How Should I Measure Vehicle Deformation Depth?

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Abstract: Determination of deformation energy is an integral part of the accident analysis. Deformation energy could be expressed by parameter EES, which could directly enter the calculation or serve as a control parameter. To determine the EES parameter, it is necessary to know the depth of plastic deformation. There is a lack of standardization in the process of deformation profile determination, because several mathematical models focus on the deformation profile according to established procedures, or the deformation depth is measured along the entire width of the deformation using evenly spaced points. Equal spacing of measurement points can be an unnecessary restriction when documenting traffic accident on accident scene. In the presented article, the differences between equal and non-equal spacing of measurement points and the subsequent influence on the EES calculation are analyzed. Statistical analysis confirmed that equal non-equal distribution of measurement points does not cause significant differences in the determined EES value, so equal spacing is not required. The non-equal spacing could better approximate the deformation profile including subsequent calculation of the EES value, when following certain rules.

1 INTRODUCTION

The crash analysis requires valid and precise data including deformation depth. Vehicle damage can be documented by several methods such as 2D measurement methods (photo documentation with measuring rods etc.) or 3D measurement methods (total station, photogrammetry, or 3D scanning). The purpose of the vehicle damage documentation needs to be considered to correctly select the most proprietary method and means with respect to their benefits and limitations (Bucsuházy et al., 2023; Topolšek et al., 2019).

The documentation process is influenced by various factors including the methods or means used, weather conditions, etc. The method usage should consider not only different conditions but also the crash type or damage extent (Hoxha et al., 2017). The damage profile serves as a basis for determining deformation energy, respectively energy equivalent speed (EES). EES express the deformation energy absorbed by a vehicle during a crash (e.g. Riviere et al., 2006), so EES is manifested in a form of plastic energy (Zeidler et al., 1985; Appel et al., 2002; Vangi, 2020). Therefore the EES value is usually not identical as vehicle impact speed. The EES and impact speed could be theoretically similar if the vehicle collided with a rigid non-deformable barrier and only plastic deformation occurred (e.g. Bucsuházy et al., 2023, Vangi, 2020, Daily and Shigemura, 2005). The EES value serves as a control parameter when analysing crash or could directly enter calculation e.g. using an Energy ring or Energy conservation law (Bradáč, 1999; Semela, 2014; Burg and Moser, 2014, 2017; Bucsuházy et al., 2023).

When documenting a real vehicle accident, the question of how to correctly measure the deformation profile arises to accurately reflect the damage. The number of measuring points when analysing deformation depth needs to reflect not only the deformation extent but also used calculation method (Nordhagen et al., 2006). When using the CRASH3 algorithm, six equally distributed measuring points along the entire length of the vehicle's deformation are widely used in forensic practice (Daily,

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2005,2006; Burg and Moser, 2014, Vangi 2020; Struble, 2020; Bucsuházy et al., 2023). Even though equal spacing is not required, the calculation process is simpler, so some calculation software assume equal spacing. In practice, uniform spacing could be an unnecessary restriction for crash investigators when documenting real traffic accidents (Struble, 2020; Vomhof, 2016). If the maximum deformation is not measured, the deformation profile can be distorted, which could influence the resulting analysis. Even though the maximum crush depth does not coincide with a crush measurement, it should be located and measured (Daily, 2015).

Singh (2005) analyzed how equally spaced measuring points and their number affect stiffness coefficients used to determine EES value using the CRASH3 algorithm. The author also highlighted that each analyzed traffic accident required individual expert judgment. Moravcová et al. (2024) analysed selected variables influencing EES calculation including number of measurement points, but only equal spacing was analysed. Vomhof (2016) on some case studies demonstrated the advantages and limitations of equally and non-equally distributed measuring points using the Force Balance calculation tool included in 4N6XPRT StifCalcs. Using a strictly equal measurement process could in some cases lead to significant deformation profile loss.

