

Correlations between road barrier parameters with ASI and THiV (EN 1317) and their impact on driver and passenger safety during a crash

Abstract: The article presents an extended analysis of the relationship between key road barrier parameters and occupant load indices: Acceleration Severity Index *ASI* and Theoretical Head Impact Velocity *THiV*. Three characteristics of high engineering importance were assessed: post spacing, barrier height, and normalized working width. In addition to classical Pearson and Spearman correlations and partial correlations (controlling for TBxx test class and vehicle type), the study presents marginal effects curves with 95% confidence intervals derived from multivariate linear models. The results confirm that greater system compliance (larger spacing and greater working width) is associated with reduced *ASI* and *THiV*, while increasing barrier height in the analyzed dataset corresponds to higher *ASI/THiV* values. The article also discusses design implications and directions for further research.

Keywords: Acceleration Severity Index (*ASI*), barrier height, EN 1317 standard, normalized working width, post spacing, road safety barriers, Theoretical Head Impact Velocity (*THiV*)

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1. INTRODUCTION

Vehicle Restraint Systems (road barriers) serve primarily to mitigate the consequences of traffic incidents by containing the vehicle and preventing roadway departure or entry into an object, area, or lane presenting an elevated collision risk; in this sense, they constitute a fundamental element of risk management in road infrastructure.

In design and certification practice, indices describing the vehicle-barrier interaction and potential occupant impact severity are of paramount importance. Within the EN 1317 standards [1-5] and associated literature [6-8], this role is fulfilled inter alia by the *ASI* (Acceleration Severity Index) and *THiV* (Theoretical Head Impact Velocity) indices, which, although related, convey distinct information regarding the acceleration profile and head kinematics.

This study focuses on the relationships between the geometric-structural characteristics of road barriers and these indices, while controlling for variability resulting from the test class (TB11, TB21, TB32, etc.) and vehicle type. It is hypothesized that greater compliance of the barrier-vehicle system (increased post spacing and greater normalized working width) leads to a reduction in *ASI* and *THiV*, which can be attributed to the elongation of the interaction duration and the reduction of peak acceleration values [9-14].

Road barriers assessed according to EN 1317 remain a central element of collision risk management. Design practice additionally utilizes guidelines from industry organizations and analyses from road safety observatories; the MASH guidelines are also considered in a comparative context [7].

Previous research results indicate that geometric parameters (post spacing, barrier height, working width as defined by EN 1317) can modulate the dynamic response (*ASI*, *THiV*); however, these relationships are often monotonic but non-linear, dependent on the test class and vehicle type, and characterized by significant scatter. Therefore, this article combines Pearson and Spearman correlations with partial correlations (controlling for TB/vehicle) and permutation inference with FDR correction to obtain a robust and transparent assessment of the strength and significance of effects within a homogeneously conducted set of EN 1317 tests (inter alia [15-17]).

2. DATA AND VARIABLES

ASI and *THiV* were adopted as the outcome (dependent) variables. The explanatory (independent) variables included post spacing, barrier height, and normalized working width. Control variables were TB test class and vehicle type, both encoded as categorical variables using one-hot encoding.

The total number of trials was $N = 126$, covering 92 road barriers (distinguished by the “barrier_type” column). In all tables and figures, post spacing, barrier height, and normalized working width are presented in meters.

The analyzed dataset originates from tests conducted in accordance with EN 1317 at the accredited Crash Test Laboratory of the Road and Bridge Research Institute (IBDiM) between 2018 and 2025 (PCA accreditation No.: AB 1025). Due to contractual obligations and accreditation requirements regarding client confidentiality (ISO/IEC 17025, Clause 4.2), raw data and derivative compilations that could allow for the reconstruction of system configurations have not been published. The results are presented in the form of statistics and indices (accompanied by calculation methods and parameters), allowing for the assessment of inference validity without compromising confidentiality.

