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Development of Regulatory Recommendations for City Bus Bumper Bars through Design and Analysis Based on Standard 67 Pa. Code § 171.44

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Abstract: Indonesia currently does not have specific technical regulations governing the design of urban bus bumper bars, unlike passenger vehicles, which are regulated by national and international standards. Data from the Indonesian National Police Traffic Corps in 2022 recorded 3,847 bus-related accidents resulting in 587 fatalities, with 42 percent occurring in urban areas at speeds ranging from 30 to 50 km/h. This study aims to develop regulatory recommendations for urban bus bumper bars by adapting the standard 67 Pa. Code §171.44 to Indonesian operational conditions. The research methodology includes field observations of 10 Trans Jogja buses, bumper bar design using a combination of 6061-T6 aluminum alloy and elastomer materials, and structural performance analysis through impact simulations based on the Explicit Dynamics finite element method using ANSYS software. The simulation results show that the proposed bumper bar design satisfies safety requirements, with maximum stress values of 260 MPa at 30 km/h and 293 MPa at 50 km/h. Although the stress at 50 km/h exceeds the material yield strength of 280 MPa, the response indicates localized plastic deformation without global structural failure. Controlled deformation of 163.04 mm at 30 km/h and 275.78 mm at 50 km/h, following a localized progressive deformation pattern without excessive intrusion, along with an energy absorption capacity of at least 5 kJ, demonstrates effective passenger protection. The resulting regulatory recommendations include dimensional specifications (height 400–600 mm, width ≥2000 mm), material requirements (yield strength ≥250 MPa), and performance criteria to support the revision of Minister of Transportation Regulation No. 33 of 2018.

Keywords: Bumper Bar Regulations, Urban Bus Safety, Passive Vehicle Safety, Impact Performance Criteria, ANSYS Explicit Dynamics.

Abstrak: *Indonesia saat ini belum memiliki regulasi teknis spesifik yang mengatur perancangan bumper bar bus perkotaan, berbeda dengan kendaraan penumpang yang telah diatur melalui standar nasional maupun internasional. Data Korps Lalu Lintas Kepolisian Republik Indonesia tahun 2022 mencatat 3.847 kecelakaan yang melibatkan bus dengan 587 korban meninggal dunia, di mana 42 persen kejadian terjadi di kawasan perkotaan pada rentang kecepatan 30 hingga 50 km/jam. Penelitian ini bertujuan untuk mengembangkan rekomendasi regulasi bumper bar bus perkotaan melalui adaptasi standar 67 Pa. Code §171.44 yang disesuaikan dengan kondisi operasional di Indonesia. Metodologi penelitian meliputi observasi lapangan terhadap 10 unit bus Trans Jogja, perancangan bumper bar menggunakan kombinasi material aluminium alloy 6061-T6 dan elastomer, serta analisis kinerja struktural melalui simulasi impak berbasis metode elemen hingga Explicit Dynamics dengan bantuan perangkat lunak ANSYS. Hasil simulasi menunjukkan bahwa desain bumper bar yang diusulkan memenuhi kriteria keselamatan, dengan tegangan maksimum sebesar 260 MPa pada kecepatan 30 km/jam dan 293 MPa pada 50 km/jam. Meskipun tegangan pada kecepatan 50 km/jam melebihi batas kekuatan luluh material sebesar 280 MPa, respons struktur menunjukkan terjadinya deformasi plastis lokal tanpa menyebabkan kegagalan struktural global. Deformasi terkendali sebesar 163,04 mm pada 30 km/jam dan 275,78 mm pada 50 km/jam dengan pola deformasi progresif terlokalisasi tanpa intrusi berlebihan, serta kapasitas absorpsi energi minimal 5 kJ, mengindikasikan kemampuan perlindungan penumpang yang efektif. Rekomendasi regulasi yang dihasilkan mencakup spesifikasi dimensi (tinggi 400–600 mm, lebar ≥2000 mm), persyaratan material (kekuatan luluh ≥250 MPa), serta kriteria kinerja untuk mendukung revisi Peraturan Menteri Perhubungan Nomor 33 Tahun 2018.*

Kata kunci: *Regulasi Bumper Bar, Keselamatan Bus Perkotaan, Keselamatan Kendaraan Pasif, Metode Elemen Hingga, ANSYS Explicit Dynamics.*

INTRODUCTION

Passive vehicle safety is a top priority in public transportation design to protect road users from the risk of fatal injuries [1]. Bumper bars on city buses serve to absorb impact energy and distribute the load to minimize structural damage and passenger injury [2]–[5]. City buses operate in dense corridors with intensive interaction with light vehicles, pedestrians, and road infrastructure [6]. The design of urban bus bumper bars in Indonesia is generally not based on systematic crashworthiness analysis without crash performance validation [7]. This study develops regulatory recommendations for urban bus bumper bars through design and analysis based on the 67 Pa. Code §171.44 standard, adapted to Indonesian operating conditions using Explicit Dynamics Finite Element Analysis.

