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Review Article

Pedestrian-Friendly Vehicle Bumper Design

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Abstract

Pedestrians are considered vulnerable users, considering their high risk of injury or even fatality in car-to-pedestrian accidents. The post-accident injuries may lead to long-term hospitalizations and deprivation of daily activities. In this regard, car manufacturers have incorporated several new features into their products in order to minimize injury (and associated fatalities) to vehicle occupants and pedestrians, especially in the last two decades. Yet hundreds of thousands of people have died on roadways each year. From this standpoint, pedestrian injuries have become a globally recognized safety concern; hence the interest (and awareness) in pedestrian-friendly vehicle designs has increased. The automobile vehicle bumper system aims to absorb the impact energy produced by the collision and, to some extent, preserve the occupant, pedestrian, and car body. So far, the researchers have performed extensive studies in order to address the relationship between vehicle design and pedestrian safety based on numerical simulations, accident data, and crash tests. In order to better understand the influence of vehicle bumper design on pedestrian safety, the present study adopted a systematic literature review approach. It aimed to help gain better insights regarding the effects of design, material selection, and geometrical modifications on the performance of the bumper system, considering pedestrian safety. The current trends in designing pedestrian-friendly vehicle bumper designs were identified and discussed.

Keywords: Automotive, Bumper, Pedestrian Safety, Injury, Finite Element.

Yaya Dostu Araç Tampon Tasarımı

Öz

Araç-yaya kazalarında yüksek yaralanma ve hatta ölüm riskleri göz önüne alındığında, yayalar araç pasif güvenliği kapsamında savunmasız kullanıcılar olarak değerlendirilmektedir. Bu kapsamda, otomobil üreticileri, özellikle son yirmi yılda, araçta bulunanların ve yayaların yaralanmasını (ve buna bağlı ölümleri) en aza indirmek maksadı ile ürünlerine birçok yeni özellik dâhil etmişlerdir. Yine de, her yıl yüzbinlerce insan trafik kazaları neticesinde hayatını kaybetmektedir. Bu noktadan hareketle, yaya yaralanmaları (ve güvenliği) konusu küresel çapta yankı uyandıran bir güvenlik sorunu haline gelmiş ve yaya dostu araç tasarımlarına olan ilgi (farkındalık) de artmıştır. Otomobil araç tampon sistemi, çarpışmanın ürettiği darbe enerjisini emmeyi ve bir dereceye kadar yolcuyu, yayayı ve araç gövdesini korumayı amaçlayan kritik bir araç bileşendir. Bu çalışmada, otomobil araç tampon tasarımının yaya güvenliği üzerindeki etkisini daha iyi anlamak için sistematik bir literatür taraması yaklaşımından faydalanılmıştır. Bu kapsamda, tasarımın, malzeme seçiminin ve geometri değişikliklerinin araç tampon sisteminin performansı üzerindeki etkisi yaya güvenliği dikkate alınarak incelenmiştir. Yaya dostu araç tampon tasarımlarında kullanılan güncel yaklaşımlar ortaya koyulmuş ve tartışılmıştır.

Anahtar Kelimeler: Otomobil, Tampon, Yaya Güvenliği, Yaralanma, Sonlu Elemanlar.

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1. Introduction

Worldwide, injuries due to pedestrian-vehicle accidents are increasing annually and remain a significant safety concern. In order to mitigate injury (and associated deaths) to vehicle occupants, car manufacturers incorporated many features into their vehicles, especially in the last two decades (Teng et al., 2010). Yet each year, around 1.3 million people are killed on roadways (World Health Organization, 2022), and it is estimated that crash injuries (both fatal and non-fatal) will cost the world economy around 1.8 trillion USD from 2015 to 2030 (Chen et al., 2019). From this standpoint, designing pedestrian-friendly vehicles is one of the primary considerations for reducing high injury/fatality risk and economic burden.

Pedestrians can suffer varying levels of injury in case of a traffic accident. In this regard, the leg and head (covers facial injuries) regions are the principal body injury areas, according to the statistics (Teng et al., 2016). Head injuries account for the highest percentage of pedestrian fatalities with 60% of all regions, while leg injuries are responsible for the highest rate among severe injuries with 50% of all regions (Ishikawa et al., 2003). Evaluating the primary vehicle parts causing pedestrian injuries is essential in order to design pedestrian-friendly vehicles. The bumper, windshield, front hood, and A-pillar can be listed as leading car parts causing pedestrian injuries. Among them, the bumper system of the vehicle accounts for 40% of total leg injuries (Ishikawa et al., 2003; Teng et al., 2016).