3. METHODS

The statistical analysis employed the following approaches: 1) Pearson and Spearman correlations, 2) partial correlations controlling for test class and vehicle type and 3) multivariable linear models utilizing post spacing, barrier height, and normalized working width as predictors, with TB class and vehicle type serving as controls. Based on the linear models, marginal effect curves were derived: for each feature, predictions were calculated as a function of that feature, while holding other predictors at reference values (medians for continuous features and the modal category combination for control variables). The 95% confidence intervals were determined based on the prediction variance calculated as: $Var(\hat{y}) = x \cdot Cov(\beta) \cdot x^T$, where $Cov(\beta) \approx \sigma^2(X^T X)^{-1}$ and σ^2 was estimated from the model residuals. In the absence of a full Student’s *t*-distribution, a normal approximation ($\pm 1.96 \cdot SE$) was applied [7-13].

The Pearson correlation coefficient r quantifies the strength of the linear relationship between variables on an interval scale and is sensitive to outliers and deviations

from linearity. The Spearman correlation coefficient ρ is rank based (non-parametric) and detects monotonic relationships, including non-linear ones. In the context of the relationship between barrier structural characteristics and dynamic response (*ASI*, *THiV*), where non-linearities (thresholds, saturation) and isolated extreme values are possible, the parallel application of r and ρ enhances inference robustness and interpretative validity. Consistency in direction and comparable magnitudes of r and ρ suggest a linear-monotonic relationship; a divergence (e.g., $\rho \gg r$) indicates monotonicity without linearity or the influence of outliers.

Significance levels were determined using the permutation method, which is recommended for finite samples. To address the multiple testing problem, the Benjamini-Hochberg (FDR) correction was applied; the article presents both p_{perm} i q_{BH} values to limit the risk of false discoveries [7-13].

The analyses were conducted using Python 3.11.x with the following libraries: pandas 2.x (data processing), numpy 1.26/2.0 (computations), matplotlib 3.8/3.9 (visualization), python-docx (reporting), and xlsxwriter (table export).

The studied dataset comprises homogeneous structural solutions and similar technologies, resulting in a narrow range of linear mass variability relative to the impact energy characteristic of the analyzed test classes. Furthermore, mass-stiffness parameters are strongly interdependent with geometry (e.g., element spacing/length), which would lead to multicollinearity and estimation instability if included simultaneously. Consequently, this analysis focuses on geometric parameters, which exhibit sufficient variability and are directly defined within the EN 1317 system.

Table 1. Pearson and Spearman correlations (road barriers)

Index	Feature [m]	Sample size n	Pearson r	Significance level	Spearman ρ	Significance level
<i>ASI</i>	Post spacing [m]	91	-0.281	0.011	-0.359	0.0005
<i>ASI</i>	Barrier height [m]	91	0.491	0.0005	0.376	0.0005
<i>ASI</i>	Normalized working width [m]	90	-0.525	0.0005	-0.573	0.0005
<i>THiV</i>	Post spacing [m]	91	-0.399	0.0005	-0.447	0.0005
<i>THiV</i>	Barrier height [m]	91	0.493	0.0005	0.370	0.001
<i>THiV</i>	Normalized working width [m]	90	-0.674	0.0005	-0.679	0.0005

4. RESEARCH RESULTS

4.1. PEARSON AND SPEARMAN CORRELATIONS

The following tables demonstrate negative correlations between post spacing/normalized working width and *ASI/THiV*, and positive correlations between barrier height and *ASI/THiV*. Adjusting for the test class and vehicle type does not alter the direction of these dependencies. The full coefficient values were presented in tables generated at an earlier stage of the work.

If the coefficients r and ρ are significant and of similar absolute value, the trend is stable and largely linear. If ρ exceeds r , the relationship is likely monotonic but non-linear (e.g., a threshold effect). The persistence of significance after controlling for confounding variables (partial correlation) indicates that the characteristic – *ASI/THiV* relationship is not merely a side effect of the test class (TB) or vehicle type selection.

The observed scatter in the plots does not preclude the existence of a significant trend, provided the sample size is sufficient and permutation tests and non-linearity-robust measures (such as Spearman correlation) are applied. In the presented data, significance persists even after controlling for TB/vehicle type (partial correlations), indicating an intrinsic contribution of the geometric features. At the same time, the effect for *THiV* is smaller and less precise (wider 95% CI); therefore, it is interpreted with caution and without excessive extrapolation.

