Approximation of bruise spot volume in pears in plots against deformation parameters

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ABSTRACT: Pears of different varieties were compressed between two flat rigid plates in loading/unloading tests. The bruise spots appearing after room temperature incubation were analysed manually, and bruise spot volumes were determined. The main parts of the paper discuss mathematical approximation of total bruise volume versus two deformation parameters defined in previous papers: hysteresis losses and degree of elasticity. The polynomial of the second order was used for this purpose, but success of this method depends on including some part of not-bruising results in the analysis. Characteristic values of hysteresis losses and degree of elasticity were used to determine the bruise index, the integral parameter, that is suitable for classifying the tested varieties as to tissue susceptibility to low-level bruising. The variety susceptibility to bruising decreased in the following order: Elektra, Erika, Vonka, Lucasova, Dicolor, Dita, Omega, Jana, Lada, Astra, Bohemica, and Delta.

Keywords: pears; bruising; compression; bruise volume; hysteresis losses; degree of elasticity; approximation of curve; quality

Fruit bruising is one of the most important factors limiting the mechanisation and automation in harvesting, sorting and transport of soft fruits and vegetables, including potatoes. Dark spots appearing near the product surface are due to the previous mechanical contacts of the products with other bodies. Force loading of round fruit can be quite variable (JOHNSON 1987), ranging from static to dynamic. Bruise extent is usually described in terms of bruise volume (BLAHOVEC et al. 1991), which is in a close relationship to the product quality.

Most attempts to reduce fruit bruising consist of excluding the varieties that are susceptible to this kind of damage. The important part of such a programme was exact and reproducible determination of level of such susceptibility for many of different varieties. Practical attempts to do it brought a lot of practical and conceptual problems. Most authors found solutions of the bruise susceptibility in linear relation between bruise volume and some form of deformation energy of the impact or loading/unloading tests (loading energy and/or absorbed energy) – e.g. HOLT and SCHOORL (1977, 1983, 1984), SCHOORL and HOLT (1986), BRUSEWITZ and BARTSCH (1989), KAMP and NISSEN (1990), HYDE and INGLE (1968), BAJEMA and HYDE (1998), MATHEW and HYDE (1997), STUDMAN (1995).

It was shown that for static bruising the experimental relation between bruise volume and the energy parameters is not linear – the bruise volume increases nonlinearly with increasing deformation energies (apples – BLAHOVEC et al. 1997, cherries – BLAHOVEC et al. 1996, pears – BLAHOVEC et al. 2002). For higher quality fruits, the conditions corresponding to no and/or very little bruise damage are the things of the most importance. The evaluation of this area was proposed by BLAHOVEC (1999). In previous papers (BLAHOVEC et al. 2002, 2003) it was shown that sensitivity to pear bruising could be expressed by characteristic hysteresis losses and/or degree of elasticity rather than by load and/or absorbed energy.

Success of this method consists in finding simple and reliable methods of approximating bruise volume – hysteresis losses (*HL*) and bruise volume – degree of elasticity (*DE*) plots for low-level loading. This is programme for this paper's aimed is to determine clear parameters expressing the susceptibility of pear tissue to bruising.

MATERIALS AND METHODS

The experimental part is identical with our previous paper (BLAHOVEC et al. 2003) and is described there.

The pears of variety group were harvested in the orchard of the orchard of the Research Institute for Pomology Ltd. at Holovousy in North-Eastern Bohe-

Table 1. Main characteristics of the tested fruits

Variety	Test dates	
	Loading	Spot analysis
Astra	23/01/03	24/01/03
Bohemica	04/12/02	06/12/02
Delta	09/12/02	10/12/02
Dicolor	27/09/02	28/09/02
Dita	24/01/03	27/01/03
Elektra	03/12/02	05/12/02
Erika	24/01/03	27/01/03
Jana	04/12/02	06/12/02
Lada	26/09/02	27/09/03
Lucasova	03/12/02	05/12/02
Omega	24/01/03	27/01/03
Vonka	26/09/02	30/09/02

