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# A Review of Kinetic Energy Dissipation Systems in Automotive Crashes

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**Abstract.** *This paper provides an overview of kinetic energy management in road safety. The various elements considered by engineers are analyzed to understand how and why the absorption of kinetic energy generated by a moving vehicle has become a major road safety issue. We examine the corrective measures designed by automotive engineers, which fall into two categories: internal vehicle measures, such as airbags, seat belts, and headrests; and external protective measures, including guardrails and impact attenuators. Impact analysis quantifies the sliding of the guardrails along the rails after an impact, thus absorbing the kinetic energy generated by the vehicle. The results indicate that progressive deformation and adjusted stiffness gradients increase impulse duration and reduce peak deceleration. The dampers primarily manage kinetic energy by redirecting it, with limited energy absorption. Design implications include optimizing post spacing and anchoring rails to the ground to guide the system's pads as they slide backward upon impact.*

***Keywords:*** *road safety, guardrail, kinetic energy, passenger protection systems.*

## 1. Introduction

The design of road safety devices that dissipate vehicle kinetic energy is essential for reducing risks to occupants, as crash test frameworks [1,2] evaluate performance based on impact severity, redirection, and permissible deformation. Energy dissipation lengthens the impact duration and reduces maximum decelerations, as measured by the EN1317 (ASI/THIV) indices [3].

Analyses show that greater system flexibility (e.g., a larger working width (W)) is correlated with a lower ASI/THIV index [4]. Deformation systems with S235 JR and S355 JR steel posts, combined with W-shaped rails, convert kinetic energy through deformation; therefore, post spacing is crucial to system rigidity. Rail height, along with consideration of post-soil interaction, optimizes energy absorption and controls deflection. It should be noted that, in accordance with EN1317, each crash attenuator installed upstream of a guardrail must include a transition element [5]. Impact resistance assessment programs also emphasize energy-absorbing devices that deform or fold the rail to prevent punctures and slow deceleration. Finally, it is important to emphasize that crash attenuators are essential when obstacles are present. At tunnel entrances, protection is provided at the beginning of the central reservation on the motorway, and at motorway exits in the event of a loss of vehicle control [6]. At motorway exits, this will primarily consist of semi-open, Y-shaped impact attenuators.

## 2. Energy dissipation by vehicle design

Today, engineers are designing vehicles to optimize kinetic energy absorption by incorporating crumple zones that absorb it during an accident. These parts of the vehicle are called crumple zones. Their role is to absorb kinetic energy during a frontal or rear-end collision.

### *2.1. Crumple zones*

A car's crumple zones are components designed by engineers to absorb kinetic energy in the event of an accident. In other words, they are designed to absorb energy during a collision. Engineers design them to deform, thus absorbing the kinetic energy that could injure or even kill the vehicle's occupants. These zones are therefore essential for saving lives in the event of a road accident.

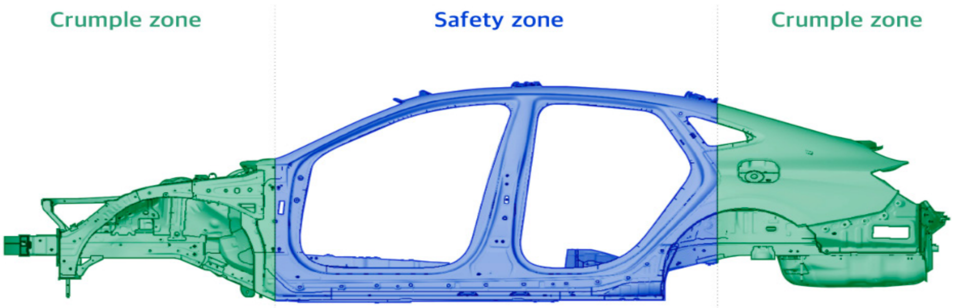


**Figure 1.** Reinforcement of the passenger compartment [7]

Regarding the passenger compartment, engineers have reinforced it to better protect occupants by minimizing deformation in the event of a road accident.

The reinforcement of this area has been refined over the years through the analysis of accident data, allowing engineers to design safer passenger compartments by carefully reinforcing specific design elements.

### *2.2. Reinforcement of the passenger compartment*

The first measure to ensure passenger safety is to reinforce the passenger compartment in first-generation vehicles. Engineers observed that the compartment's deformation caused injuries and deaths among passengers. Indeed, in an accident, whether a head-on collision or a rollover, it is the passengers who absorb the vehicle's kinetic energy. This is what motivated the initial reinforcement of the passenger compartment in first-generation vehicles. In this first generation, the focus is solely on reinforcing the frames around the vehicle doors, see Figure 2.