Table 1 presents the summary of results and the corresponding significance levels (p_{perm} , q_{BH}) for the Pearson and Spearman correlations. Table 2 presents the summary of results and the corresponding significance levels (p_{perm} , q_{BH}) for the Partial correlations.

Table 2. Partial correlations (TBxx control/vehicle)

Index	Feature [m]	Sample size n	Partial r	Significance level
<i>ASI</i>	Post spacing [m]	91	0.569	0.0015
<i>ASI</i>	Barrier height [m]	91	0.926	0.0005
<i>ASI</i>	Normalized working width [m]	90	0.663	0.0005
<i>THiV</i>	Post spacing [m]	91	0.597	0.001
<i>THiV</i>	Barrier height [m]	91	0.955	0.0005
<i>THiV</i>	Normalized working width [m]	90	0.711	0.0005

4.2. LINEAR MODELS AND MARGINAL EFFECTS

Tables 3 and 4 present a summary of the model coefficients for the outcome variable *ASI* (estimates $\pm 95\%$ CI) and a summary of the model coefficients for the outcome variable *THiV* (estimates $\pm 95\%$ CI).

Table 3. Model estimates for *ASI* ($\pm 95\%$ CI)

Term	Estimate	95% CI – Lower	95% CI – Upper
_Const	0.7350	0.4170	1.0530
Post spacing [m]	0.0238	-0.0174	0.0651
Barrier height [m]	0.6114	0.2963	0.9265
Normalized working Width [m]	-0.3831	-0.5635	-0.2027
Test_class_TB31	-0.3401	-0.6076	-0.0726
Test_class_TB32	-0.0588	-0.1501	0.0325

Table 4. Model estimates for *THiV* ($\pm 95\%$ CI)

Term	Estimate	95% CI – Lower	95% CI – Upper
_Const	25.1939	20.5695	29.8182
Post spacing [m]	0.0998	-0.4998	0.6994
Barrier height [m]	8.8730	4.2915	13.4545
Normalized working Width [m]	-8.1772	-10.8000	-5.5544
Test_class_TB31	-5.1407	-9.0305	-1.2509
Test_class_TB32	-0.7286	-2.0561	0.5988

The figures below present the marginal effects (prediction $\pm 95\%$ CI) for *ASI* and *THiV* with respect to each of the analyzed features [8], [12].

In Figs. 1-12 the dependence of *ASI* or *THiV* on the following barrier features are presented.

Figs. 1-12 also illustrate the dependence of the index on a given feature (in [m]), along with an interpretation of the direction and strength of the relationship