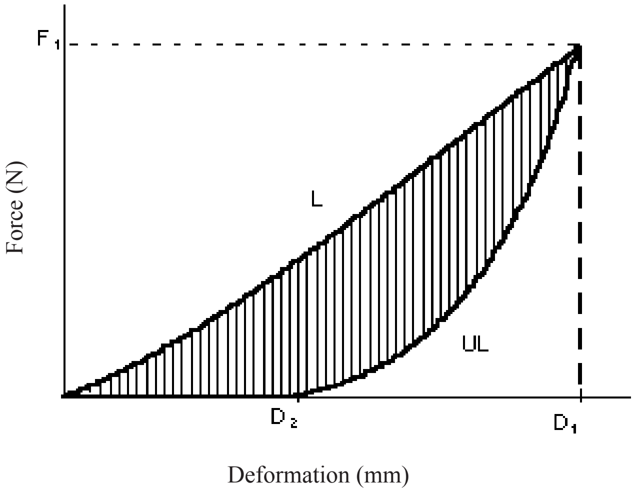

Fig. 1. Schematic representation of the loading test of a pear between two plates. It consists of two parts: loading of the fruit (L) at a constant deformation rate up to total compression force F_1, followed by unloading at the same but reversed deformation rate (UL). The first parts begin at zero force and zero deformation and ends at force F_1 and deformation D_1, the second part begins at the end state of the first part and ends at zero force and deformation D_2. The area between loading part and the axis D represents loading energy W_L, the unloading energy W_U – the recovered part of the loading energy – is represented by the area between unloading part and the axis D. The marked area between the curves L and UL is the so called absorbed energy

mia. The fruits were harvested in a stage of harvesting maturity. The details about testing dates are given in Table 1. Every test was performed on forty defect-free fruits that were divided into the four groups with ten fruits per group. The fruits were than compressed individually between two plates at a constant deformation rate of 0.167 mm/s. The fruits' axis was oriented to be parallel with the compression plates. After reaching the desired force the fruit was unloaded at the opposite deformation rate. All the loading-unloading tests were performed using an Instron™ Universal Testing Machine (UTM) – model 4464 – at usual laboratory conditions (temperature 20–22°C). The UTM software was used to evaluate of the loading curves. The following parameters were obtained (Fig. 1, BLAHOVEC et al. 1996, 1997): loading energy (W_L), unloading energy (W_U), absorbed energy ($W_A = W_L - W_U$, shaded area in Fig. 1), maximum deformation (D_1), inelasic deformation (D_2), degree of elasticity ($DE = 1 - D_2/D_1$) and hysteresis losses ($HL = W_A/W_L$).

The pears were stored after the harvest in cold store at about 4°C and tested approximately after 24–72 hours tempering at room temperature. After test the fruits were left on the table in a laboratory at room temperature (20–22°C) for about 24–72 hours. The fruits were then cut in the middle of the two bruised spots perpendicularly to the fruit surface at the diameters (d) and depths (t) of the spots were measured. These were used to calculate the bruise volume of the individual spot based on the formula given by BARREIRO (1999):

$$V = \pi d^2 t/6 \qquad (\text{cm}^3) \qquad (1)$$

The total bruise volume ($TBV = V_1 + V_2$) was determined for every fruit from both the bruise spots ($V_1 + V_2$) formed in a test.

RESULTS AND DISCUSSION

Approximation of TBV-HL and TBV-DE plots

The crucial role in analysing the test results is played by the precise determination of *HL* and *DE* values that correspond to the characteristic bruise spot volumes. The first step of this aim is the best approximation of *TBV-HL* and *TBV-DE* plots, especially for small *TBV*. Previous attempts to do it with shifted power function (BLAHOVEC et al. 2002) led to problems with determining the characteristic value for zero *TBV*: zero initial derivative of the power function tended to decrease this value. This is why we used another function that could have nonzero derivative for $TBV = 0$ and is really simple: the polynomial of the second order:

$$TBV = aX^2 + bX + c \qquad (2)$$

where X is independent variable (*HL* and/or *DE)*. This approximation can be solved directly by the least square method. This process consists of determining the parameters a, b, and c (e.g. by Microsoft Excel).