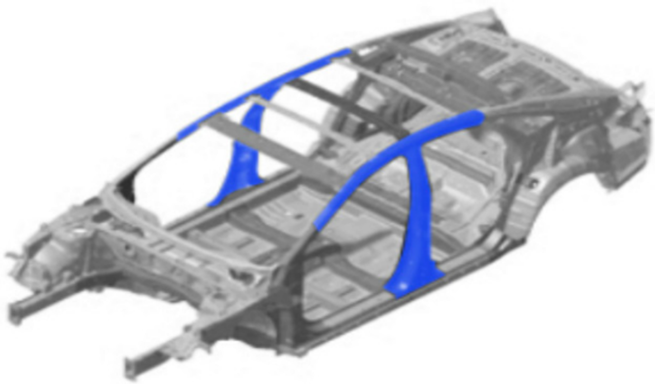

**Figure 2**. Passenger compartment reinforcement – 1st generation [7]

In the second generation, thanks to the analysis of accident data from hospitals and road safety authorities, engineers gathered enough information to further optimize the vehicle's passenger compartment. The focus here is on reinforcing the front of the cabin to prevent the legs of front passengers from being trapped in the bodywork in the event of hood deformation during a frontal impact (Figure 3).

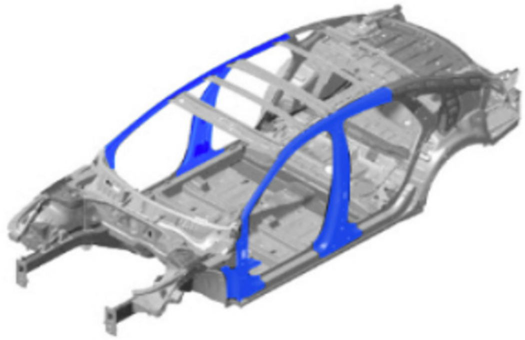

**Figure 3.** Passenger compartment reinforcement – $2^{nd}$ generation [7]

For the third generation of passenger compartment design, engineers have gained sufficient experience identifying key areas requiring reinforcement. Furthermore, a better understanding of construction materials has allowed for the selection of the most suitable options. In this generation, knowledge gained from advances in computation and computer simulation has enabled more refined and safer designs, with components undergoing a series of virtual tests (Figure 4).

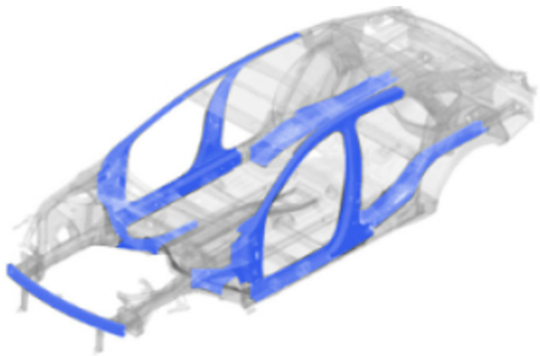

**Figure 4.** Passenger compartment reinforcement – $3^{rd}$ generation [7]

### *2.3. Interior safety devices*

In vehicles, it is important to note that measures are also taken to absorb passengers' kinetic energy and protect them from frontal and side impacts that could result in serious or even fatal injuries. These measures include seat belts, airbags, and headrests. These two systems, as shown in Figure 5, work together to progressively slow occupants' movement, absorbing and dissipating the kinetic energy generated during a collision, thereby improving overall safety.

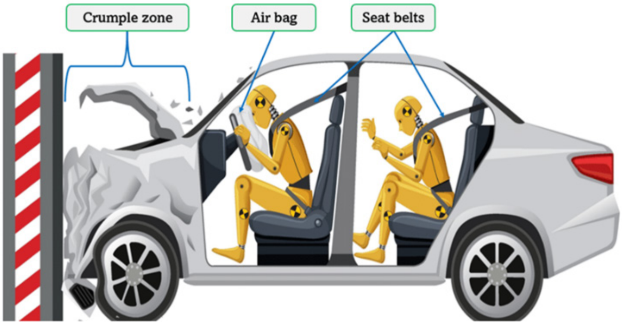


**Figure 5.** Safety devices in the vehicle [8]

Most people pay little attention to headrests when getting into a car, let alone consider them a safety feature. Yet, headrests do more than just improve rear visibility and provide comfortable head support; they play a vital role in protecting the head and neck in the event of an accident and help prevent injuries such as whiplash. People can experience severe crashes with no neck injury if there is little or no movement of the head relative to the torso (Figure 6).