Despite the growing trend of using EDR, it is still necessary to validate the calculation methodology and crash reconstruction. The vehicle fleet's age does not allow EDR data to be used when analyzing all crashes until EDR technology becomes sufficiently widespread. EDR data can be beneficial for crash reconstruction and significantly reduce subjective errors such as errors arising when documenting a crash at a crash scene. When using EDR data for crash reconstruction, these still need to be verified and subsequently analyzed. Some crash types or conditions could lead to inaccuracy of the data or the possibility of obtaining the data may be also limited due to the collision character (such as significant deformation, control unit damage, vehicle skid before the crash, lower impact speed, significant mass difference etc.) (Struble, 2020; Nouzovský et al., 2021; Coyne, 2010; Bortles, 2016; Bohm, 2020).

Even though some of the previous papers demonstrated in selected case studies differences of equal and non-equal spacing of measurement points, the authors mostly do not further address the question of what effect the measurement process has on the resulting EES calculation. To fill this gap, this paper aims to analyse potential differences in the calculated EES when using equal and non-equal spacing. With regard to the difficulties associated with the equal spacing of measuring points when documenting vehicle damage directly at the accident scene, this article aims to analyze whether an even distribution of measuring points is necessary to be required.

2 METHODS

For the EES calculation, the CRASH3 algorithm will be used as one of the most frequently used calculation methods (Mrowicki et al., 2020). The crush profile will be determined using six measurement points as it is widely used in forensic practice when using the CRASH3 algorithm (Daily, 2005,2006; Burg and Moser, 2014, Vangi 2020; Struble, 2020; Bucsuházy et al., 2023). The effect of measurement point number on the resulting EES value is not the subject of this study.

2.1 Data Set

The used dataset contains 28 vehicles (see Table 1 and Table 2) with different stiffness characteristics, different classes, and manufactured years (model years 1994 to 2019). For the purpose of the study were used real traffic accident data collected by the Czech In-Depth Investigation team (project CzIDAS conducted by Transport Research Centre) and also crash tests data conducted by IFE BUT. The crash overlap varied, and so did the resulting crash deformation extent. The vehicles in the dataset were

Table 1: Dataset – vehicle characteristics (Frontal Impact).

	Vehicle	Weight [kg]	Year	Offset [%]
Frontal Impact	Skoda Fabia I	1000	2000	30
	Skoda Fabia III	1100	2015	30
	Opel Astra	950	1991	100
	Mitsubishi Carisma	1100	1995	100
	VW Bora	1555	2000	80
	Skoda Octavia I	1364	2004	50
	Skoda Octavia I	1365	2011	50
	Ford Focus	1352	2007	30
	Skoda Fabia	1490	2006	100
	Skoda Octavia I	1305	2011	80
	Honda Civic	1170	1996	100
	Skoda Felicia	892	1994	100
	Skoda Rapid	1294	2016	100
	Skoda Superb III	1476	2016	80
	Subaru Forester	1424	2002	45
	Toyota Corrola	1003	1989	100
	Opel Omega	1655	1998	100
	multipla č.	1337	2000	100
	Karoq	1661	2017	100
	Škoda Fabia	1058	2004	100

Table 2: Dataset – vehicle characteristics (Side Impact).

	Vehicle	Weight [kg]	Year	Offset [%]
Side Impact	Skoda Fabia III	1100	2015	50
	Skoda Superb III	1470	2015	35
	Skoda Karoq	1658	2019	25
	Peugeot 207	1324	2010	40
	Skoda Rapid	1294	2016	45
	Skoda Felicia	931	1994	60
	Chrysler Voyager	1762	1999	50
	Kodiaq	1879	2016	40

subsequently divided based on the damage type (frontal and side crash). Twenty vehicles were damaged in the front part (full-overlap and damage off-set) and eight vehicles were damaged on the left or right side of the vehicle in the area between the A to C pillar. Analysed vehicles were not equipped with EDR.