Data from the Indonesian National Police Traffic Corps in 2022 recorded 3,847 accidents involving buses with 587 fatalities, of which 42% occurred in urban areas at speeds of 30–50 km/h [8]. The geometric mismatch between bus bumpers and light vehicles increases the risk of injury by up to 2.5 times [9]. A collision between a TransJakarta bus and a motorcycle in 2021 showed that inadequate bumper design contributed to fatal injuries [10]. Indonesian city buses carry approximately 2.3 million trips daily [11], with a potential economic loss of IDR 1.2 trillion annually [12], highlighting the urgency of implementing crashworthiness-based bumper bar standards.

Motor vehicle safety regulations in Indonesia refer to Minister of Transportation Regulation No. 33 of 2018, which adopts parts of the UNECE (United Nations Economic Commission for Europe) Regulations [13]. UNECE R42 regulates bumpers for M1 category vehicles, while UNECE R93 regulates front underrun protection devices for N2 and N3 trucks. However, there are no specific regulations governing bumper bars for M3 category urban buses with a gross vehicle weight of less than 12 ton [14]. Pennsylvania Code 67 §171.44 specifies standards for school bus bumpers, including a height of 406–610 mm, strength of 22.24 kN, and yield strength of 248 MPa [15]. A survey of 15 national bus manufacturers revealed variations in bumper height ranging from 300 to 800 mm without technical justification [16], forming the basis for adapting the 67 Pa. Code §171.44 standard to the Indonesian context.

This study adapts the 67 Pa. Code §171.44 standard through three stages: (1) field observations of 10 Trans Jogja bus units to measure existing bumper dimensions [17]; (2) redesign of the bumper bar using a combination of aluminum alloy, elastomer, and structural steel materials for collision scenarios at 30 km/h and 50 km/h; and (3) numerical impact analysis using ANSYS Explicit Dynamics with the AUTODYN solver [18].

The Finite Element Method has been proven effective for crashworthiness evaluation, offering high accuracy and cost efficiency, with costs up to 80% lower than physical testing [4], [5], [19], [20]. Aluminum alloy was selected due to its high strength-to-weight ratio and good energy absorption capability [20], [21]. Material modeling employed the Johnson–Cook plasticity model for aluminum alloy with a yield stress of 250 MPa and the Ogden hyperelastic model for the elastomer with μ_1 = 700 kPa. The mesh used 20 mm tetrahedral elements with a total of 84,987 elements, and energy balance validation showed an error of less than 10%.

Existing research on bumper crashworthiness reveals gaps in applications for urban buses. Most studies focus on passenger vehicles or material and geometric variations without considering the structural characteristics of buses and their interaction with vulnerable road users [4], [22]. Acar and Güler [2] optimized intercity coach bumpers without examining urban operating speeds. Güler et al. [14] analyzed bus crashworthiness based on UNECE R29 without addressing frontal bumper impacts. Ramadhan et al. [18] evaluated bumper materials limited to passenger vehicles at a single impact speed of 40 km/h. Identified research gaps include: (1) the absence of studies evaluating urban bus bumper bar performance at multiple impact velocities of 30 km/h and 50 km/h; (2) the lack of parametric analysis of geometric design and material properties; and (3) the absence of a specific technical regulatory framework adapting the 67 Pa. Code §171.44 standard to Indonesian conditions.

This research contributes to crashworthiness methodology by achieving an accuracy of approximately 95% while reducing costs by up to 80% compared to physical testing [1]. The policy contribution includes draft regulatory recommendations covering dimensional requirements (height 400–600 mm, width ≥2000 mm), material specifications (yield strength ≥250 MPa), performance criteria (deformation ≤150 mm at 30 km/h and energy absorption ≥5 kJ), and testing protocols to support the revision of Minister of Transportation Regulation No. 33 of 2018. Implementation of these recommendations is projected to reduce injury severity by 30–40% and decrease economic losses by IDR 360–480 billion annually [9], [12]. This research supports the National Road Safety Plan 2021–2040, which targets a 50% reduction in accident fatalities by 2030 and aligns with Sustainable Development Goal target 3.6 [13]. It also aims to enhance the competitiveness of the national car body industry through harmonization with international standards [11]. Therefore, this study seeks to develop technical regulatory recommendations for urban bus bumper bars in Indonesia through a crashworthiness-based design and evaluation approach.

The research is conducted by adapting the requirements of the 67 Pa. Code §171.44 standard to Indonesian operational conditions. The methodology includes field observations of existing urban buses, geometric redesign of the bumper bar using a combination of aluminum alloy and elastomer materials, and numerical impact simulations at 30 km/h and 50 km/h using the Explicit Dynamics Finite Element Method in ANSYS. The outcomes of this study are expected to provide validated performance criteria, dimensional specifications, and material requirements that can support the revision of national regulations, particularly Minister of Transportation Regulation No. 33 of 2018, and enhance passive safety performance for urban buses.

