

Estimation of the EES parameter value – a case study of the Toyota Yaris Hybrid

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Motor vehicles undergo plastic deformation when they collide with each other or with another obstacle, leading to a loss of the system's kinetic energy. The work of permanent deformation of a vehicle involved in a collision is equal to the loss of kinetic energy and is often represented as the value EES, i.e., Energy Equivalent Speed. This article describes three well-known and commonly used methods for estimating the value of deformation work: comparative, analytical, and graphical methods. The later section presents the calculation of the EES parameter using a comparative approach for a hybrid passenger vehicle struck by a motorcycle. Possible differences in estimating the EES parameter value have been identified using this method for both standard and hybrid vehicles.

Key words: *EES parameter, comparative method, hybrid vehicles, car deformation, case study*

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1. Introduction

The constantly increasing number of cars on the roads results in a high daily number of accidents. According to the 2024 Annual Police Report [21] on road accidents, the number of passenger vehicles increased by more than 2 million between 2020 and 2023. Although the number of cars fell by 16% between 2023 and 2024, the number of road accidents increased by almost 3% during this period. Moreover, the share of vehicle-to-vehicle collisions remains approximately 53% of total accidents. To enhance safety, new obligations are being imposed on car manufacturers, among other measures. One of these is the obligation to equip new vehicles with so-called black boxes, or EDRs (Event Data Recorders), which are mandatory in the European Union from 7 July 2024. The purpose of this device is to record the vehicle's speed before and during a collision.

However, for older vehicles without a black box installed, calculating collision speed is subject to certain limitations. In the absence of skid marks or evidence of wheel lock-up, which would allow the calculation of speed at the time of the accident, it is possible to estimate the speed based on the extent of vehicle deformation.

As the literature review shows, many authors address the problem of estimating vehicle collision speed using the Energy Equivalent Speed (EES) parameter, presenting both the theoretical foundations and practical applications of selected methods [2, 17]. In [2], a comparative analysis of EES estimation methods for vehicles with different structural materials was performed, demonstrating a significant influence of material characteristics and impact type on the obtained deformation energy values. In turn, [17] presents the results of experimental studies aimed at assessing the applicability and limitations of selected EES methods in the context of changes in vehicle stiffness resulting from technological development.

The practical application of the comparative method is also presented in [4], where collision speed was estimated on the basis of post-accident photographic documentation and damage data for a collision between a Fiat Punto

and a Smart Roadster, classified as vehicles with atypical mass and structural parameters.

Another group of publications comprises studies employing simulation tools based on the finite element method. In [29], a finite element model available in the PC-Crash software was used to determine the EES parameter of a passenger car damaged as a result of a collision with an atypical obstacle, namely the rear of a wheel loader. The authors demonstrated a significant influence of the adopted structural vehicle model on the deformation pattern and the resulting EES value. A similar approach is presented in [16], where the authors emphasize the high sensitivity of simulation results to input parameters and the need to verify simulation outcomes using alternative EES estimation methods.

In many studies, the authors do not limit their analyses to a single computational method. Examples include publications [1, 7, 17], in which the collision speed was estimated using the CRASH3 method and subsequently verified using the comparative method or crash test data. Such an approach enables an assessment of result reliability and facilitates the identification of limitations inherent to individual methods.

The literature also reports alternative approaches to EES estimation, including the application of the Monte Carlo method [26] for uncertainty analysis, the triangle method [25] for simplified energy loss estimation based on deformation geometry, and the total differential method [15] for quantifying uncertainty in EES calculations. An interesting complement to classical approaches is provided in [28], where the possibility of estimating EES solely on the basis of photographic documentation was assessed; however, the authors demonstrated that this method can serve only as an auxiliary tool.

An important source of reference data in EES analyses is provided by crash test reports, particularly studies based on the NHTSA (National Highway Traffic Safety Administration) test databases [15, 20], which enable the evaluation of the influence of vehicle design and age on defor-

mation characteristics and energy absorption during a collision.

A different, more methodological perspective on the problem of EES determination is presented in [18], where the authors focus on analyzing the influence of the deformation profile description on calculation results obtained using the CRASH3 algorithm. In contrast to studies comparing reconstruction methods or computational tools, this publication addresses the selection of an appropriate number of measurement points for describing vehicle deformation.

This study constitutes a complementary contribution to existing research on the EES parameter, shifting the emphasis from the computational model itself to the quality and representativeness of input data, which is particularly important for improving the repeatability and comparability of accident reconstruction results.