However, application of the polynomial to the obtained results is not simple. We will describe it here for the *TBV-HL* plot of variety Delta. The obtained variety results can be divided into two groups (Fig. 2): i) the results, in which some bruise spots were observed and non-zero *TBV* was determined for them (circles filled by grey) and ii) the results, in which no bruise spots were

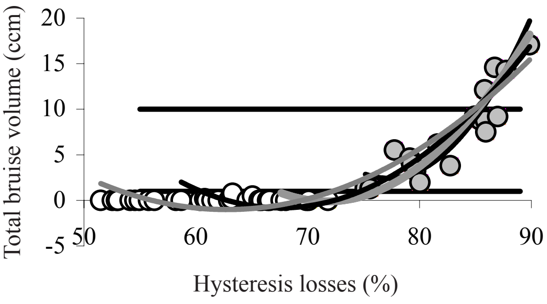

Fig. 2. Total bruise volume (variety Delta) plotted against hysteresis losses. Polynomial of second order were used for approximation the data sets differed by number (m) of the results with $TBV = 0$ (open circles in the figure). Horizontal lines denoted *BV* corresponding to bruise spot volumes 0.5 cm^3 ($TBV = 1$ for two spots formed onto the fruit during a test) and 5 cm^3 ($TBV = 10$). Further details are given in Table 2

Table 2. Plot of total bruise volume (*TBV*) against hysteresis losses for variety Delta – the main parameters depending on number (*m*) of the results with $TBV = 0$ included into regression by polynomial of the second order

m	*a**	*b**	*c**	R^2	HL_0 (%)	$HL_{0.5}$ (%)	HL_5 (%)	*NSW*** (%)
0	0.1085	–16.759	649.4	0.829	*n*	*n*	85.6	*n*
5	0.0560	–8.028	287.8	0.860	73.2	76.2	85.2	1.47
20	0.0358	–4.844	162.9	0.881	72.4	74.7	85.0	4.80
30	0.0225	–2.821	87.6	0.858	69.5	72.2	84.9	6.70

* *a, b, c* are parameters of polynomial second order $BV = a\,HL^2 + b\,HL + c$ (*R* is the correlation coefficient)
indexes at *HL* in the table denote to which individual bruise volume the *HL* corresponds
** *NSW* – negative semi-width is one half of *HL* interval in %, in which the polynomial gave negative *TBV*: $NSW^2 = 0.25(b/a)^2 – c/a$
n denotes *not defined*

observed ($TBV = 0$, open circles). Fig. 2 shows that application of the polynomial of the second order to the results of i led to the curve not-crossing the *HL* axis, thus having no solution for $TBV = 0$ (see also Table 2 for $m = 0$). The desired crossing of the polynomial was reached by adding a part of the results (given by number *m*) of group ii into group i before regression. The results of such approximation are also given in Fig. 2 and Table 2. The $HL_{0.5}$ criterion is based on small bruise spots that are close to EU limit (diameter less than 1 cm – BARREIRO 1999), that correspond to volume few tenths of cm^3 (BLAHOVEC 2001).

With increasing number *m* of the added $TBV = 0$ results, the parameters of approximation were changed. Also the difference between both the crossings of the polynomial and *HL* axis increased with increasing *m*. Half of the difference is termed 'negative semi-width' (*w*). Fig. 3 shows the changes in *HL* bruise characteristics: – *HL* values corresponding to formation of bruise spots of volume 0.5 cm^3 ($HL_{0.5}$) and *HL* values corresponding to crossing of the polynomial with *HL*-axis (HL_0) in Fig. 3a and correlation coefficient in Fig. 3b. Semi-widths of 2–5% produced the highest correlation coefficients with corresponding variation in $HL_{0.5}$ and HL_0 less than 2% (Fig. 3). Similar relations were obtained in other cases.

Fig. 4 contains representative *TBV-HL* (a) and *TBV-DE* (b) approximations for variety Delta. The characteristic values for susceptibility to bruising were determined similarly as in the previous paper (BLA-