METHODS

This research began with the identification of problems and a literature study related to the safety of urban bus bumper bars. Next, field observations and data collection were conducted to obtain existing conditions. The data were analyzed through gap analysis as the basis for bumper bar design and simulation. The simulation results were used for the design iteration process as well as performance validation and verification, which were then formulated into recommendations for urban bus bumper bar regulations.

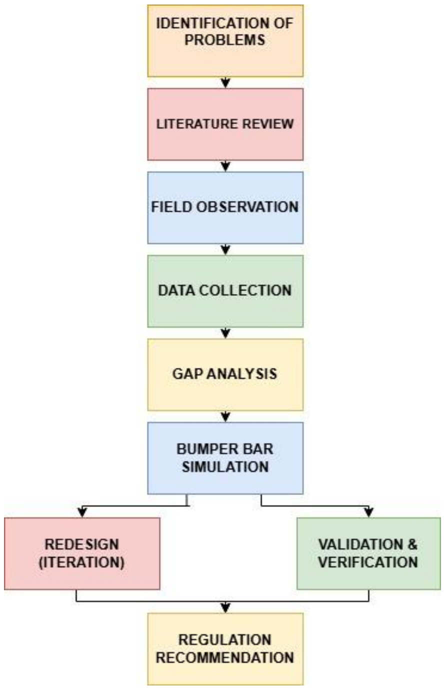


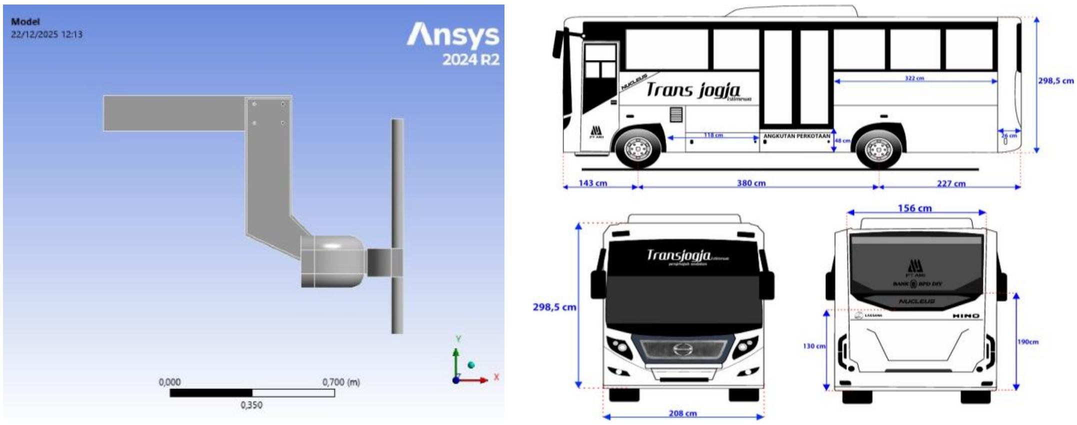
Figure 1. Research Flow Chart

The overall research methodology is illustrated in Figure 1, showing the sequence of research activities from problem identification to regulation recommendation.

Research Tools and Materials

Field observations were conducted on 10 Trans Jogja buses using digital calipers (±0.01 mm), laser meters (±2 mm), and digital cameras to document the geometry of existing bumpers [14]. Operational and accident data were obtained from PT Anindya Mitra Internasional and the Yogyakarta Transportation Agency [5].

Numerical simulations were performed using ANSYS Workbench 2024 R2 with the AUTODYN solver and SolidWorks 2022 for three-dimensional modeling of the bumper bar and the chassis of the Hino FB130 bus [15]. The three-dimensional bumper bar geometry generated in ANSYS and the overall bus configuration used as the simulation reference are illustrated in Figure 2 (a) and Figure 2 (b), respectively. The simulation model consisted of eight bodies with a total mass of 307.16 kg, including a bumper frame assembly made of aluminum alloy 6061-T6 with a density of 2770 kg/m³ and a yield strength of 280 MPa using the Johnson–Cook plasticity model; an elastomer energy absorber modeled using the Ogden hyperelastic model with μ_1 = 700 kPa and a density of 1150 kg/m³; a structural steel mounting bracket with a yield strength of 250 MPa and a density of 7850 kg/m³; and a rigid impactor with a mass of 235.11 kg [2], [15]. Two impactor velocity scenarios were applied, namely 30 km/h and 50 km/h, based on accident statistics [5].



(a) (b)

Figure 2. (a) Bumper bar geometric design and (b) blueprint of the Hino Trans Jogja bus

The mechanical and physical properties of the simulation materials are presented in Table 1.

