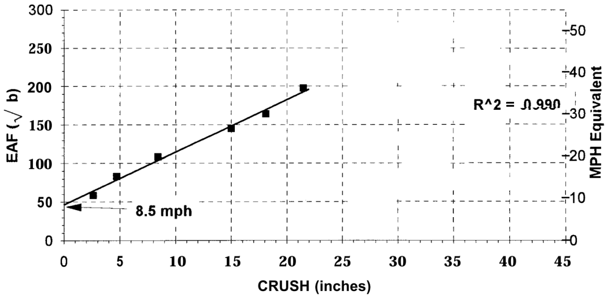

Figure 10. Ford Escort 1981-85, linear up to 35 m/h.

Bi-linear relationship

Varat [5], Jiang [1] and many others recommended that bi-linear approximation should be done with one linear relationship up to 30 m/h and second for 30 to 50 m/h.

Since for YUGO GV exists points for 35 m/h (35,1 and 34,9 m/h) and 30 m/h (29,3 m/h), and onset is estimated at 5 m/h, first part of bi-linear relationship is approximated for 5 and 30 m/h and second for 30 and 35 m/h.

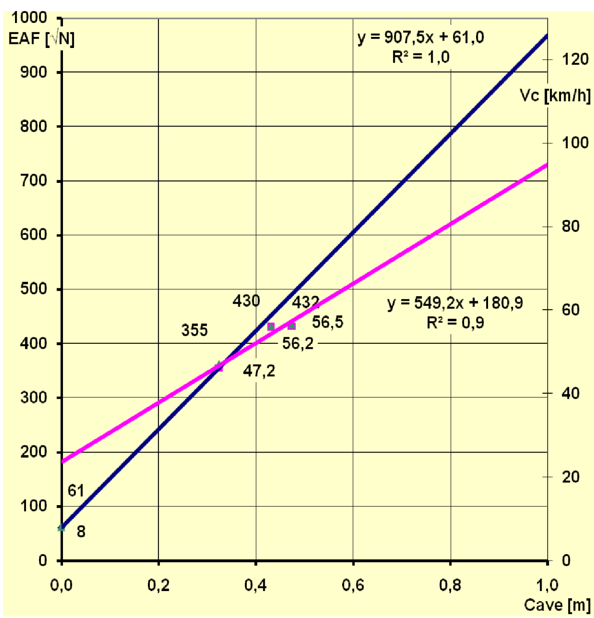

Figure 11. Bi-linear ***EAF*** **vs deflection approximation.**

Two linear relationships are defined as:

$$EAF_1 = EAF_{01} + \sqrt{B} \cdot C = 61 + \sqrt{823556} \cdot C$$

$$EAF_2 = EAF_{02} + \sqrt{B} \cdot C = 180,9 + \sqrt{301621} \cdot C$$

This bi-linear relationship is mathematicaly defined with next equations:

$$f(C) = EAF = \begin{Bmatrix} 61 + \sqrt{823556} \cdot C, & 0 \le C \le C_{30} \\ 180.9 + \sqrt{301621} \cdot C, & C_{30} \le C \end{Bmatrix}$$

$$C_{30} = 0.324\ m$$

In second part of bi-linear approximation EAF_0 would be 180.9 $\sqrt{N}$. Using equation for EAF and expressing v:

$$v = \sqrt{\frac{L_C \cdot EAF^2}{m}}$$

we can calculate corresponding onset velocity:

$$v = \sqrt{\frac{1.41 \cdot 180.9^2}{1052}}$$
$$= 6.62\ m/s = 23.8\ km/h = 14.8\ m/h$$

This velocity is equal to one recommended by researchers [1, 3, 5] for second part of bi-linear fitting.

The representer of frontal stiffness (B) for the first part of bi-linear would be $823556\sqrt{N}$ and for the second part, $301621\sqrt{N}$. This means that stiffness is about 2.7 times lesser in second phase, than in the first (about 37%).

Nonlinear (2nd order polynomial) relationship

It should be beard in mind that all nonlinear approximation has been done only for max test speeds, so there is no exact recommendations for fitting above that speed.

Fitting 2nd order polynomial relationship through YUGO GV test data yield us to (Figure 12)

$$EAF = 60.4 + 1188.6 \cdot C - 822.8 \cdot C^2$$

Relationship shows great amount of softening for speeds above max tested, and for speeds over 65 km/h is unuseable, because graph starts to fall down.