The conducted literature review indicates that existing studies on EES determination primarily compare computational methods, simulation tools, and selected input parameters, such as structural material characteristics, vehicle age, and applied technological solutions. Numerous studies have demonstrated that these factors may significantly influence deformation behavior and the amount of energy absorbed during a collision. At the same time, vehicles are typically treated as a homogeneous group, without differentiation by powertrain type.

Meanwhile, hybrid vehicles, compared to vehicles equipped exclusively with internal combustion engines, feature a different structural layout due to additional components, such as traction batteries, electric motors, and structural reinforcements required for their installation. These differences may affect mass distribution, local stiffness, and energy-absorption mechanisms during a collision, and consequently the determined EES value. The lack of consideration of these aspects in previous studies justifies further research focused on assessing the influence of hybrid powertrains on the EES estimation process.

2. Methods of estimating vehicle deformation work

2.1. General proceedings

According to the laws of physics, every moving body has its own velocity and, consequently, kinetic energy [23]. It can be calculated using formula (1):

$$E_k = \frac{1}{2} * m * v^2 \text{ [J]} \quad (1)$$

where: E_k – kinetic energy [J], m – vehicle mass [kg], v – vehicle velocity [m/s].

During collisions with elastic-plastic bodies, kinetic energy is lost within the system. The loss is equal to the total deformation work (W_D) of both vehicles, which can be expressed as (2):

$$\Delta E \cong W_D \quad (2)$$

where: ΔE – a loss of kinetic energy [J], W_D – deformation work [J].

In practice, the work of permanent deformation is usually represented as equivalent to kinetic energy, using the parameter EES (Energy Equivalent Speed) [27]. This parameter is expressed in units of m/s and corresponds to the

speed at which an identical vehicle, when collided with a rigid, non-deformable barrier, would undergo identical plastic deformations [24]. The kinetic energy lost by the vehicle during a collision is entirely absorbed by its deformation (3):

$$E_d = W_D = \frac{m * EES^2}{2} \quad (3)$$

where: E_d – kinetic energy of deformation [J], EES – Energy Equivalent Speed [km/h], W_D and m – like before.

Hence, the value of the EES parameter can be determined from equation (4):

$$EES = \sqrt{\frac{2 * W_D}{m}} \quad (4)$$

where: EES, W_D and m – like before.

To estimate the EES parameter, the following methods can be applied:

1. comparative, using available catalogues containing actual cases of vehicle damage with known W_D
2. graphically, using rasters, i.e., distribution grids of W_D
3. analytical, using appropriate mathematical formulas to calculate W_D depending on the depth of vehicle body deformation [27].

Research carried out [2] indicates that different materials used in vehicle construction have a substantial impact on the magnitude of residual deformation, and therefore on the correct estimation of the EES parameter using the methods discussed. Furthermore, when comparing identical vehicle models from different production years that differ in construction materials, including rigidity, it has been shown that newer vehicles experience less deformation [15]. Therefore, in light of the growing number of "new generation" vehicles on the roads, it is appropriate to review the methods used so far for assessing traffic theory issues related to collisions.

2.2. Comparative method

The comparative method relies heavily on the database to identify the vehicle model that matches the one for which the EES parameter value is sought. The identified vehicle must be identical not only in the make and model but also in the extent of its damage. If an appropriate vehicle cannot be found, the one with the most similar construction and a comparable deformation pattern should be chosen [7]. In this scenario, it is essential to consider the difference in the masses of the cars being compared using the appropriate formula (5) [17]:

$$EES_{\text{vehicle}} = \sqrt{\frac{m_{\text{etalon}}}{m_{\text{vehicle}}}} * EES_{\text{etalon}} \quad (5)$$

where: EES_{vehicle} – EES parameter value sought, m_{etalon} – mass of the vehicle selected from the catalogue [kg], m_{vehicle} – mass of the vehicle for which we are seeking the EES value [kg], EES_{etalon} – EES parameter value for the vehicle selected from the catalogue.

Among the available catalogues, the database in the PC-Crash program [22], Dr. Melegh's database [6], or the online databases [8–10, 19] can be mentioned, which, in addition to the Melegh catalogue data, also contain other cases. This method is considered the simplest and is there-

fore the most commonly used. However, its drawback is the limited range of vehicles available in the databases, mainly the absence of the latest models.