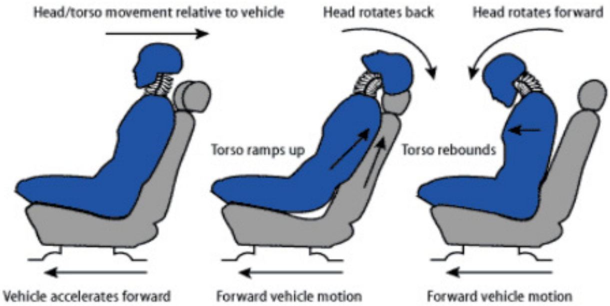


**Figure 6.** Head behavior during different movements of a moving vehicle [9]

For young passengers, especially babies and toddlers, car seats or booster seats with special seat belts play a crucial role in absorbing and distributing collision energy (Figure 7). These car seats are designed to securely hold infants and absorb and distribute impact forces across the strongest parts of their bodies, primarily the shoulders and hips. This helps prevent serious injuries by minimizing the concentration of impact energy and reducing the risk of ejection or contact with the vehicle's hard surfaces. When used correctly, car seats, in conjunction with seat belts, significantly increase the chances of survival and reduce the severity of injuries to young passengers in a collision.

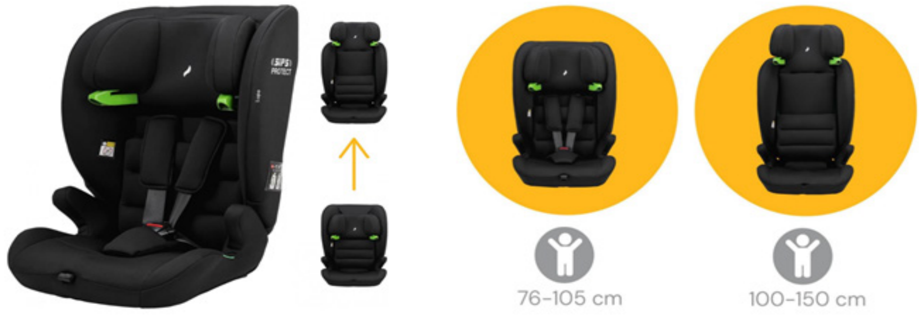


**Figure 7.** Seat as an energy-absorbing device for young passengers/babies [10]

It is important to note that standard seat belts are not designed for infants. Therefore, it is necessary to use properly installed car seats or booster seats compatible with the vehicle's seat belt system to protect young passengers.

## 3. Energy dissipation by road safety guardrails

As we have already mentioned, absorbing kinetic energy is crucial for saving lives on the road in the event of an accident. This is why engineers design guardrails to prevent serious injuries and fatalities in road accidents. These guardrails, installed along the roadside or in the median strip of highways, deform by absorbing the vehicle's kinetic energy upon impact.

### *3.1. Road safety guardrails*

Safety barriers are devices installed at the roadside or on the central reservation to reduce the impact of road accidents on the passengers involved. They come in various shapes and are made from a range of materials, including steel, wood, cables, and plastic. There are also models that combine wood and steel. Before being installed on the roadway, they must undergo crash tests in accordance with the European standard EN 1317 to be approved for use in European countries. These tests are carried out by independent crash-testing centers recognized and certified by the road authorities.

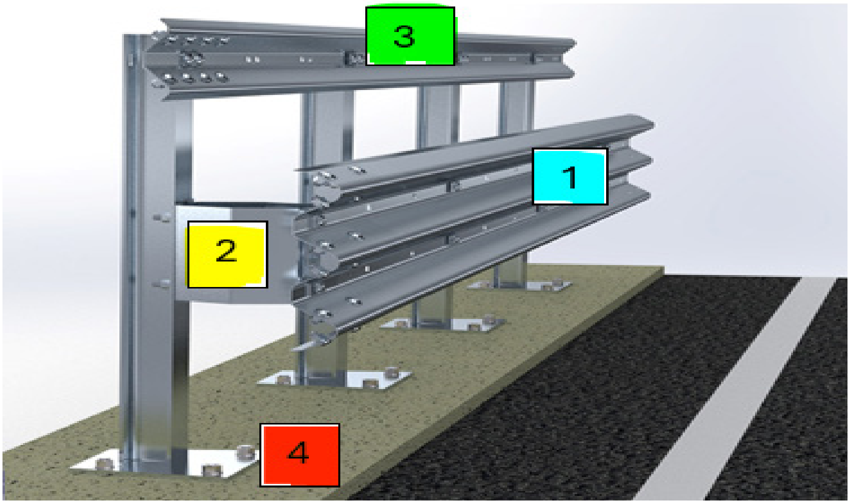


**Figure 8.** The 4-step energy absorption by the guardrail impact

The barrier illustrated in Figure 8 absorbs kinetic energy in four stages:

- The triple-wave bar (1) is impacted and absorbs some of the kinetic energy.
- If the vehicle is not stopped or diverted onto the roadway, the spreader bar (2) is activated; it deforms while absorbing kinetic energy.
- If the vehicle continues to impact the barrier, the double-wave bar (3) comes in action to absorb the remaining energy.
- If these first three elements fail, the ground anchor bolts are activated. This barrier has a high containment level (H4B). The anchor bolts will only be stressed in the event of a collision with a heavily loaded truck or bus.

### *3.2. Crash cushion*

A crash cushion is a safety device designed to absorb a vehicle's kinetic energy during a collision, reducing the risk of passenger injuries and minimizing damage to vehicles and road infrastructure. Placed at the ends of guardrails or in front of bridge posts or piers, they attenuate the vehicle's kinetic energy, thus mitigating the severity of accidents and saving lives.

Engineers use specific materials such as steel, plastic, or a combination of both to design the crash cushions. They use special materials that deform upon impact. This device is designed to slow vehicles after an impact, redirect them safely, and prevent them from hitting the primary obstacle protected by the crash cushion.

Crash cushions are mitigation systems installed in high-risk accident areas, such as two-way roads, highways with potential intersections, exit ramps, and construction sites, to protect workers and construction materials. As mentioned earlier, they are specifically designed to absorb the kinetic energy of a stationary vehicle upon impact, significantly reducing its speed and thus preventing fatal accidents, serious injuries, or even death to the occupants.

Parallel crash attenuators are typically mounted on rails or a single rail to guide retractable plates in the event of an impact or collision. Their selection is based on specific criteria defined by road safety authorities or the companies that manufacture these products.

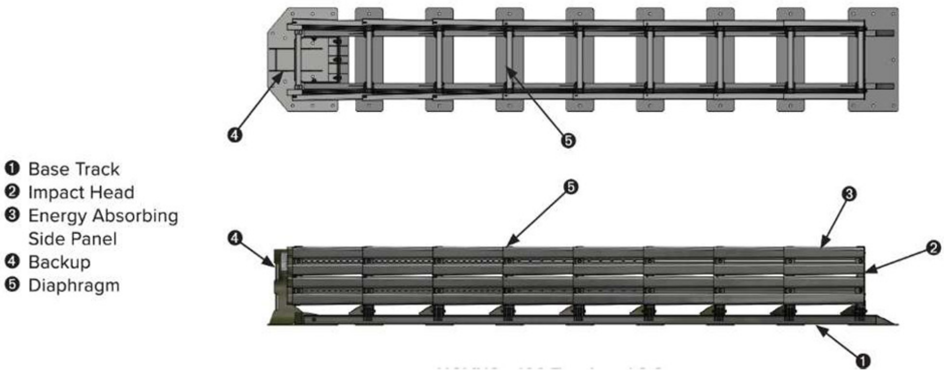


**Figure 9.** Parallel crash cushion [11]

The Y-shaped safety cushion functions exactly like a conventional steel airbag. It absorbs kinetic energy by retracting after impact. It is commonly found installed at highway exits to protect drivers who have lost control of their vehicle while exiting the highway.

**Figure 10.** Y-shaped crash cushion [12]

Trapezoidal crash attenuators are installed on high-speed roads, such as highways, at tunnel entrances, median barriers, or highway exits. However, their selection is reserved for road safety professionals or relevant road authorities. This type of attenuator is capable of absorbing very high kinetic energy, such as that of trucks. Its installation, therefore, requires technical expertise and must be performed by professionals. This is especially important because even a small error during installation can cause malfunction and, as a result, reduce protection for road users in case of an accident.

**Figure 11.** Trapezoidal road safety crash cushion [12]

## 4. Conclusion

Kinetic energy absorption systems are essential for saving lives on roads worldwide. Therefore, they must be installed correctly, whether they are internal vehicle devices, such as airbags and seat belts, or external devices, such as guardrails and impact attenuators.

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