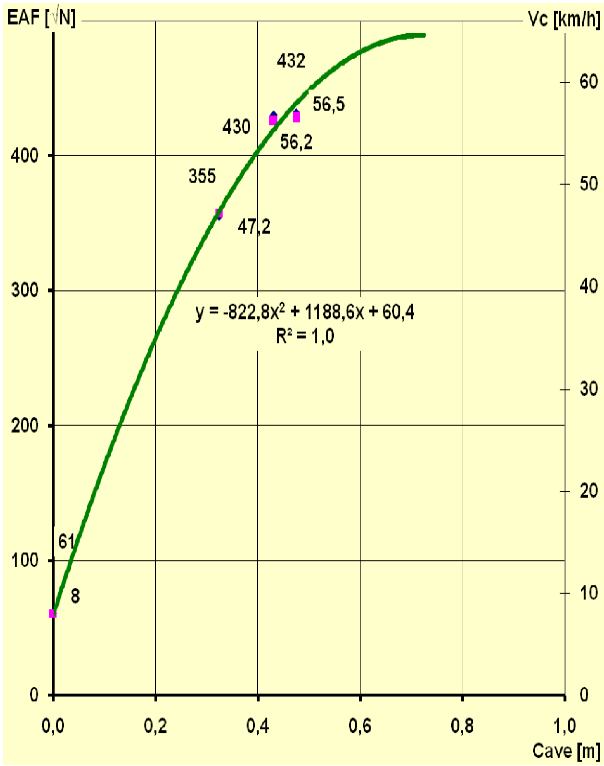

Figure 12. 2nd order polynomial *EAF* vs deflection approximation.

2nd order polynomial fitting using only one 56 km/h and rest data points has been done also. This yield to two relationships: softer and stiffer 2nd order polynomial. It could be said that these lines are boundary and, based on analyzed data set, represent marginal values.

Both of these lines shows some softening with speed, but the "stiffer" one (blue line on Figure 13) could be usefull for speeds over 80 km/h while "softer" one is unusable for speeds over 62 km/h.

Relationship were expressed as:

$$EAF_H = 60.7 + 1062.8 \cdot C - 475.98 \cdot C^2$$

$$EAF_S = 60.7 + 1178.7 \cdot C - 833.67 \cdot C^2$$

As a comparison, Figure 14 shows nonlinear approximation for Ford Escort 1981-85 [5]. It can be seen that this one is very similar to "stiffer" one for YUGO GV, but is a bit "softer".

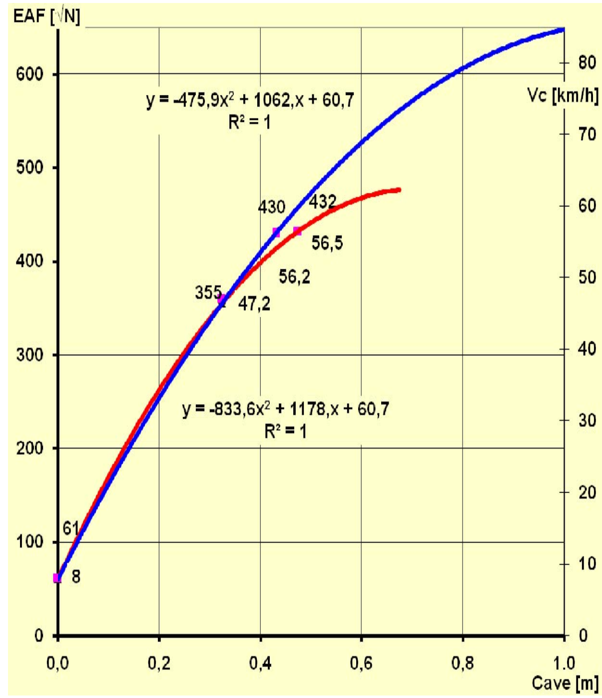

Figure 13. Two 2nd order polynomial *EAF* vs deflection approximations.

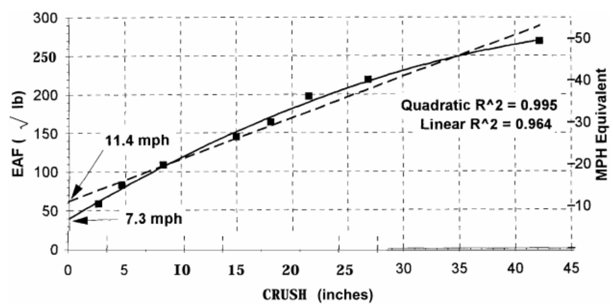

Figure 14. Ford Escort 1981-85, up to 50 m/h.