With the rapid increment of global motorization, Governments and insurance companies forced car manufacturers to follow more advanced safety requirements. In most pedestrian-vehicle accidents, the lower extremities of the pedestrians are impacted due to the collision of the front bumper (Rambhad et al., 2020). The task of the bumper system is to absorb the energy produced by the collision and, to some extent, preserve the passenger/pedestrian and the car body. In general, the vehicle bumper system consists of three main components: (1) fascia, (2) bumper beam, and (3) energy absorber (Davoodi et al., 2012). The fascia is a non-structural component utilized to mitigate the drag force. The purpose of the bumper beam is to absorb the low-impact energy produced by the crash. Lastly, the energy absorber is utilized in order to dissipate kinetic energy during the collision (Davoodi et al., 2008).

In order to better understand state-of-the-art pedestrian-friendly vehicle bumper design, the present study performed a systematic literature review. Mainly, the research works utilized Finite Element Analysis (FEA) simulations and multi-objective optimization approaches to improve the bumper design being examined and interpreted. This systematic literature review aims to provide insightful information by evaluating the influence of design, material selection, safety concerns (regulations), and geometrical modifications (for instance, multi-objective optimization) on bumper performance, considering pedestrian safety.

2. Material and Method

The present study adopted a systematic literature review approach in order to review and evaluate the scientific papers published from 2017 to 2022. The ScienceDirect® electronic database was utilized for screening and collecting the articles. To achieve this end, the following keywords were entered into the ScienceDirect® database: (1) automotive, (2) bumper, (3) pedestrian safety, (4) injury, and (5) finite element. Consequently, n = 47 records were identified. In this regard, the exclusion and inclusion criteria applied to the collected papers are presented in Figure 1.

Inclusion and Exclusion	Criteria	Details
Exclusion	Search engine results	No open access (NOA)
		Non-related (NR)
		Weakly related (WR)
Inclusion	Search engine results	Closely related (CR)
		Partially related (PR)

Figure 1. Exclusion and inclusion criteria identified within the present study

Afterward, four phases of exclusion and inclusion criteria were applied to the collected records (n = 47), and n = 2 and n = 30 papers were excluded due to the NOA and NR + WR criteria, respectively (see Figure 2).

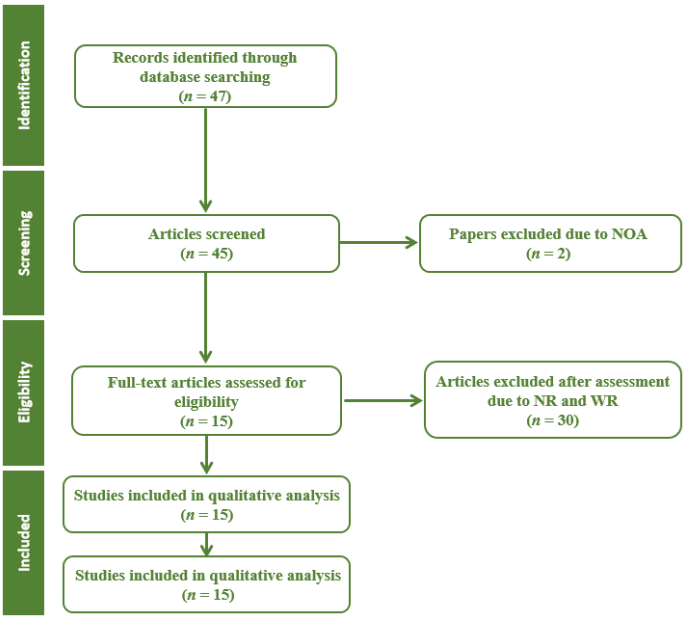

Figure 2. Phases of exclusion and inclusion criteria

3. Results and Discussion

Distribution of the papers published in the ScienceDirect® electronic database by years and subject areas is depicted in Figures 3 and 4, respectively. It is worth mentioning that the number of articles was increased in recent years, especially in the last three years (see Figure 3). Figure 4 also depicts that most of the studies were performed in the "Engineering" and "Materials Science" fields.

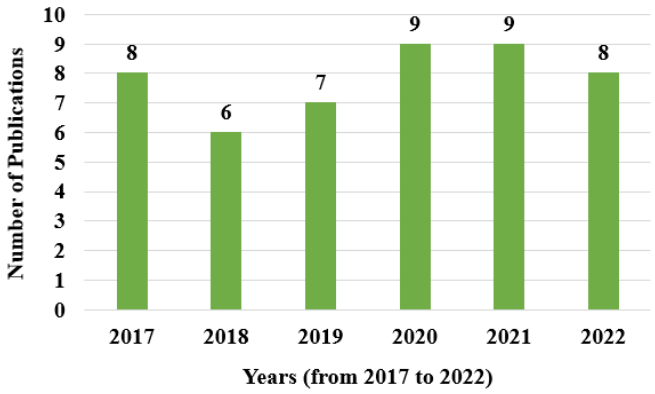

Figure 3. Distribution of the number of publications by years

Engineering	Materials Science	Social Sciences
22	13	6
Medicine and Dentistry	**Energy**	**Environmental Sciences**
2	1	1

Figure 4. Distribution of publications by subject area

The results of the systematic literature review are detailed in this section. To this end, the papers collected from the ScienceDirect® database were summarized and further interpreted. Mainly, the research works (n = 15) utilized FEA and multi-objective optimization techniques in order to design pedestrian-friendly vehicle bumpers were evaluated (see Figure 5).