2.2 Vehicle Profile Documentation

The vehicle damage was documented using 3D scanning - Faro Focus 120 laser scanner or a Leica RTC360 laser scanner - as the most precise method which allows efficient, accurate, and quick data collection. Besides the conventional methods for measuring vehicle damage (such as photo-documentation of damage with a measuring rod), laser scanning allows also variation in post-process measurement (Morales et al.., 2015; Coleman et al., 2015, Tandy et al., 2012, Grimes et al., 2018; Kamnik et al., 2020; Kamnik et al., 2022).

The processing procedure will be demonstrated by the example from a real traffic accident.

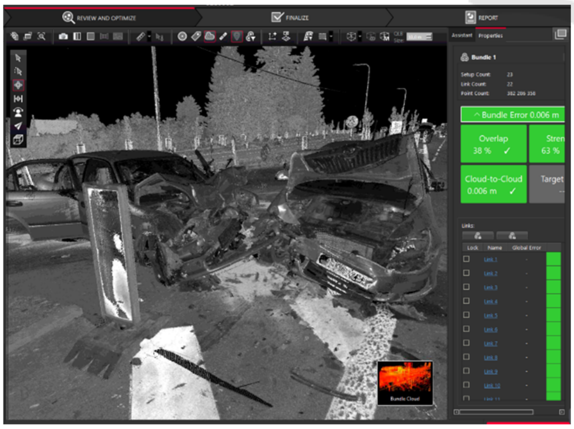

Figure 1: Point cloud processing of a nighttime traffic accident.

The postprocessing was realised using Geomagic Control software. Using 3D model obtained from laser scanning allows to select a 2D cut at a defined height. The cut for frontal damage was determined at the bumper height (respectively height of the vehicle impact bar) and for side damage at the collision opponent's bumper height (respectively height of the collision opponent's impact bar).

Before measuring the deformation profile, it is necessary to determine the deformation width - considering the character of the deformation, the width was defined either from the edge to the edge of the vehicle, from the edge of the vehicle to the end of the deformation or from the beginning of the deformation to the end of the deformation. The vehicle deformation profile was determined using six measuring points (5 zones). When using equal spacing of measuring points, the width of the deformation was subdivided by the number of zones.

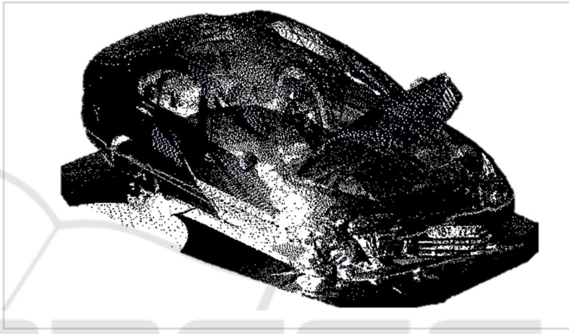

Figure 2: Processing a scan of the Skoda Octavia vehicle in the Geomagic Control software.

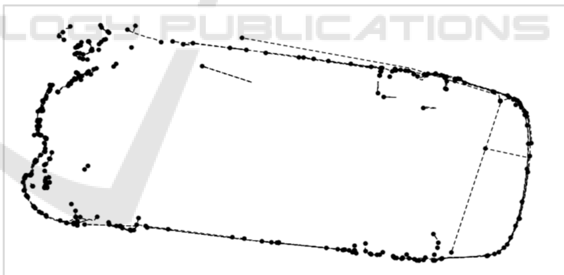

Figure 3: 2D cut at the height of Skoda Octavia vehicle bumper.