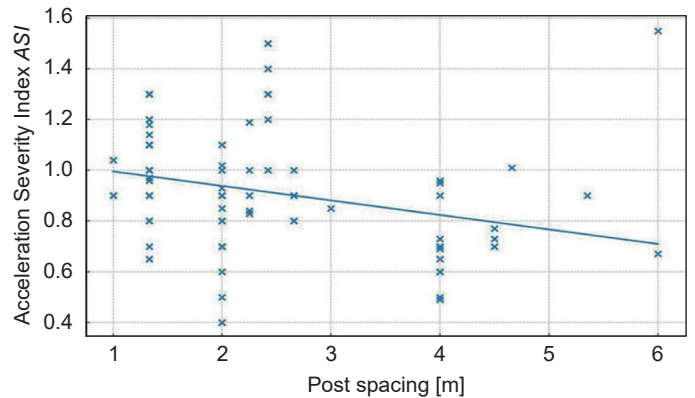


Fig. 1. Relationship between *ASI* and post spacing or element length

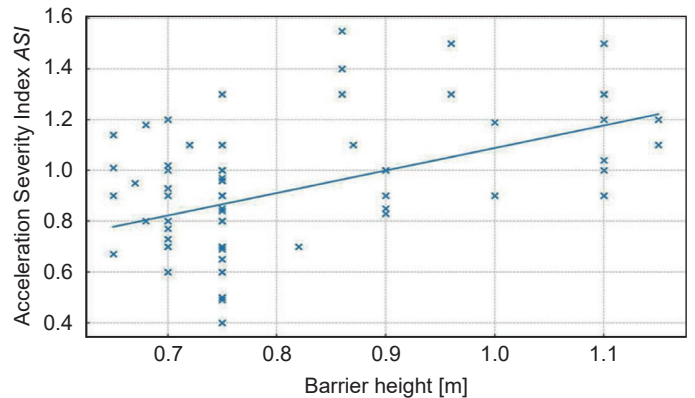


Fig. 2. Relationship between *ASI* and barrier height

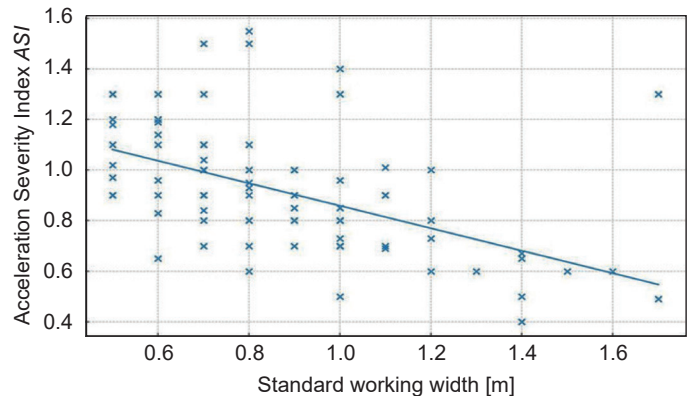


Fig. 3. Relationship between *ASI* and standard working width

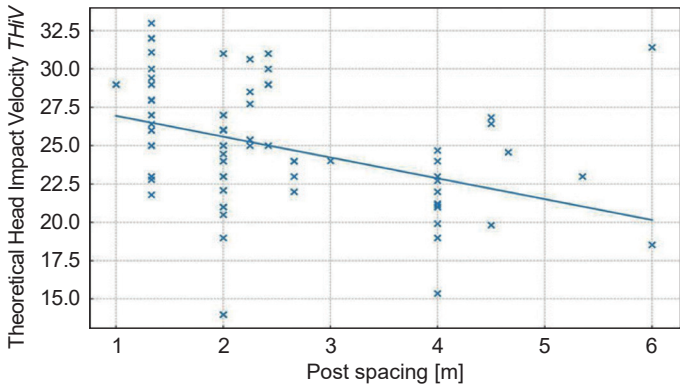


Fig. 4. Relationship between THIV and posts spacing or element length

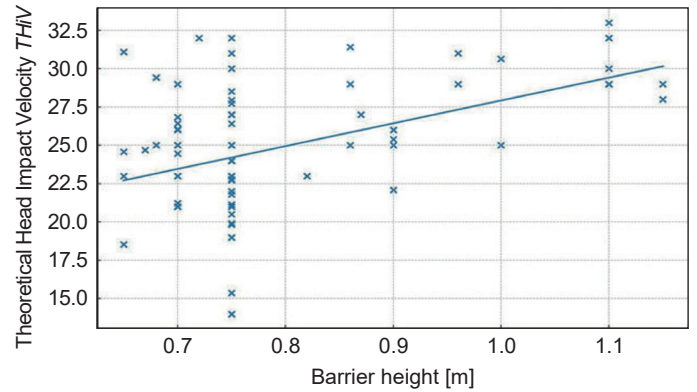


Fig. 5. Relationship between THIV and barrier height

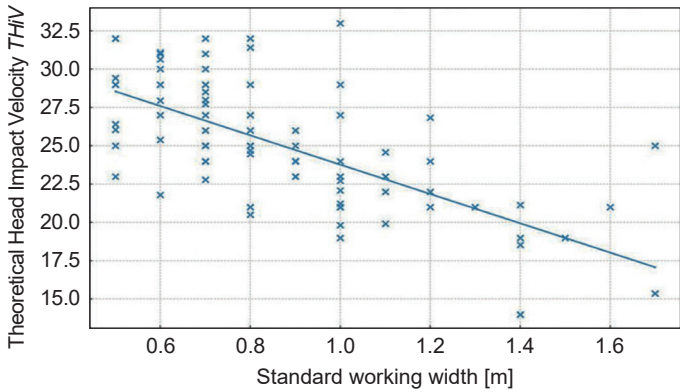


Fig. 6. Relationship between THIV and standard working width

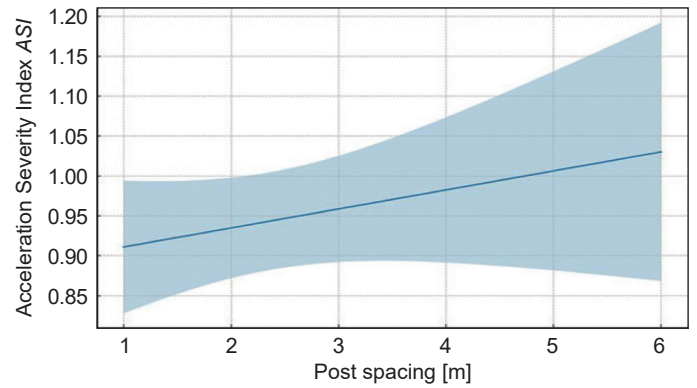


Fig. 7. Relationship between ASI and post spacing or element length

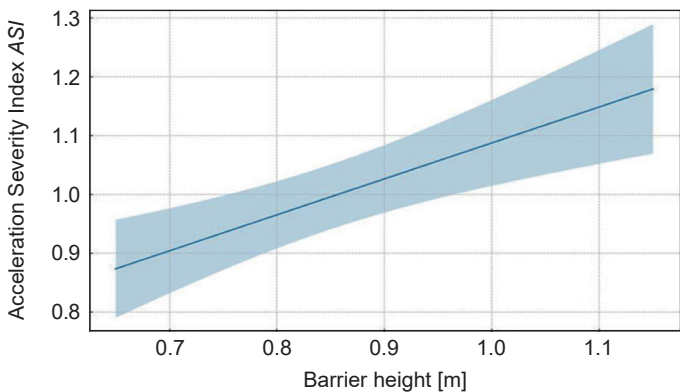


Fig. 8. Relationship between ASI and barrier height

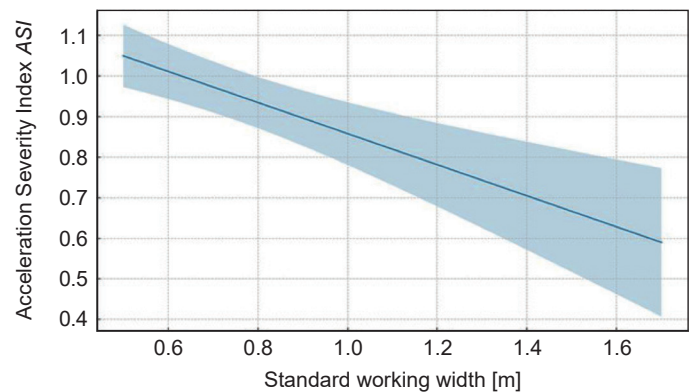


Fig. 9. Relationship between ASI and standard working width

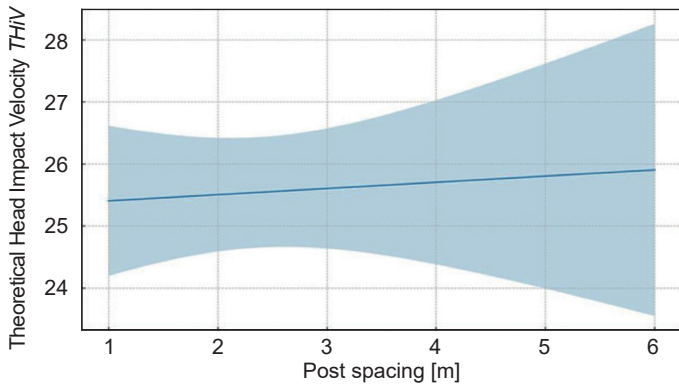


Fig. 10. Relationship between $THiV$ and post spacing or element length

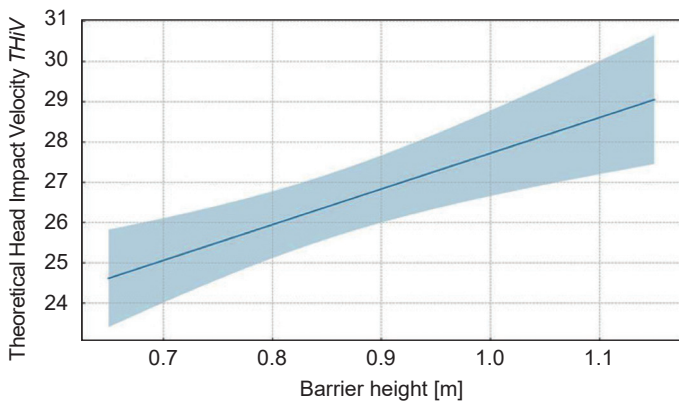


Fig. 11. Relationship between $THiV$ and barrier height

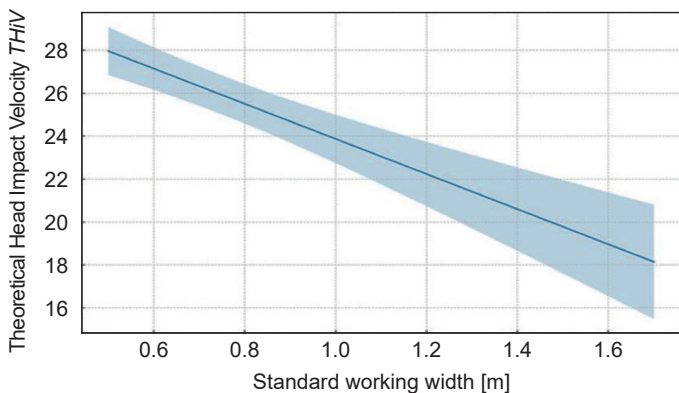


Fig. 12. Relationship between $THiV$ and standard working width