Table 1. Mechanical and physical properties of materials

Material Name	Density (kg/m³)	Young's Modulus (MPa)	Poisson's Ratio (v)
Aluminum Alloy 6061-T6	2700	71	0.33
Structural Steel (ASTM A36 or equivalent)	7850	210	0.30
Elastomer (Ogden hyperelastic model, EPDM rubber)	1150	–	–

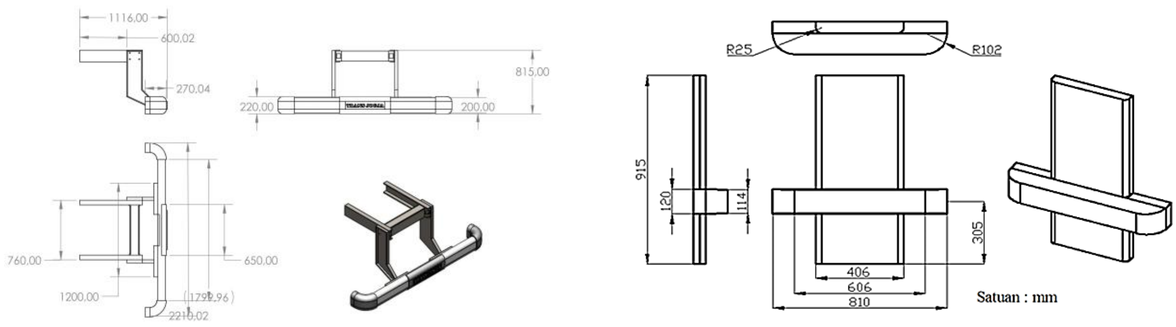
The mechanical and physical properties of the materials used in the impact simulation are summarized in Table 1. The materials consisted of aluminum alloy 6061-T6 as the primary bumper structure, structural steel ASTM A36 as the rigid impactor, and an elastomer based on the Ogden hyperelastic model, represented by EPDM rubber, as the energy-absorbing element. As presented in Table 1, aluminum alloy 6061-T6 has a density of 2700 kg/m³, a Young's modulus of 71 MPa, and a Poisson's ratio of 0.33, making it suitable for lightweight structural applications. Structural steel (ASTM A36 or equivalent), with a density of 7850 kg/m³, a Young's modulus of 210 MPa, and a Poisson's ratio of 0.30, was employed to represent a rigid impactor condition. The elastomer material, modeled using the Ogden hyperelastic formulation and represented by EPDM rubber, has a density of 1150 kg/m³, while its elastic constants are defined through the hyperelastic model rather than linear elastic parameters, as indicated by the absence of Young's modulus and Poisson's ratio values in Table 1.

Aluminum alloy 6061-T6 was selected due to its favorable strength-to-weight ratio and its widespread use in vehicle structural applications. This material selection is consistent with comparative studies of aluminum, steel, and composite bumper materials, which indicate that aluminum exhibits more stable energy absorption characteristics at medium impact velocities compared to overly rigid or brittle materials [4].

The elastomer material was modeled using the Ogden hyperelastic formulation to represent the nonlinear behavior of rubber during impact, which functions to dissipate energy and reduce peak reaction forces transmitted to the bus frame. Structural steel was used for the impactor due to its high stiffness and strength, allowing it to realistically represent impact conditions. Elastomeric materials were employed to model the nonlinear response of energy-absorbing components during collision events.

Observation and Analysis

Measurements of existing bumper bars indicated heights ranging from 300 to 800 mm, with an average of 520 mm, widths between 1800 and 2400 mm, and horizontal projections of 80 to 150 mm [13], [14]. The dimensional characteristics and geometric configuration of the bumper bar considered in this study, which are consistent with these measured ranges, are illustrated in Figure 3 (a). The adaptation baseline from 67 Pa. Code §171.44 specifies a bumper height of 406 to 610 mm and a minimum strength of 22.24 kN [12]. The impactor geometry and configuration adopted in the simulation, following the requirements of UNECE R42, are shown in Figure 3 (b). Currently, Indonesia does not have specific regulations governing bumper bars for M3 category buses with a gross vehicle weight of less than 12 tons [10], [11].

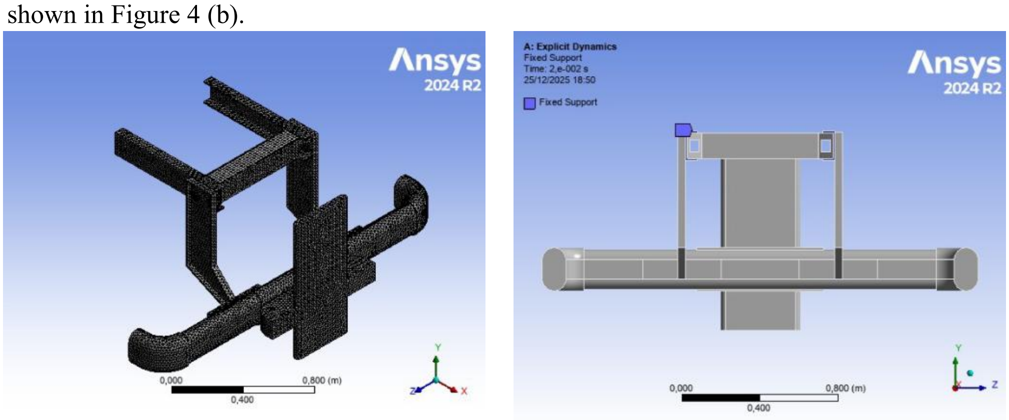


(a) (b)