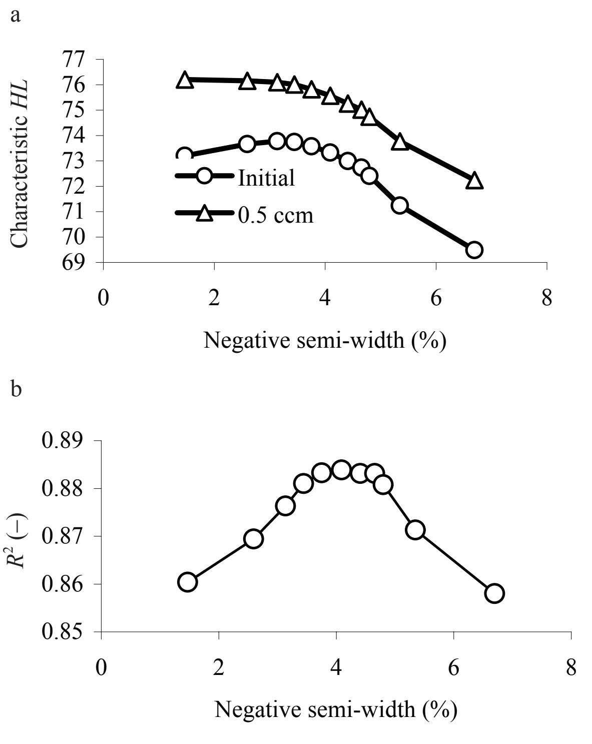

Fig. 3. Parameters of *TBV-HL* approximation by the polynomial of the second order (Fig. 2 and Table 2) plotted against the negative semi-width (*NSW* see Table 2)
a) Parameters HL_0 and $HL_{0.5}$; b) R^2 of the approximation

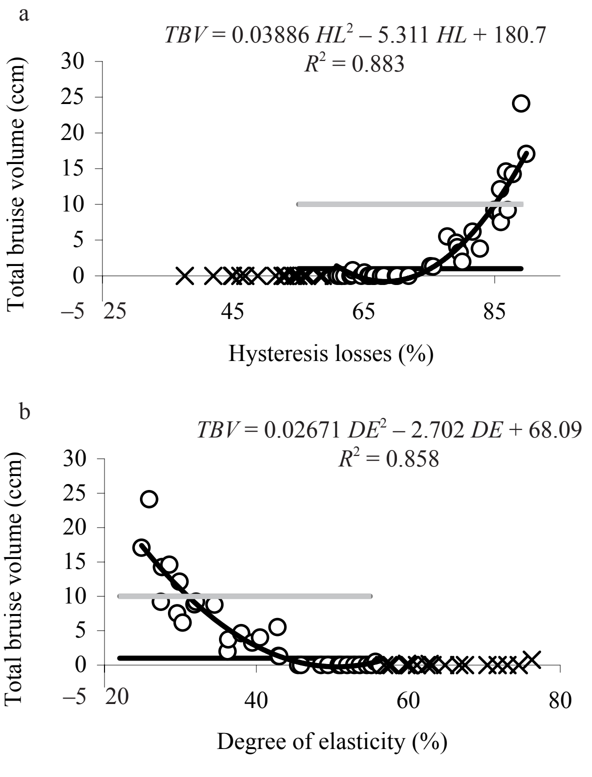

Fig. 4. Examples of the final *TBV-HL* (a) and *TBV-DE* (b) approximations – variety Delta. The circles denote the results used to the polynomial approximation, the crosses denote the other results. Horizontal lines determine $HL_{0.5}$ (black) and H_5 (grey)

HOVEC et al. 2002). The characteristic parameters HL_{BV} and $DE_{BV,}$ corresponding to bruise volume BV, are denoted here similarly as in Eq. (2) by X_{BV} and are given by solution of the following equation:

$$aX_{BV}^2 + bX_{BV} + c - 2(BV) = 0 \qquad (3)$$

because TBV equals the total BV of two individual bruise spots formed in one test. Solution of quadratic Eq. (3) is:

$$X_{BV} = \frac{-b \pm \sqrt{b^2 - 4[c - 2\,(BV)]}}{2a} \qquad (4)$$

where the plus sign is used for HL and the minus sign for DE.

HL_0 was determined as the higher HL-value at the polynomial curve crossing with the HL-axis: i.e., the HL value at TBV = zero. Similarly DE_0 was determined as the lower DE-value at the polynomial curve crossing with DE-axis. $HL_{0.5}$, $DE_{0.5}$ and HL_5, DE_5 are given also at crossings of the corresponding polynomials for $TBV = 1$ cm^3 (black horizontal line in Fig. 4) and $TBV = 10$ cm^3 (grey horizontal line in Fig. 4), respectively.