Combined relationship

In order to provide best fitting, and inspired by Varat's foundings [5] that quadratic equation is more suitable for upper speed register (over 30 m/h), Nesic [4] approximated *EAF* vs deflection with linear relationship for speeds up to 30 m/h and non-linear (quadratic) for higher speeds.

Equations that describes combined approximation are:

$$EAF_1 = EAF_{01} + \sqrt{B} \cdot C = 61 + \sqrt{823556} \cdot C$$

$$EAF_2 = \sqrt{B} \cdot C = \sqrt{443699} \cdot C^{0,552}$$

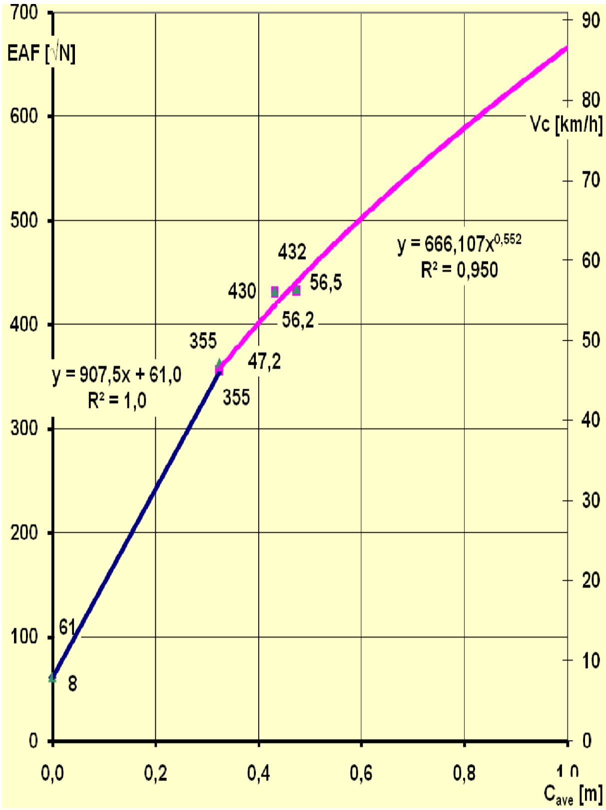

Figure 15. Combined EAF **vs deflection**

relationship.

First equation describes linear relationship for speeds up to 30 m/h, and second for speeds over 30 m/h. Equivalent uniform deformation for "crossover" speed of combined relationship (30 m/h), would be $C_{ave} = 0{,}324\ m$.

Combined relationship would be fully mathematicaly defined as:

$$f(C) = EAF = \begin{Bmatrix} 61 + \sqrt{823556} \cdot C, & 0 \le C \le C_{30} \\ \sqrt{443699} \cdot C^{0{,}552}, & C_{30} \le C \end{Bmatrix}$$

$$C_{30} = 0.324$$

Combined relationship demonstrate softening with higher speeds, and at the top of the researched range (for the average deflection of 1 m), speeds are slightly higher than demonstrated by quadratic approximation for Ford Escort (Figure 14).