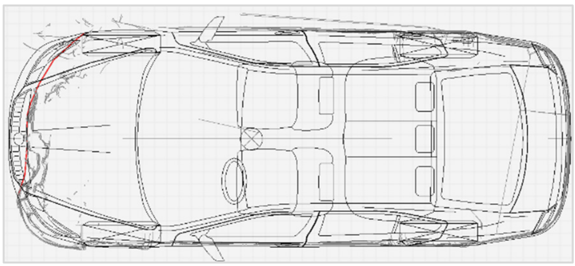

Figure 4: Comparison of a 2D cut of a damaged vehicle and an undamaged Skoda Octavia vehicle model.

When using a non-equal spacing of measuring points, the measuring points were considered at deflection points, i.e. points at which the deformation profile significantly changes. Such spacing allows us to accurately approximate the deformation profile incl. determining the maximum deformation.

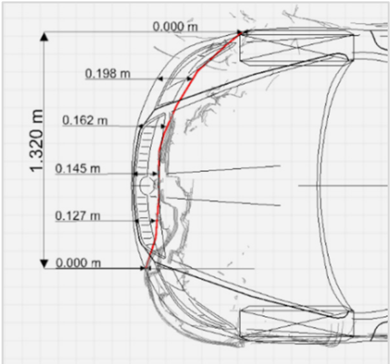

Figure 5: Measuring the depth of deformation of the Skoda Octavia vehicle.

3 RESULTS

The paper aims to analyse potential differences in the calculated EES value when using equal and non-equal measuring points for crush measurement.

For the comparison were used differences in the calculated EES when using equal and non-equal measuring points for crush measurement and analysed EES value. Analyzed EES value was determined based on vehicle crash tests (measured values in crash tests) and using a combination of methods for EES determination (Triangle method, Comparison method, CRASH3 software using various number of measuring points, Energy grid, or Estimation by a Professional/Expert – see e,g, Campbell, 1974; Shaper, 1981; Bradáč, 1999; Vangi, 2020, Bucsuházy et al., 2023).

EES when using equal and non-equal measuring points for deformation profile determination was calculated using CRASH3 software for frontal impacts. Determination of the vehicle side EES value was based on Newton's third law (Use of the Law of Action and Reaction) with the known EES value of the collision opponent. The deformation depth is also part of this calculation.

The differences among calculated EES when using equal and non-equal measuring points for crush measurement and analyzed EES value are illustrated in the following figures (see figure 6 and 7).

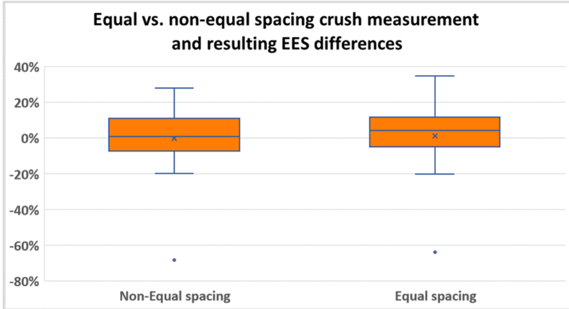

Figure 6: The difference in the analyzed and calculated EES value using equal and non-equal spacing crush measurement.

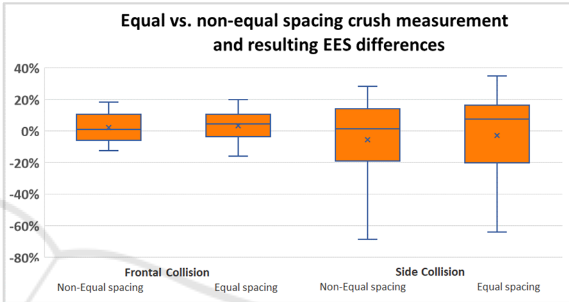

Figure 7: The difference in the analyzed and calculated EES value using equal and non-equal spacing crush measurement – frontal and side collision.