2.3. Graphic method

To apply the graphic method, it is essential to use deformation work distribution grids of the vehicle's body. Each section of the grid shows the work required to deform that part of the vehicle [27]. In 1974, Campbell [3] proposed a grid model assuming an even distribution of deformation energy across the vehicle's width and height. Subsequently, Röhlich developed this model based on crash-test results, indicating that the deformation energy does not distribute evenly [13]. He developed deformation work distribution grids for the following areas of the vehicle: front, rear, sides, front corners, and rear corners. Currently, the use of these grids is limited, as they are suitable only for vehicles weighing 950 kg with rear-wheel drive and a front-mounted engine [27]. Only A-segment vehicles, including the Toyota Aygo, Fiat 500, and Peugeot 107, currently comply with the mass criterion. It is also necessary to consider the structural and technological differences between current vehicles and designs from the 1970s and 1980s.

2.4. Analytical method

Analytical methods constitute the largest group of methods for estimating the EES parameter. Various authors suggest applying different mathematical models or combining certain methods, such as comparative and analytical methods.

An example is [4], where the author calculated the EES parameter for the unique sports vehicle, the Smart Roadster. This car collided with a Fiat Punto, for which the EES parameter was estimated by comparing it with three other similar vehicles. Knowing that the maximum force acting on both vehicles during the collision is the same for each [11], the author first calculated the plastic component of the deformation energy for the Fiat vehicle and, based on this, determined the EES parameter for the Smart vehicle.

Meanwhile, Wach [26] presents the Monte Carlo method, which involves repeatedly performing calculations using the same mathematical model. Calculation data are randomly selected from specified uncertainty ranges. This method is used, for example, in the PC-Crash program to obtain optimal pre-collision movement parameters of the vehicles involved in the incident. This program performs 100 iterations, allowing it to avoid situations where other algorithms might get stuck in a local minimum [5].

Vangi describes a method known as the "triangle method" [25], which combines a visual assessment of vehicle deformation with methods for measuring residual deformation to evaluate energy loss in any vehicle deformation profile. In this method, a stiffness curve is determined for a reference vehicle, the EES parameter of the tested vehicle is then established, and the deformation energy is calculated.

The vehicle's deformation energy can also be calculated using the CRASH3 algorithm, based on NHTSA's published results [5]. This is a computer program from CALSPAN Corporation, whose name is an acronym for Calspan Reconstruction of Accident Speeds on the High-

way. It allows analysis of vehicle collisions, determining their speed, energy, and direction of movement using analytical techniques [14]. Many factors influence the determination of EES using the CRASH3 computational algorithm, particularly stiffness, availability of studied or comparable vehicles, and the limited range of crash tests performed [18]. As demonstrated in [12], the uncertainty in estimating the EES parameter using the described method is the lowest among commonly applied approaches, such as the simplified method or the method implemented in the PC-CRASH software.

3. Case study for a hybrid vehicle

The results of calculating the EES parameter for the 2018 Toyota Yaris Hybrid vehicle, which was struck by a Honda CBR600F motorcycle, are summarized below. The vehicles involved in the incident are shown in Fig. 1 and Fig. 2, respectively. Before the collision, the motorcycle was traveling on a main road in a built-up area with a 50 km/h speed limit. The Toyota Yaris Hybrid was stopped on a secondary road, right next to the intersection with the main road. The driver initiated a left turn onto the main road. While at the intersection, he noticed a motorcycle approaching. The driver decided to stop the vehicle within the motorcycle's lane of travel. The motorcycle driver failed to avoid the vehicle, resulting in a head-on collision. The motorcycle struck the center of the Toyota's front bumper.

In the analysis of damage to the Honda CBR600F motorcycle, an empirical formula (6) cited in the literature [24] was applied, which allows estimation of the motorcycle's collision speed based on the reduction in the wheelbase length between its front and rear wheels:

$$v_k = 1.38 \cdot d + 16.58 \quad (6)$$

where: v_k – motorcycle's collision speed, d – reduction of the wheelbase [cm].