Innovations associated with material selection (for instance, hybrid material combination), geometry modifications, and multi-objective optimization techniques are valuable instruments for designing a pedestrian-friendly vehicle bumper system. In this regard, Yang et al. (2020) tested a hybrid-material vehicle bumper made of an aluminum-steel combination and aimed to reduce pedestrian lower extremity injury. Their study employed FEA to achieve this end and compared the efficacy of the proposed aluminum-steel hybrid design with other counterparts through FEA simulations. Due to its advantages, for example, lower strength and stiffness, the aluminum-steel bumper design showed superior performance than its steel counterpart in terms of pedestrian lower extremity injury. Qi et al. (2018) first proposed an innovative double-hat thin-walled bumper design using a hybrid material combination. With this in mind, the researchers also indicated that the approach identified within the research work holds great promise for reducing vehicle mass and improving pedestrian safety. They further improved the initial design by utilizing aluminum foam in order to fill the hybrid-material beam. The nonlinear explicit FEA simulations revealed that the foam filler could enhance the specific energy absorption. However, it also should be highlighted that the empty beam design has a lower initial peak force, meaning that lower risk for pedestrian safety (i.e., better protection).

Later, Sun et al. (2021) aimed to improve the (1) energy absorption and (2) intrusion of the vehicle bumper system and employed a multi-objective optimization technique to achieve this end. Their study first modeled a real-life impact scenario and then validated the established model by comparing FEA findings with the available experimental data. It was indicated that the results of the research work could help gain better insights regarding vehicle bumper design. Ahmed (2020) emphasized that the main reason behind pedestrian-vehicle accidents (e.g., fatal injury and deaths) is the pedestrian-to-vehicle collision and therefore developed an FEA-based approach to simulate the car-to-pedestrian impacts. The research work considered the EURO-NCAP requirements during FEA simulations. As a result, the developed FEA-based model was found to be a suitable instrument in order to evaluate the car-to-pedestrian impacts and developments regarding the composite structure of the hood. Recently, Lei et al. (2021) utilized a sedan in order to carry out an experimental test campaign investigating the influence of various lower extremities. The findings of the research work demonstrated that placement of upper body mass could increase the risk of knee ligament damage. The study also proposed a multi-objective optimization algorithm to optimize the front-end structures. A nonlinear explicit FEA model was built to simulate pedestrian lower extremity injury.