Significant outliers (especially in the case of a side impact) illustrated in figures 6 and 7 are caused by the diversity of the condition of vehicles in the dataset (such as significant corrosion). This incorrect EES estimation was realized when calculating the EES of the Skoda Felicia vehicle, whose load-bearing parts of the body incl. impact bar were subjected to a high degree of corrosion. The calculation does not consider such a significant degree of corrosion, which can lead to an incorrect determination of the EES value. Calculated EES value does not correspond with EES value obtained based on the vehicle crash test. High deviation can be also caused by an inaccurate determination of the opponent's EES value, which could negatively affect the subject vehicle EES calculation. The sensitivity of the EES opponent's EES value is not subject of this study.

There were also higher deviation in the EES calculation of the Skoda Superb III vehicle (side collision), where the EES value was underestimated by 35% when using equal spacing and by 28% when using non-equal spacing. The underestimation of EES when using the equal distribution of the measuring points was mainly influenced by the fact that the measuring points did not coincide with a maximum deformation depth. The EES calculation for side collision is very sensitive to parameter average crush depth.

A slight overestimation of the EES value was detected also when analyzing VW Bora (frontal collision) - by 16% when using equal spacing (see figure 8). While in the case of non-equal spacing, the measuring points (see figure 9) are focused mainly in the region of the impact bar, the equal spacing includes the maximum deformation depth outside the impact bar, which may subsequently affect the EES calculation.

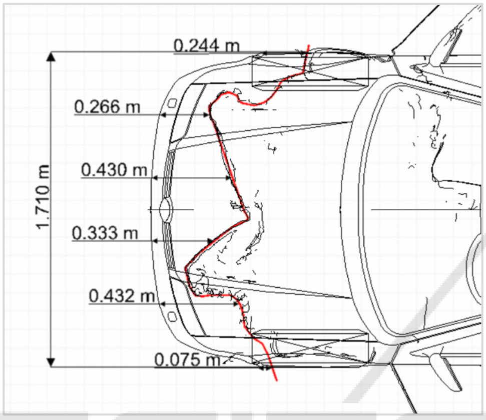

Figure 8: VW Bora – equal spacing.

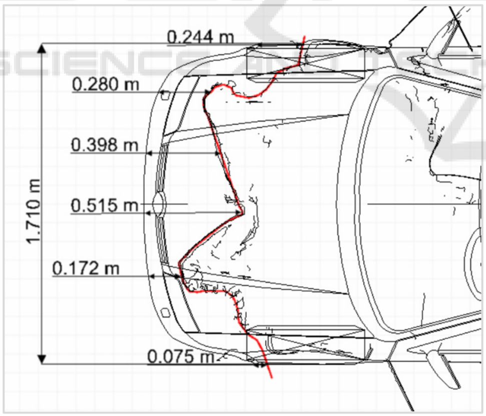

Figure 9: VW Bora – non-equal spacing.

An analogous problem led to slight inaccuracies in the EES calculation of the Ford Focus vehicle when using non-equal spacing (overestimation of EES by 13%). The maximum deformation depth when using non-equal spacing was measured outside the impact bar region (see figure 10). When using equal spacing, the EES value was determined correctly – in this case study the maximum deformation depth measured coincided with the measuring points in the region of impact bar (see figure 11).

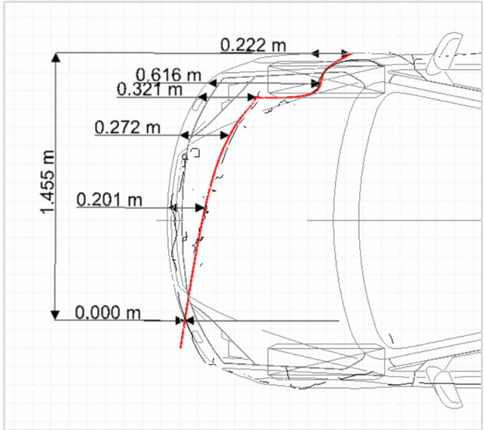

Figure 10: Ford Focus – non-equal spacing.