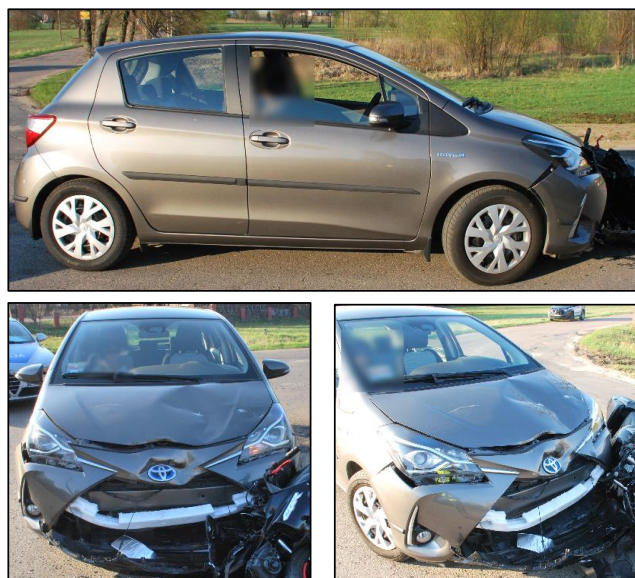


Fig. 1. Illustration of the deformation of the Toyota Yaris Hybrid vehicle



Fig. 2. Illustration of the deformation of the Honda CBR600F motorcycle

The wheelbase reduction for this motorcycle was 11 cm \pm 1 cm. The motorcycle's collision speed was determined to be 30 to 33 km/h.

Measuring the deformation depth of the Toyota Yaris Hybrid was impossible because only photos of the damaged vehicle were available. Moreover, the available photographs were insufficient to generate a point cloud, which would have allowed an approximate measurement of these depths using computer software. Deformation meshes (rasters) were unavailable for this vehicle, so it was impossible to determine the resulting deformation work (W_D). The only option in this case was to use a comparative method.

The same vehicle model, i.e. the Toyota Yaris Hybrid, was not found in the available EES databases. To implement the comparative method, several similar vehicles were selected from the DSD ReconData database [22] and the Melegha database [6]. The selected vehicles had similar damage – deformed front ends, including the front bumper and engine cover. Vehicles with a weight within \pm 20% of the target vehicle's weight were selected for comparison. The accepted mass deviation was due to data availability – only 5 similar vehicles were available within the \pm 10% mass range, which was deemed an insufficient sample. On the other hand, accepting a deviation beyond 20% signified taking into account vehicles that were too structurally dissimilar, which went against the aim of the comparison.

As mentioned in the theoretical introduction, a drawback of these databases is the absence of the latest vehicles. It should therefore come as no surprise that all the vehicles used were significantly older than the vehicle under study – the selected vehicles were from 1998 to 2010. Furthermore, none of the vehicles selected for comparison were hybrid vehicles. The list of selected vehicles for comparison is shown in Fig. 3 (from the DSD ReconData database) and in Fig. 4 (from the Melegha database).

The EES parameter for the Toyota Yaris Hybrid vehicle was then calculated using formula (5). Due to the lack of precise mass data for this vehicle, a vehicle mass of 1100 kg was assumed for calculations, based on the manufacturer-provided average mass for this vehicle model. The values of the m_{etalon} and EES_{etalon} parameters were taken from the appropriate databases. The results of the calculations are presented in Table 1.

The calculations presented indicate that the EES parameter for the Toyota Yaris Hybrid was within the range of 15–29 km/h, with an average of 20 km/h. Since the Toyota vehicle in the study was stationary at the moment of impact, the results should be compared with the Honda motorcy-

cle's collision speed. Thus, it can be stated that the average speed at which damage occurred to the Toyota vehicle, estimated using the comparative method, is approximately 33–39% lower than the calculated collision speed of the motorcycle (30–33 km/h).

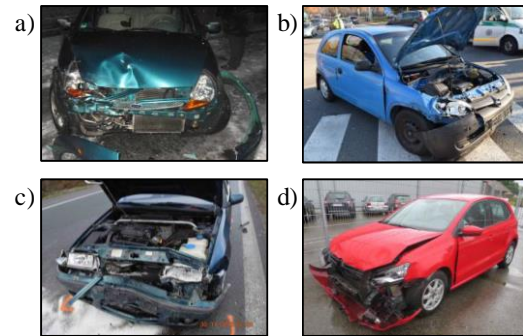


Fig. 3. Selected cases of deformed vehicles from the DSD ReconData database: a) Ford Ka, b) Opel Corsa, c) Skoda Felicia, d) VW Polo