Bruising parameters

Approximations of TBV-HL and TBV-DE plots were performed for all the tested varieties; results are given in Tables 3 and 4. Besides the characteristic HL and DE, the derivatives d(TBV)/d(HL) and d(TBV)/d(HL) in characteristic points are also given. The derivatives can be understood as a measure of the error in a spot volume caused by errors in determining the independent variable (HL or DE). The derivative value 0.578 cm^3/% at HL_0 for variety Erika (Table 3) means that the 1% error in determination of HL_0 leads to 0.578 cm^3 error in determination of TBV, i.e. it could be related to bruise spot volume error ±0.289 cm^3. Thus the higher derivative value, the grater the error in TBV. On the other hand, the higher is the derivative the higher the precision in determination of HL. The same conclusions can be accepted also for DE.

The derivatives given in Tables 3 and 4 can be determined directly by differentiation of Eq. (2) and inserting the values $X = X_{BV}$ from Eq. (4):

$$\left(\frac{d\,(TBV)}{dX}\right)_{BV} = \pm\sqrt{b^2 - 4a\,[c - 2\,(BV)]} = \pm\, 2aw' \qquad (5)$$

where w' is one half of 'X' distance between the left and the right solution of Eq. (3). For $BV = 0$, $w' = w$ (the negative semiwidth) of the approximation. It is clear that there exists some relation between the derivatives values (Tables 3 and 4) and the number m from Table 2.

Bruising index

Two sets of characteristic parameters were obtained for every variety. HL parameters decreased with increasing susceptibility to bruising, whereas the opposite trend was observed for DE parameters. These two sets of the parameters can be unified into one set of parameters, termed bruising index (BI):

$$BI_i = HL_i/DE_i,$$

the integral parameter decreasing with increasing susceptibility to bruising. The results obtained in our research are given in Fig. 5, where the tested varieties are arranged under the increasing BI_0.

Fig. 5 shows that both indexes BI_0 and $BI_{0.5}$ should lead to very similar classification of the pear varieties as to their susceptibility to bruising. Unfortunately, the same conclusion cannot be made for BI_5, which leads to another order of classification than that based on BI_0 or $BI_{0.5}$. This fact is important also for classification of

Table 3. Bruising parameters obtained for hysteresis losses (0, 0.5, and 5 are volumes of corresponding bruise spots in cm^3)

Variety	R^2	HL – coordinates (%)			HL – derivatives (cm^3/percent)*		
		0	0.5	5	0	0.5	5
Astra	0.903	71.59	74.34	85.05	0.267	0.461	1.219
Bohemica	0.891	74.02	75.96	83.74	0.386	0.643	1.671
Delta	0.883	72.88	75.15	85.02	0.352	0.529	1.295
Dicolor	0.886	68.58	71.81	80.58	0.117	0.502	1.549
Dita	0.592	65.69	67.84	77.51	0.381	0.550	1.311
Elektra	0.806	53.89	61.66	82.71	0.048	0.209	0.646
Erika	0.891	61.15	62.70	71.13	0.578	0.710	1.425
Jana	0.895	62.44	66.17	79.45	0.178	0.358	0.997
Lada	0.881	68.83	71.38	82.06	0.305	0.479	1.207
Lucasova	0.718	61.83	65.93	80.93	0.168	0.320	0.879
Omega	0.842	66.79	69.10	77.44	0.292	0.573	1.586
Vonka	0.811	58.61	63.30	82.75	0.165	0.262	0.664