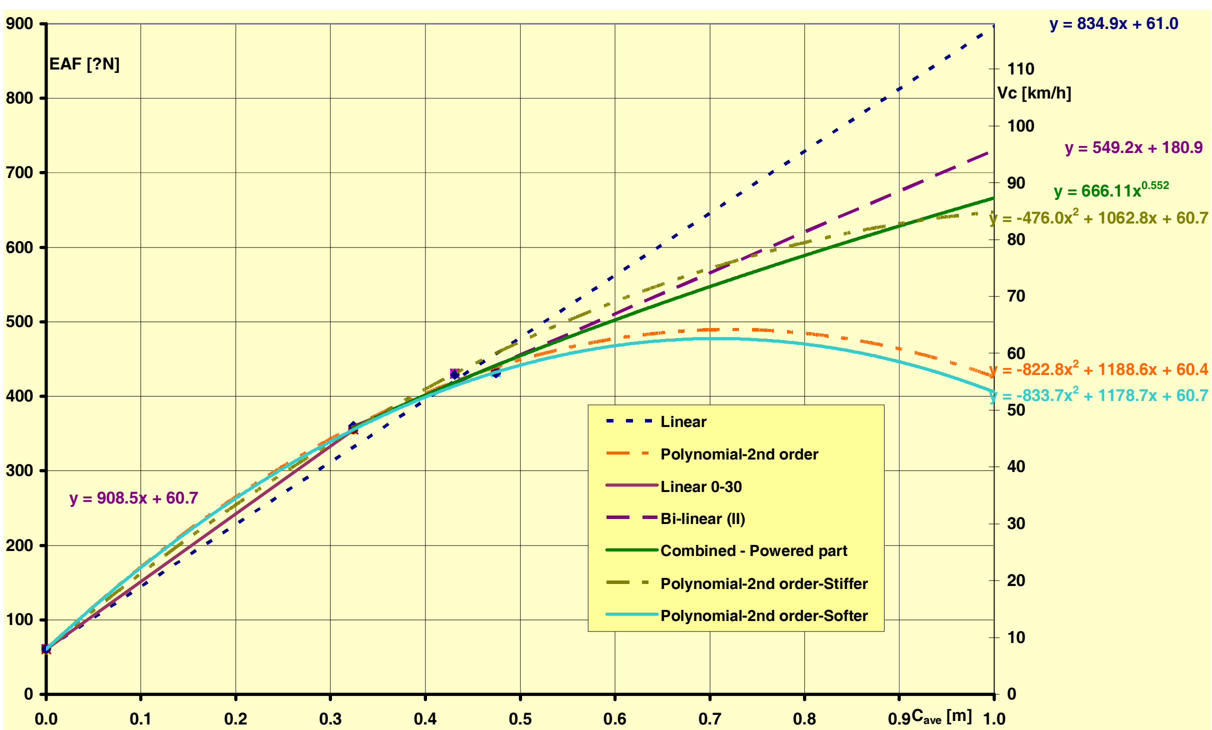

Figure 16. Summarium of YUGO GV case study.

Table 2. Known errors of YUGO GV case study approximations.

		Linear	Bi-linear	Quadratic	Quadratic-softer	Quadratic-stiffer	Combined
[m]	[m/s]	[%]	[%]	[%]	[%]	[%]	[%]
C_{ave}	V	∈	∈	∈	∈	∈	∈
0,474	56,50	**5,7**	**2,1**	**1,6**	**0,0**	**5,9**	**2,1**
0,431	56,20	**-2,3**	**-3,0**	**-2,4**	**-3,8**	**0**	**-2,7**

DISCUSSION

All showed approximation were conducted based on the available NHTSA crash test results for YUGO GV.

Results from previous researches, that shows that it is acceptable solution to estimate speed that start to cause residual deformation (onset speed) as 5 m/h, have been used. They have also showed that it is acceptable to approximate *EAF* vs deflection with linear relationship up to speed of 30 m/h, although in extreme condition it can be expected substantial error in lower range of speeds (or deflections) as, for instance, up to -19% for VW Rabbit and 9.3% for Ford Escort, according to Varat [5].

However, error is more significant if a vehicle that shows nonlinear relationship is approximated with linear relationship, because errors in lower register are then even higher, and goes up to 40%.

On the other side, Jiang [1] estimated that, if linear approximation is conducted with only one data point, error goes up to 26%, and could be even 50% if relationship placed on the higher data margin for certain vehicle category was established.

In this case study linear approximation (Figure 16), known errors vary but are acceptable in any case, even for the worst scenario.

According to known errors in table 2, it could be seen that any relationship is good enough for all known data points. However, there are substantial differencies in higher range of speeds and deflections. Quadratic and "softer" quadratic are completely unusable and linear is "too stiff". "Stiffer" quadratic, bilinear and combined are pretty close. Between those three, quadratic shows highest maximal error (5.9%), so it is least recommendable. Combined showed two errors same as bi-linear, but slightly better for one error (0,3% better). Thereat, for maximal average deflection of 1 m, combined gives speed of about 85 km/h, while bi-linear gives higher speeds (for about 10 km/h). Frontal performance of YUGO GV in this region is not known, but it is for FORD ESCORT (Figure 14) [5], where it can be seen that, for 1 m average deflection, speed is about 80 km/h. This can be considered as slightly advantage toward combined approximation over the researched region (0 to 1 m of deflection).

However, it should be recognized that, least error over 47 to 56.5 km/h region, is achieved by quadratic relationship. This make it appropriate for approximation in that region of speeds and corresponding deflections.

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