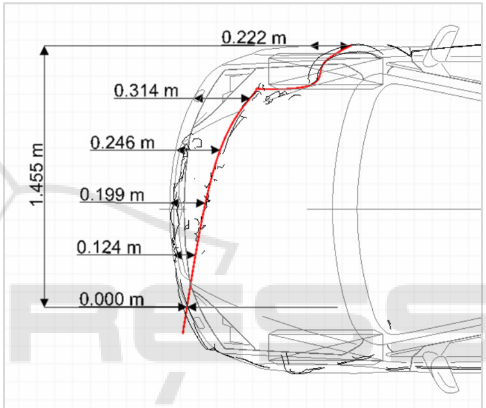

Figure 11: Ford Focus – equal spacing.

Based on the case studies (VW Bora and Ford Focus) the question of using deformation width only in the region of impact bar arises. However, the analysis of deformation width variation is not the subject of the study. Measuring of the maximum deformation depth should consider the location of the impact bar considering the stiffness of the vehicle and its parts.

Overestimation or underestimation of EES value can also be caused by using the inappropriate substitute vehicle (vehicle with known EES value or stiffness) from the crash test database, which is used to determine the stiffness characteristic. The most frequently used and publicly available crash test databases (NHTSA, IIHS) contained new vehicles. Even if a parametrically similar substitute vehicle is found in the crash test database, in case of an extensive corrosion of the vehicle in question is not possible to create appropriate stiffness characteristics (as could be seen from the already mentioned Skoda Felicia or the analyzed Toyota Corolla where the calculated EES values do not correspond with the

EES values obtained based on measured data from vehicle crash tests).

To analyse potential differences in the calculated EES value when using equal and non-equal measuring points for crush measurement, the obtained values were statistically tested. Mann-Whitney Test confirmed that the differences between calculated EES when using equal and non-equal spacing of measuring points are not statistically significant. Similarities in the resulting EES differences are illustrated also by box plots on the figures (see figure 6 and 7). The differences are not statistically significant even when considering separately frontal and side impacts (see figure 7).

The equal spacing shows slightly higher variability in resulting EES, but the difference in the median values is approx. 2 km/h which is not significant especially considering the fact that the EES value is determined in technically acceptable range frequently with e.g. 5% tolerance. So the median difference and also 25. and 75. Percentile values are in the tolerance with respect to the inaccuracy/technically acceptable tolerance of the EES determination.

Figure 12 and 13 demonstrates the influence of the average crush depth on the resulting EES value when using equal and non-equal spacing. The resulting EES obviously increases with the higher average deformation depth. A trend line better fits the data when using equally spaced measuring points. The data visualisation confirmed negligible difference when using equal and non-equal crush profile measurement for both frontal and side impacts/damage.

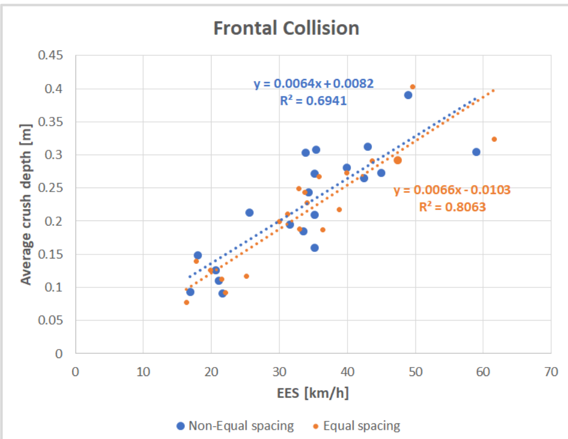

Figure 12: Dependence of the average deformation depth on the resulting EES value in frontal impacts.