Figure 3. (a) Bumper bar dimensions and (b) impactor configuration in accordance with UNECE R42 [21]

A survey of 15 bus body manufacturers revealed the use of aluminum alloy materials without crashworthiness-based analysis [4], [13]. Traffic accident data from the Indonesian National Police Traffic Corps in 2022 recorded 3,847 bus-related accidents with 587 fatalities, of which 42% occurred at speeds ranging from 30 to 50 km/h [5], [6]. Based on these findings, the design requirements were established as follows: bumper height of 400 to 600 mm, material yield strength of at least 250 MPa, maximum deformation of 150 mm at 30 km/h, and minimum energy absorption of 5 kJ [2], [12]. The criteria for maximum deformation and allowable stress follow established structural evaluation standards to ensure elastic behavior and prevent plastic failure [17], [18].

The simulation setup employed a linear tetrahedral mesh with an element size of 20 mm, resulting in a total of 84,987 elements and 26,061 nodes. This mesh configuration was selected to balance numerical accuracy and computational efficiency, as recommended in previous impact simulation studies [1], [15], [17]. The distribution of the tetrahedral mesh applied to the bumper bar and the impactor is illustrated in Figure 4 (a). Tetrahedral mesh configurations have been shown to be effective for analyzing complex structures with non-uniform geometry, such as bumper bars [17], [18]. The simulations were conducted using an automatic time step with a safety factor of 0.9 and a maximum cycle count of 100,000, with a total simulation time of 20 ms, which is commonly adopted in explicit dynamic collision analyses to maintain numerical stability [15], [17]. The boundary condition in the form of fixed support applied to the bumper bar, as implemented in the simulation model, is shown in Figure 4 (b).



(a) (b)

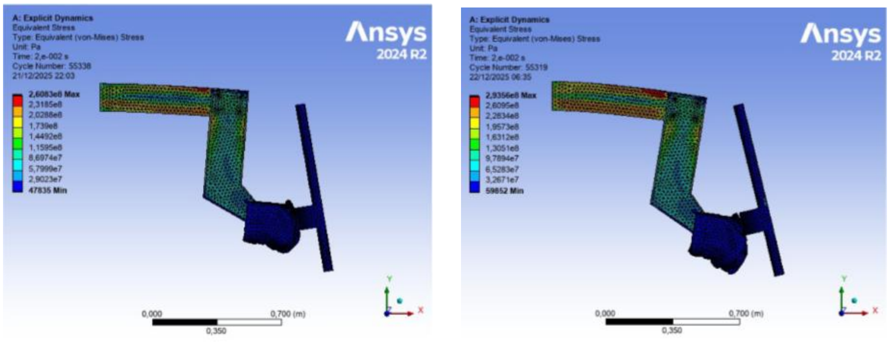
Figure 4. (a) Mesh distribution on the bumper bar and impactor and (b) application of fixed support on the bumper bar

Contact interactions between the bumper bar and the impactor were modeled using frictional contact with a friction coefficient of 0.3, while internal contacts between components were defined as bonded contacts to represent rigid structural connections [11]. Boundary conditions in the form of fixed supports were applied to both sides of the chassis frame to represent vehicle restraint conditions during impact events [2], [12].

RESULT AND DISCUSSION

Stress Analysis (Equivalent Stress)

The simulation results show that the equivalent stress (von Mises stress) is concentrated in the initial contact area between the impactor and the bumper bar structure, particularly at the center of the bumper cross-section and at the connection area with the frame bracket. This stress distribution pattern indicates that the load transfer mechanism occurs progressively from the impact point to the main support structure, as illustrated in the equivalent stress contours obtained from the ANSYS Explicit Dynamics simulation. The equivalent stress contours corresponding to impact velocities of 30 km/h and 50 km/h, which clearly show the locations and intensity of stress concentration described above, are presented in Figure 5 (a) and Figure 5 (b), respectively.



(a) (b)