The results corroborate the hypothesis that more compliant systems (characterized by larger post spacing and greater working width) lead to a reduction in ASI and $THiV$ indices. This phenomenon can be attributed to the elongation of the interaction duration and the consequent reduction of peak acceleration values.

The observed positive dependence between barrier height and $ASI/THiV$ may stem from the fact that, in practice, taller barriers are frequently designed and anchored with greater rigidity, particularly in contexts involving constrained space (e.g., bridge barriers) or when lower Working Width (W) classes are required. However, potential interactions must be considered: the effects of height may diminish with increased spacing (lower global stiffness), and the material properties and contact kinematics (profile shape, connection types) may condition the energy dissipation characteristics.

Given the limited sample size in certain TB class subgroups, mixed-effects modeling (with random intercepts for barrier family/system and potentially for laboratory/test) is recommended, as well as the use of splines to capture potential non-linearities. To ensure robustness, it is advisable to conduct leave-one-system-out validation and a sensitivity analysis regarding the removal of high-leverage observations [18-25].

Several considerations are pertinent to design practice:

- increasing compliance – for instance, through wider post spacing or the selection of a system with a larger working width – can be an effective method for reducing $ASI/THiV$, provided the road context (available free space, obstacles behind the barrier) permits;
- in striving to limit occupant impact severity, it is necessary to balance containment class requirements with Working Width (W) class requirements, as solutions that are excessively stiff imply higher deceleration forces;
- where the application of high barriers is mandatory, it is advisable to compensate for the increased stiffness through other means, such as adjusting post spacing, optimizing cross-sectional geometry, or employing connections with controlled deformability;
- the analysis is based on the available variables and may not account for significant structural nuances, such as element thickness, steel grade, anchorage details, the presence of curbs, base plate widenings, cable chains, etc. The effects were estimated using a linear approximation. It is indicated to apply mixed models and non-linear models (GAM), as well as to carefully examine interactions between features. Extending the test database to include additional systems and contextual layers (road vs. bridge, transition zones, pavement type, impact angle) is recommended to generalize the results [8], [23-25].