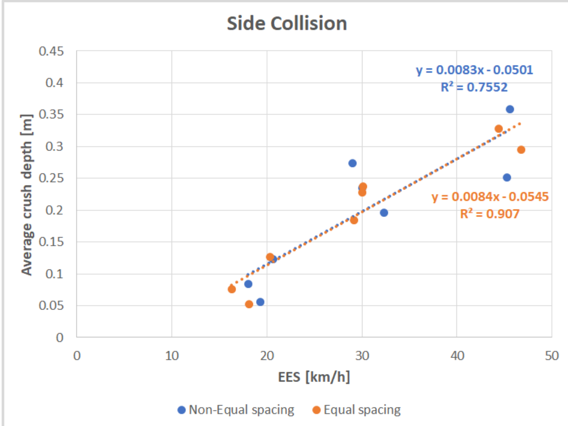

Figure 13: Dependence of the average deformation depth on the resulting EES value in side impacts.

The correlation between measured and calculated EES values when using equal and non-equal spacing was also analyzed.

For frontal and also side impacts are the correlation coefficients almost identical for equal and non-equal spacing. For frontal impacts (figure 14) reached 0.958 for both types of spacing. For side impacts (figure 15) are correlation coefficients lower than for frontal impact (0.7 for equal spacing and 0.68 for non-equal spacing, so the difference is negligible). The lower correlation coefficient and also lower reliability of trendlines are mainly influenced by the limited number of side impacts in analyzed dataset.

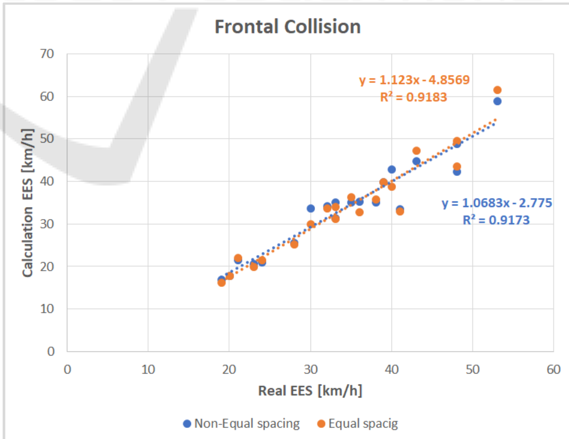

Figure 14: Correlation between measured and calculated EES values - frontal impact.

If the deformation profile character is significantly heterogeneous (does not have a simple geometry) it seems more at deflection points (where the deformation profile changes), so the measured

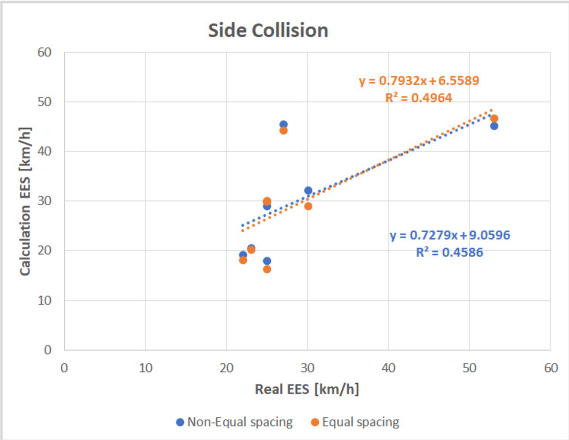

Figure 15: Correlation between measured and calculated EES values - side impact.

profile more corresponds with the real deformation profile extent. In the case of equal spacing, these points may be omitted (ie, for example, the maximum deformation depth), which may lead to an underestimation of the calculated EES value. This can be illustrated by figure 16, where equal spacing is marked in red and non-equal spacing in blue.

The procedure of non-equal spacing seems more feasible even in real conditions.

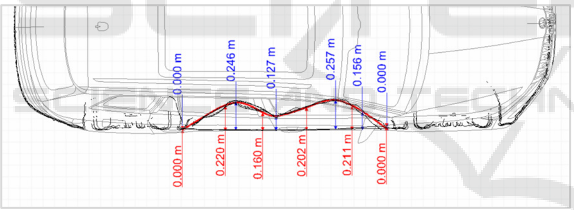

Figure 16: Measurement crush depth – equal and non-equal spacing.