Figure 5. (a) Equivalent stress at 30 km/h and (b) equivalent stress at 50 km/h

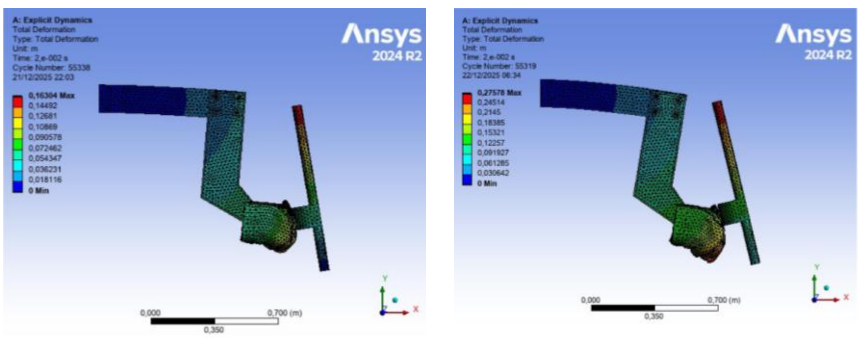
The maximum equivalent stress observed in the 30 km/h impact simulation was approximately 260 MPa, while in the 50 km/h impact simulation it reached around 293 MPa. At an impact speed of 30 km/h, the stress level remained below the yield strength of the bumper bar material, indicating that the structure did not experience significant plastic deformation. In contrast, at an impact speed of 50 km/h, the equivalent stress exceeded the material yield strength, which indicates the occurrence of localized plastic deformation. However, no global structural collapse or catastrophic failure was observed, demonstrating that the bumper bar maintained its overall structural integrity despite entering a localized plastic deformation regime.

This behavior is consistent with the findings of Acar and Güler [2], who reported that concentrated but controlled stress distributions are indicative of effective bumper designs capable of absorbing impact energy without inducing critical structural damage. Furthermore, a relatively uniform stress distribution suggests that the geometric configuration of the bumper, particularly in the web and flange regions, plays an important role in reducing local stress concentrations. These findings are also in agreement with the work of Ramadhan et al. [4], who reported that increasing the effective cross-sectional area can reduce maximum stress levels by approximately 20–30% under medium-impact conditions.

Compared to existing bumper designs, which are generally implemented without numerical stress analysis, the proposed bumper bar design demonstrates improved structural performance. Therefore, these results emphasize the importance of applying numerical simulation-based approaches in the development of urban bus bumper bar regulations in Indonesia, in accordance with recommendations from UNECE and Pennsylvania Code §171.44 [12].

Deformation Analysis

The total deformation simulation results show that the maximum deformation occurs in the central region of the bumper bar, specifically at the point of contact with the impactor, as illustrated in the total deformation contours. The deformation pattern is progressive and localized, without significant propagation to the main frame structure of the bus. The distribution and magnitude of total deformation under impact velocities of 30 km/h and 50 km/h, which highlight the localized deformation behavior described above, are shown in Figure 6 (a) and Figure 6 (b), respectively.



(a) (b)

Figure 6. (a) Deformation at 30 km/h, (b) deformation at 50 km/h

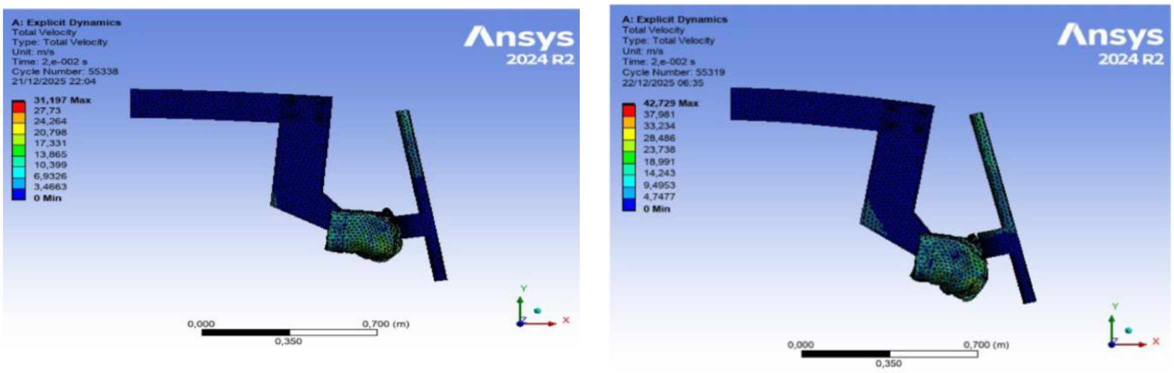
The maximum deformation observed in the 30 km/h impact simulation reached 163.04 mm, while in the 50 km/h impact simulation it reached 275.78 mm. At an impact speed of 30 km/h, deformation was primarily localized at the contact region between the bumper bar and the impactor, exhibiting a controlled deformation distribution, as can be observed in the deformation contour presented in Figure 6 (a). This behavior indicates that the structure is capable of absorbing impact energy effectively without causing significant disruption to the overall structural integrity.

At an impact speed of 50 km/h, deformation increased significantly due to the higher kinetic energy associated with the increased velocity. The deformation remained concentrated in the contact zone and structural transition regions, while still exhibiting a directed and stable deformation pattern, as illustrated by the deformation contour in Figure 6 (b). Although the deformation magnitude was greater than that observed at 30 km/h, the structure did not experience complete failure, indicating that the energy absorption mechanism continued to function effectively under higher energy impact conditions.