5. CONCLUSIONS

The analysis of 126 crash tests conducted in accordance with EN 1317 indicates that, within the studied population, the geometric characteristics of barriers are significantly associated with the vehicle-barrier system response as measured by occupant severity indices *ASI*.

The following main findings were identified:

1. Increased post spacing and greater normalized working width are statistically significantly associated with a decrease in *ASI* values. The effect sizes should be classified as weak to moderate; these findings were confirmed by both Pearson and Spearman correlations, as well as after applying the False Discovery Rate (FDR) correction for multiple comparisons and in partial correlations controlling for test class and vehicle type.
2. Regarding *THiV*, the direction of the relationship (lower *THiV* associated with larger spacing and greater working width) is consistent with observations for *ASI*; however, the effect is smaller and less precise, accompanied by greater data scatter and wider 95% confidence intervals.
3. The sample consisted of homogeneous structural solutions with a narrow range of linear mass variability relative to the impact energy characteristic of EN 1317 tests. “Mass-stiffness” parameters are strongly interdependent with the selected geometric features (e.g., element spacing and length), which precludes their reliable separation in this sample and could lead to multicollinearity and estimation instability. Consequently, the analysis

focuses on geometric parameters, which exhibit sufficient variability within the studied dataset and are directly defined in the EN 1317 system.

4. No consistent strong pattern was identified across the entire sample for barrier height; observed relationships are weaker and more dependent on test class and vehicle type. This suggests that design decisions should also account for functional requirements (containment and redirection) and situational constraints.
5. The scatter of points visible in the plots does not preclude the existence of a trend. Given the sample size of this dataset, a trend may be statistically significant if it is monotonic (reflected by Spearman correlation) or approximately linear (Pearson correlation). The conclusions are supported by permutation tests (distribution-free) and FDR correction, as well as partial correlations, which indicate that the relationships are not merely a derivative of differences between test classes or vehicle types.
6. Within the analysed range of variability, increasing post spacing and using a larger normalized working width favors the reduction of occupant load *ASI*. However, it must be noted that the shaping of barrier geometry must remain in compliance with structural capacity and vehicle redirection requirements (maintaining containment class), as well as installation conditions. In the case of *THiV*, the results are indicative and require cautious interpretation – geometric selection alone cannot replace a holistic assessment of interactions and vehicle-barrier contact conditions.

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Korelacje parametrów barier drogowych z ASI i THiV (EN 1317) i ich wpływ na bezpieczeństwo kierowcy oraz pasażerów podczas zderzenia

Streszczenie: W artykule przedstawiono rozszerzoną analizę związku pomiędzy kluczowymi parametrami barier drogowych a wskaźnikami obciążenia pasażerów: Acceleration Severity Index ASI oraz Theoretical Head Impact Velocity THiV. Oceniono trzy cechy o wysokim znaczeniu inżynierskim: rozstaw słupków, wysokość bariery oraz znormalizowaną szerokość pracującą. Oprócz klasycznych korelacji Pearsona i Spearmana oraz korelacji częściowych (z kontrolą klasy testu TBxx i typu pojazdu) zaprezentowano krzywe efektów marginalnych z przedziałami ufności 95%, wyznaczone na podstawie wielowymiarowych modeli liniowych. Wyniki potwierdzają, że większa podatność układu (większy rozstaw oraz większa szerokość pracująca) wiąże się z obniżeniem ASI i THiV, zaś wzrost wysokości bariery w analizowanym zbiorze danych koresponduje z większymi wartościami ASI i THiV. W pracy odniesiono się także do konsekwencji projektowych oraz kierunków dalszych badań.

Słowa kluczowe: wskaźnik ASI, bariery drogowe, norma EN 1317, rozstaw słupków, wskaźnik THiV, wysokość bariery, znormalizowana szerokość pracująca.