5 DISCUSSIONS

The paper aims to analyze differences in EES calculation when using non-equal and equal spacing of measurement points for the deformation profile determination. For the purpose of the analysis dataset used includes 28 vehicles from real traffic accidents and crash tests. The EES calculation was conducted using CRASH3 algorithm. The deformation profile was analyzed using 6 measuring points, which is common in forensic practice (Daily, 2005,2006; Burg and Moser, 2014, Vangi 2020; Struble, 2020; Bucsuházy et al., 2023).

Equal spacing is widely used when analyzing deformation in laboratory conditions (crash tests) or when postprocessing the data obtained from the accident scene. But it is necessary to highlight that equal spacing deformation profile measurement could be difficult in the practise when documenting real crashes as described e.g by Struble (2020). Crash tests into rigid non-deformable barrier lead to an almost rectangular deformation profile, so equal spacing is suitable.

However, in real accidents (especially narrow obstacle impacts, crashes with overlap, etc.) is the resulting deformation rectangular only rarely. In most cases, the resulting deformation profile is irregular. Using strictly equal spacing in case of an irregular deformation profile can cause the maximum deformation depth to be missed (not measured).

Demonstrated case studies shows that non-equal spacing of measurement points can lead to more accurate EES calculation, which confirms the conclusions described by Vomhof (2016). But certain rules need to be followed. When using non-equal spacing and deformation width from edge to edge of the vehicle, the first and last measuring points should be on the vehicle edge, but the other measuring points should be concentrated into the region of impact bar. Positioned of measuring points outside the impact bar leads to incorrect calculation of the EES value.

With regard to the difficulties associated with the equal spacing of measuring points when documenting vehicle damage directly at the accident scene, this article aims to confirmed that equally spacing is not required (which was shows using statistical analysis of EES calculated based on deformation profile determined using equal and also non-equal spacing of measurement points).

Study faced several limitations:

- Dataset included only 8 side impacts, which is insufficient for detailed statistical analysis. The increase of the vehicles in the dataset could increase the precision of obtained results.
- For the deformation profile determination was used six measurement points – which is widely used in forensic practise especially using CRASH3 algorithm. The increase of measurement points should lead to better approximation of the deformation profile. The analysis of measurement point variation is not the subject of the study and should be further analysed.
- Calculated EES was compared with analysed EES obtained based on vehicle crash tests (measured values in crash tests) and using a combination of methods for EES

determination. The EES is determined in technically acceptable range.
- Resulting EES value could be significantly affected by the selected substitute from the crash test database. Using of CRASH3 algorithm faced also limitations related to assumption of linear stiffness characteristics.

Deformation profile is not the only factor affecting the EES calculation. The EES calculation is influenced by various factors such as mentioned vehicle stiffness, conditions of the vehicle, used method and means etc.). The further research should be focused on the comprehensive analysis of more factors which enters the calculation (such as the number of measurement points, deformation width etc.).

6 CONCLUSION

The accident analysis i.e. reconstruction approach works backward from the evidence of the crash investigation which includes vehicle damage analysis. The determination of deformation energy which could be expressed by the EES parameter is influenced by the accuracy of input parameters including the deformation depth. While documenting traffic accidents at the accident scene, the conditions and time restrictions could influence the precision of the obtained data. Equal spacing of measurement points can be an unnecessary restriction and, in some cases, can also lead to inaccuracy in the resulting analysis. Statistical analysis confirmed that equal non-equal distribution of measurement points does not cause significant deviations in the determined EES value, so equal spacing is not required. The determined EES values are within the technically accepted range. The non-equal spacing could better approximate the deformation profile incl. subsequent calculation of the EES value, when following certain rules.

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