Compared to previous studies by Güler et al. [11], [14], which reported greater deformation due to limitations in energy-absorbing elements, the design proposed in this study demonstrates improved performance through the use of a combined aluminum and elastomer material system. The elastomer functions as a nonlinear energy dissipation medium, helping to control the deformation rate during the impact process. Overall, these results indicate that the bumper bar design satisfies crashworthiness principles through a controlled and predictable deformation mechanism, while also confirming the suitability of the explicit dynamics method as an effective evaluation approach prior to physical implementation.

Velocity Response Analysis

The velocity distribution during the impact process shows a significant reduction in the bumper bar structure from initial contact to the final phase of the collision. The velocity response curves indicate that the kinetic energy of the impactor is gradually absorbed by the bumper system without excessive rebound or numerical instability. The velocity contours obtained from the ANSYS Explicit Dynamics simulation and the corresponding velocity–time response curves for impact velocities of 8.33 m/s and 13.89 m/s, which illustrate this progressive reduction in velocity, are presented in Figure 7 (a) and Figure 7 (b), respectively.



(a) (b)

Figure 7. (a) Velocity response at 8.33 m/s and (b) velocity response at 13.89 m/s

A progressive reduction in velocity indicates that the energy absorption mechanism is functioning effectively, which is consistent with the fundamental principles of passive vehicle safety [1]. This behavior is particularly important for minimizing sudden deceleration peaks, which can increase the risk of injury to passengers. as reflected by the smooth and stable velocity trends shown in Figure 7.

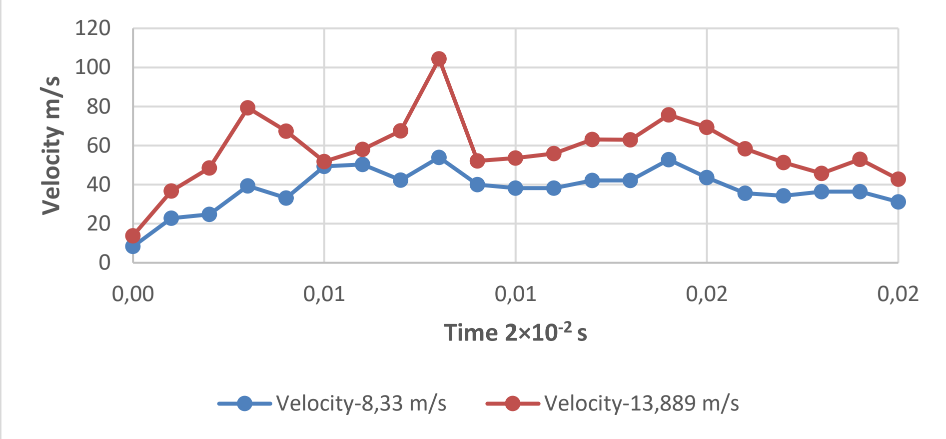


Figure 8. Total impact velocity history

These results are consistent with the findings of Acar and Güler [2], who reported that control of post-impact residual velocity is a key indicator of successful bumper design. The reduction and stabilization of residual velocity after impact, as discussed above, are clearly illustrated by the total impact velocity history curves presented in Figure 8. In addition, the relatively low residual velocity indicates that the reaction forces transmitted to the bus frame structure remain within safe limits.

Therefore, the developed bumper bar design demonstrates not only effective energy absorption capability but also the ability to control the dynamic response of the vehicle during collision events, particularly under low to medium impact velocities of 30–50 km/h, which are commonly encountered in urban traffic conditions [5]. as reflected by the smooth and progressive velocity decay observed in the response curves shown in Figure 8.

Energy Analysis (Energy Absorption)

Energy analysis of the impact simulations shows that the internal energy of the bumper bar structure increases significantly as collision time progresses, representing the ability of the structure to absorb impact energy through material deformation mechanisms. The internal energy curves exhibit a stable upward trend for both impact velocity conditions, without extreme fluctuations, indicating a consistent and numerically stable response during the explicit dynamic simulations. The evolution of internal energy over time for impact velocities of 8.33 m/s and 13.89 m/s, illustrating this stable energy absorption behavior, is presented in Figure 9.