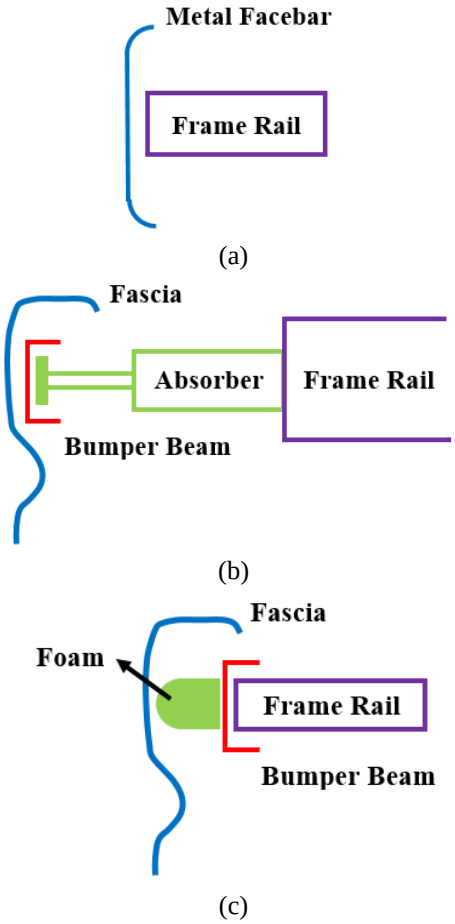

Figure 5. Common bumper designs

Chu et al. (2019) aimed to rationalize the subjective assessment while choosing a lightweight vehicle safety scheme and developed a multi-objective method to achieve this task. The researchers considered three different materials (i.e., high-strength steel, glass fiber-reinforced aluminum laminates, and polymer composite-metal hybrid) to evaluate and validate the efficacy of the developed multi-objective approach. In this regard, some quantitative criteria (for instance, maximum deflection and energy absorption) were evaluated utilizing FEA. Wang et al. (2018) explored a novel vehicle bumper system comprising a Negative Poisson Ratio (NPR) beam plus an NPR absorber. It was indicated that the NPR absorber could achieve relatively high protection for pedestrians (lower leg injury) in case of a vehicle-to-pedestrian accident. Godara and Nagar (2020) considered eight beam cross-sections in order to optimize the design of the frontal bumper system. The research work defined the material of the bumper system as carbon fiber composite. FEA simulations were utilized to analyze the automotive bumper beam in terms of displacement and stress at 10, 20, and 30 km/h.

Nachippan et al. (2021) carried out FEA simulations in order to define the best bumper material, considering passenger/pedestrian safety. To this end, three different material properties were considered, and the models were evaluated in terms of strain, stress, and deformation. Decker et al. (2019) performed FEA simulations and physical tests to assess and interpret overall pedestrian safety (i.e., adult and child). During the trials, the research considered the EURO-NCAP Pedestrian Protocol (v. 8.5) and utilized human body models. In this regard, four different cars were modeled to simulate impacting vehicles.

Both primary vehicle contact and the following (secondary) ground contact may lead to pedestrian injuries (Chandak et al., 2021; Zhang et al., 2022). It is estimated that above 300,000 pedestrians were killed only in 2019 (Shang et al., 2021). In this regard, pedestrian safety has become a globally recognized safety concern. So, the effects of vehicle bumper design and the countermeasures to be taken are highly significant to minimize car-to-pedestrian accidents and, thus, associated fatalities. Shang et al. (2021) conducted comprehensive research in order to evaluate pedestrian injuries emphasizing the absence of a validated pedestrian model for ground contact. It aimed to investigate the effects of contact characteristics and the initial pedestrian location on the following (i.e., secondary) ground contact. Later, Kim et al. (2017) aimed to optimize the design of the automotive vehicle hood in order to mitigate pedestrian head injuries and employed FEA to achieve this end. In this regard, two different composite materials were considered as possible candidates. As a result, the proposed final design within the scope of research work reduced weight while improving collision performance. Zhou et al. (2022) chose the B-pillar component to study head impact protection. Their research work aimed to demonstrate the effects of temperature on steel-plastic structures in terms of head impact protection. It also benefited from FEA simulations to achieve the identified objectives within the scope of the research work. Huang et al. (2020) performed computational biomechanical analyses and aimed to evaluate head injury risk, considering a traffic accident scenario. Recently, Liu et al. (2022) defined 12 design variables and performed an optimization study in order to simulate a traffic accident. It aimed to develop an intelligent approach enabling accident reconstruction.

The present study utilized a systematic review approach to evaluate and interpret the state-of-the-art vehicle bumpers designs in terms of pedestrian safety. A total of n = 47 papers were collected through the ScienceDirect® electronic database, and n = 32 records were excluded due to NOA + NR + WR criteria. In this regard, the research articles (n = 15) employing FEA simulations and optimization techniques in order to improve the automotive vehicle bumper design are being examined and interpreted (Ahmed 2020; Chu et al., 2019; Decker et al., 2019; Godara and Nagar, 2020; Huang et al., 2020; Kim et al., 2017; Lei et al., 2021; Liu et al., 2022; Nachippan et al., 2021; Qi et al., 2018; Shang et al., 2021; Sun et al., 2021; Wang et al., 2018; Yang et al., 2020, Zhou et al., 2022). The systematic literature review reveals that mainly three methods have been adopted to optimize automotive vehicle bumpers, considering pedestrian safety: (1) hybrid material selection (for instance, aluminum-steel), (2) geometrical modifications, and (3) multi-objective optimization approaches.

It is also worth mentioning that the present study is only limited to records published in the ScienceDirect® electronic database between 2017 to 2022. The identification phase was performed utilizing the following keywords: (1) automotive, (2) bumper, (3) pedestrian safety, (4) injury, and (5) finite element.

4. Conclusions and Recommendations

Pedestrian injuries due to car-to-pedestrian accidents are increasing annually and have become a globally recognized safety concern. With this in mind, this systematic literature review aims to help gain better insights by evaluating the influence of design, material selection, and geometrical modifications on bumper performance, considering pedestrian safety. To this end, the research works (n = 15) utilized FEA simulations, and multi-objective optimization approaches were mainly evaluated and interpreted. The current approaches to obtaining pedestrian-friendly vehicle bumpers were identified and discussed.

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