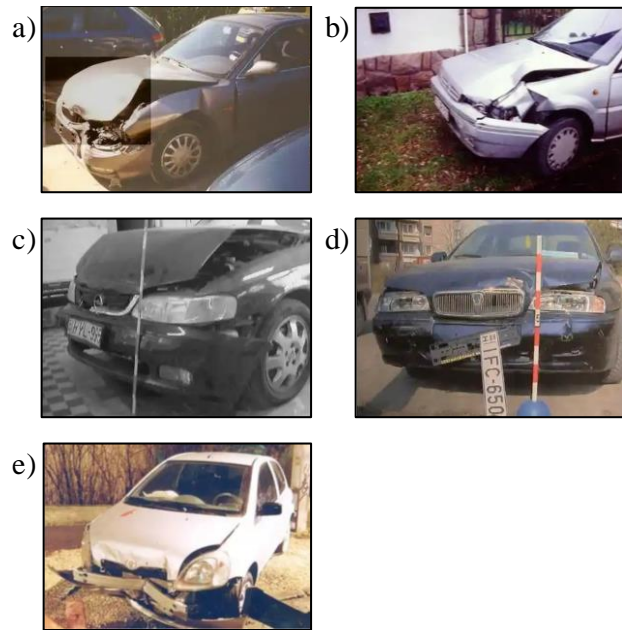


Fig. 4. Selected cases of deformed vehicles from Dr. Melegha's database: a) Nissan Almera, b) Nissan Almera, c) Opel Vectra, d) Rover 400, e) Toyota Yaris

Table 1. Calculation results of the EES parameter for the Toyota Yaris Hybrid vehicle

Brand & model	Year of production	m_{etalon} [m]	EES_{etalon} [km/h]	$EES_{vehicle}$ [km/h]
Ford Ka	2001	946	20	19
Opel Corsa	2001	905	17	15
Skoda Felicia	1998	985	23	22
VW Polo	2010	1077	20	20
Mazda Xedos	1995	1145	21	21
Nissan Almera	1997	1060	16	16
Opel Vectra	1998	1270	27	29
Rover 400	2001	1120	16	16
Toyota Yaris	2002	1000	24	23

The vehicles selected for comparison, despite having similar parameters (external design, mass), sustained simi-

lar damage at lower collision speeds. This shows that the Toyota Yaris Hybrid is more resistant to deformation than older vehicles, and consequently, a comparable damage pattern required greater deformation work of the body structure. Construction materials used in older vehicles were much more prone to deformation.

The most similar result ($EES_{\text{vehicle}} = 29 \text{ km/h}$) was obtained from the comparison of the Opel Vectra B. It can be concluded that, structurally, this vehicle most closely resembles the Toyota Yaris Hybrid.

The results obtained are therefore subject to an error exceeding 10%, hence their use in the analysed case is not appropriate. It should be noted that the well-known methods for estimating the EES parameter for newer vehicle designs, including hybrid vehicles, may not always be appropriate. There is, therefore, a need to conduct a more comprehensive analysis of the influence of the construction parameters of newer-generation vehicles on the range of their deformation following a collision.

4. Final conclusions

Among the available methods for estimating the EES parameter, the best results are obtained using analytical methods. However, their use requires measuring the actual depth of vehicle deformation. Without this capability, the chance of correctly determining the EES parameter decreases. An alternative is to generate a point cloud and measure the approximate depth of deformation using appropriate computer software. However, this requires appropriate photographic material, i.e., a sufficient number of photos of the damaged vehicle, taken from various angles.

If the available input data is insufficient, the comparative method remains. Still, it is important to consider that a suitable vehicle may not be found in the available databases. This is especially true when estimating the EES

parameter for newer generation vehicles, including hybrid or electric vehicles.

It is advisable to search for more relevant cases in the catalogues. The more similar the cases are, the fewer errors the results should have. Nevertheless, it should not be forgotten that vehicles similar in shape, mass, and extent of damage differ in their internal construction and materials used, which affects the value of the EES parameter.

In the analyzed case, where a Toyota Yaris Hybrid collided with a Honda CBR600F motorcycle, due to insufficient photographic material and the lack of precise deformation depth, the only option was to use the comparative method. No identical vehicles were found in the available databases, either by model or by design (hybrid vehicle). The vehicles most similar in appearance, weight, and extent of damage were older ones, aged 8–20 years.

The results showed that the reference material used was inadequate. The obtained EES values differed by over 30% from the collision speed calculated for the motorcycle. This discrepancy in results may indicate differences in body stiffness between the tested vehicle and the comparison vehicles.

The conducted analysis indicates that the currently used methods for estimating the EES parameter do not explicitly account for structural differences arising from vehicle drive systems. Hybrid vehicles, compared to vehicles equipped exclusively with internal combustion engines, exhibit a different mass distribution and additional structural components, such as traction batteries and electric motors, which may affect deformation behavior and the amount of energy absorbed during a collision. The results confirm that neglecting these differences in selecting reference vehicles or comparative data may lead to significant discrepancies in the determined EES values, underscoring the need for further research on vehicles equipped with alternative drive systems.

Nomenclature

EDR event data recorder

EES energy equivalent speed

NHTSA National Highway Traffic Safety Administration

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