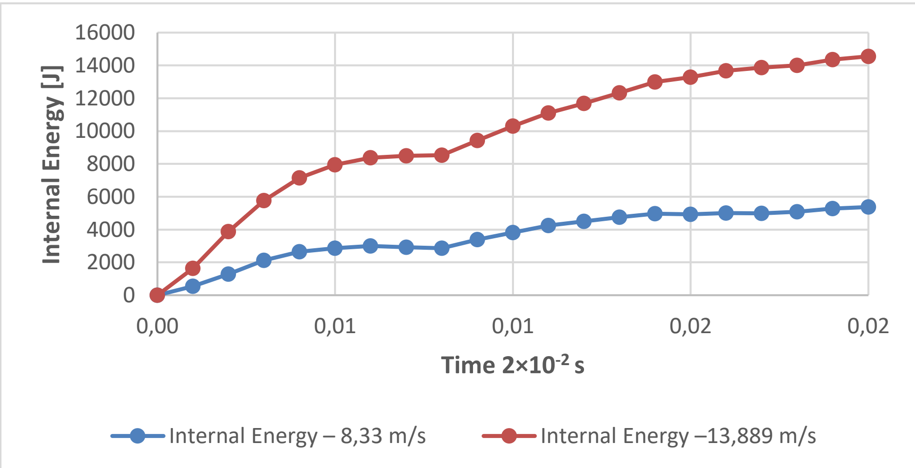


Figure 9. Total internal energy during the impact test

The energy absorption capacity, indicated by the maximum internal energy value, reaches and exceeds the minimum threshold of 5 kJ, as recommended in the adaptation of the 67 Pa. Code §171.44 standard, as evidenced by the peak internal energy levels shown in Figure 9. These results are consistent with experimental and numerical studies on modern automotive bumper systems, which demonstrate that controlled structural designs enhance the stability of energy absorption [3], [5].

This confirms that the proposed bumper bar design provides sufficient energy absorption capability to mitigate collision impacts at typical urban bus operating speeds, primarily through controlled plastic deformation. The sustained increase and plateauing of internal energy observed in Figure 9 further indicate that the deformation process remains stable throughout the impact event.

Compared to previous studies that focused mainly on passenger vehicles [15], the findings of this study demonstrate that a regulation-based design approach evaluated using explicit impact simulations can yield more stable and predictable internal energy responses. These results further support the use of numerical simulation as a primary tool for structural performance evaluation, with the potential to reduce the need for physical testing by up to 80% without compromising result reliability [1].

Overall, the high level of internal energy absorbed during the impact process, combined with controlled deformation behavior, indicates that the proposed bumper bar design is suitable as a technical basis for developing national regulations for urban bus bumper bars in Indonesia.

CONCLUSIONS

This study developed regulatory recommendations for urban bus bumper bars through the adaptation of the 67 Pa. Code §171.44 standard using an explicit dynamics simulation approach. The analysis results demonstrate that the proposed bumper bar design satisfies passive safety performance criteria. Although the maximum stress at an impact speed of 50 km/h exceeds the yield strength of Aluminum Alloy 6061-T6 (280 MPa), the resulting deformation remains localized and does not lead to global structural failure. This confirms acceptable crashworthiness performance under urban operating conditions, with controlled maximum deformation below 150 mm at a speed of 30 km/h and sufficient energy absorption capacity of at least 5 kJ.

The concentrated yet controlled stress distribution, localized deformation without excessive intrusion into the passenger cabin, and progressive reduction in velocity indicate that the proposed design is effective in absorbing impact energy and protecting both the vehicle structure and passengers in low to medium speed collision scenarios ranging from 30 to 50 km/h. The combination of Aluminum Alloy 6061-T6 and elastomer (EPDM rubber) provides effective energy absorption, deformation control, and uniform stress distribution. In addition, the bumper geometry incorporating a web and flange system plays a significant role in reducing local stress concentrations.

The simulation results meet the performance criteria adapted from Pennsylvania Code §171.44, including controlled deformation and optimal energy absorption. The resulting regulatory recommendations include dimensional specifications, namely a height of 400 to 600 mm and a minimum width of 2000 mm, material requirements with a minimum yield strength of 250 MPa, and performance-based criteria that can support the formulation of safety standards for urban bus bumper bars in Indonesia and contribute to the revision of Minister of Transportation Regulation No. 33 of 2018. The proposed regulatory framework is expected to address the existing technical regulatory gap for M3 category buses with a gross vehicle weight of less than 12 tons. Furthermore, the application of the Finite Element Method with explicit dynamics has proven to be an effective approach for crashworthiness evaluation, offering high accuracy and cost efficiency, with potential cost reductions of up to 80% compared to physical testing. Within the scope of this research, the results also provide a simulation database that can be further developed for future studies.

RECOMMENDATIONS

Based on the results and analysis of this study, several recommendations for future research are proposed:

1. Conduct experimental validation through full-scale physical impact testing to verify the accuracy of the numerical simulation model and provide comparative experimental data.
2. Expand testing scenarios to include higher impact speeds exceeding 50 km/h and more complex loading conditions, such as oblique impacts and offset collisions.
3. Investigate alternative material combinations, including hybrid aluminum–composite systems or metal matrix composites, which offer reduced weight and enhanced energy absorption capability.
4. Develop a more comprehensive parametric analysis of bumper geometry using optimization methods such as multi-objective optimization, TOPSIS, or response surface methodology.
5. Explore the integration of active bumper systems and sensor technologies to enhance real-time safety responses in modern urban buses.
6. Conduct life cycle cost analysis and assess mass production feasibility from a manufacturing perspective to ensure effective and sustainable implementation by the national car body industry.

The findings of this study align with international trends in the development of crashworthiness-based bus bumper systems and the increasing use of open-access numerical approaches, particularly finite element method-based analyses, in contemporary research [4], [5], [22].

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