* $\dfrac{d(TBV)}{d(HL)}$ calculated from the polynomials at corresponding point

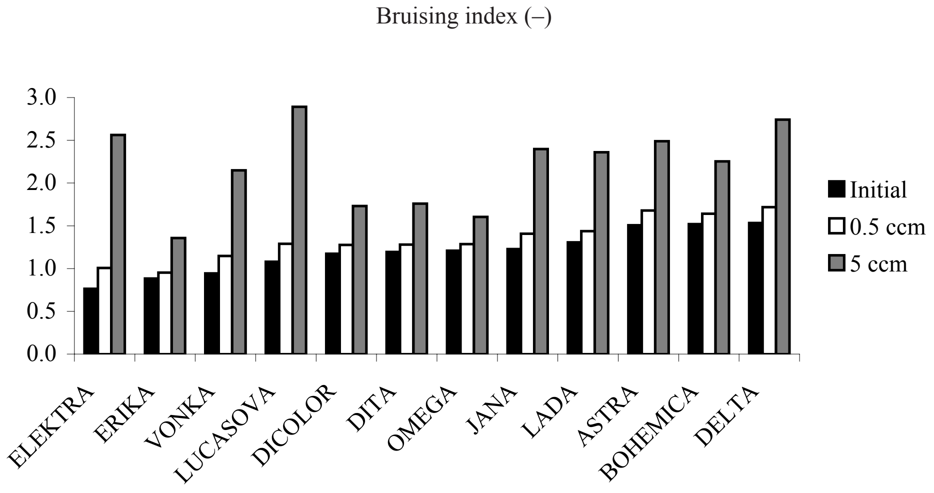

Fig. 5. The bruising index at three bruising levels for the tested varieties

Table 4. Bruising parameters obtained for degree of elasticity (0, 0.5, and 5 are volumes of corresponding bruise spots in cm^3)

Variety	R^2	*DE* – coordinates (%)			*DE* – derivatives (cm^3/percent)*		
		0	0.5	5	0	0.5	5
Astra	0.674	47.53	44.26	34.16	–0.163	–0.449	–1.333
Bohemica	0.725	48.73	46.30	37.16	–0.290	–0.531	–1.437
Delta	0.858	47.57	43.76	31.00	–0.161	–0.364	–1.046
Dicolor	0.803	58.44	56.24	46.56	–0.365	–0.542	–1.318
Dita	0.563	54.99	53.03	44.05	–0.421	–0.598	–1.407
Elektra	0.686	70.63	61.26	32.28	–0.057	–0.157	–0.465
Erika	0.816	69.16	65.77	52.40	–0.218	–0.371	–0.975
Jana	0.551	50.84	46.99	33.14	–0.175	–0.344	–0.955
Lada	0.833	52.72	49.65	34.77	–0.278	–0.373	–0.836
Lucasova	0.627	57.28	51.11	27.99	–0.114	–0.210	–0.569
Omega	0.803	55.24	53.72	48.28	–0.443	–0.876	–2.431
Vonka	0.737	62.10	55.22	38.53	–0.030	–0.260	–0.818

* $\frac{d(TBV)}{d(DE)}$ calculated from the polynomials at corresponding point

the other varieties and the other fruits. For testing the susceptibility of fruits to bruising, it is necessary to test fruits at a loading level that is close to the loading levels occurring during formation of bruise spots in real handling situations. For testing susceptibility to formation of small bruise spots, the loading levels should be as low as those where small bruise spots are formed.

CONCLUSIONS

A second order polynomial can be used to approximate of *TBV-HL* and *TBV-DE* relationships. The success of the method consists in incorporating the suitable part of the results that lead to zero bruise volume. Bruising index vas determined as a ratio of characteristic *HL*- and *DE*-values. Bruising index is a level dependent mean – the success of its application depends on correctly matching it to the load level to be studied. The variety susceptibility to bruising decreased in the following order: Elektra, Erika, Vonka, Lucasova, Dicolor, Dita, Omega, Jana, Lada, Astra, Bohemica, and Delta.

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Aproximace objemu otlaků vzniklých v hruškách v závislosti na deformačních parametrech

ABSTRAKT: Hrušky různých odrůd byly stlačovány mezi dvěma plochými a tuhými deskami v tlakovém testu s následným odtížením. Otlaky, které se objevily po inkubaci při pokojové teplotě, byly ručně vyhodnocovány a objemy těchto otlaků byly určeny. Hlavní části práce diskutují matematickou aproximaci celkového objemu otlaků na deformačních parametrech definovaných v předešlých pracích: hysterezních ztrátách a stupni elasticity. K tomu byl použit polynom druhého řádu, ale ukázalo se, že úspěch této metody závisí na rozšíření regresního souboru o další výsledky, při nichž nevznikly otlaky. Charakteristické hodnoty hysterezních ztrát a stupně elasticity byly použity k určení *indexu otlaku*, integrálního parametru, který je vhodný pro klasifikaci testovaných odrůd podle otlačitelnosti pletiv plodů při nízkých hladinách vnějšího zatížení.

Klíčová slova: hrušky; otlak; tlak; objem otlaku; hysterezní ztráty; stupeň elasticity; aproximace křivky; kvalita

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