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Development of an Anti-Slip Mechanism for Enhanced Seat Belt Safety

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Abstract

A seat belt on the other hand is a safety feature that is an integral part of any vehicle that has the sole responsibility of holding passengers in case of any abrupt deceleration. However, it is important to note the fact that normal seat belts tend to slide off during the times of serious accidents and this can compromise the safety of the passengers. Present work is aimed at design and fabrication of an enhanced mechanism of the anti-slip technology which can be applied to seat belts to ensure better protection and comfort to the occupant. The developed configuration employs a high-friction belt and mechanical locking mechanism in order to minimize belt slip under dynamic load conditions. Components which passed through the preliminary design and analysis stage were actually constructed and physical tests such as endurance, static, and dynamic tests, and some pretended crash-tests were conducted on vehicle prototypes. Comparing the findings with standard systems, a considerable decrease of the forward movement and slippage is revealed that proves the effectiveness of the described anti-slip mechanism for the enhancement of the restraint's reliability. This work serves as the basis and can be considered as one of the first steps in the progress toward the enhancement of the vehicular safety systems and may be aimed at establishing the later standards in the automotive field.

Keywords: Seat belt safety, anti-slip mechanism, occupant protection, automotive safety, crash testing, restraint systems, high-friction materials, slippage reduction, vehicle safety design

INTRODUCTION

Seat belts play a vital role in vehicle safety by restraining occupants during sudden deceleration or crashes, preventing them from hitting hard interior surfaces or being ejected. Studies show seat belts reduce front-seat passenger deaths by 45% and serious injuries by 50%. By distributing crash forces to stronger body parts like the chest and pelvis, they lower the risk of internal injuries. Modern seat belts often work with airbags and tensioners but are only effective when worn correctly. Thus, seat belts are globally mandated and essential for vehicle safety, making their durability and reliability crucial in automotive safety engineering (Figure 1).

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Seat belt slippage is a common yet often overlooked issue that significantly affects the effectiveness of vehicle restraint systems. It occurs when the belt webbing moves excessively through the latch plate or retractor during a crash, allowing the occupant to move more than intended, increasing injury risk. Causes include low friction at the latch, worn webbing, weak retractors, and poor fit—especially for children or smaller individuals. Even small delays in restraint during a crash can compromise coordination with airbags. Despite modern advances, many belts still lack anti-slip mechanisms. Minimizing slippage through better design is crucial for improving safety performance in real-world crashes (Figure 2).

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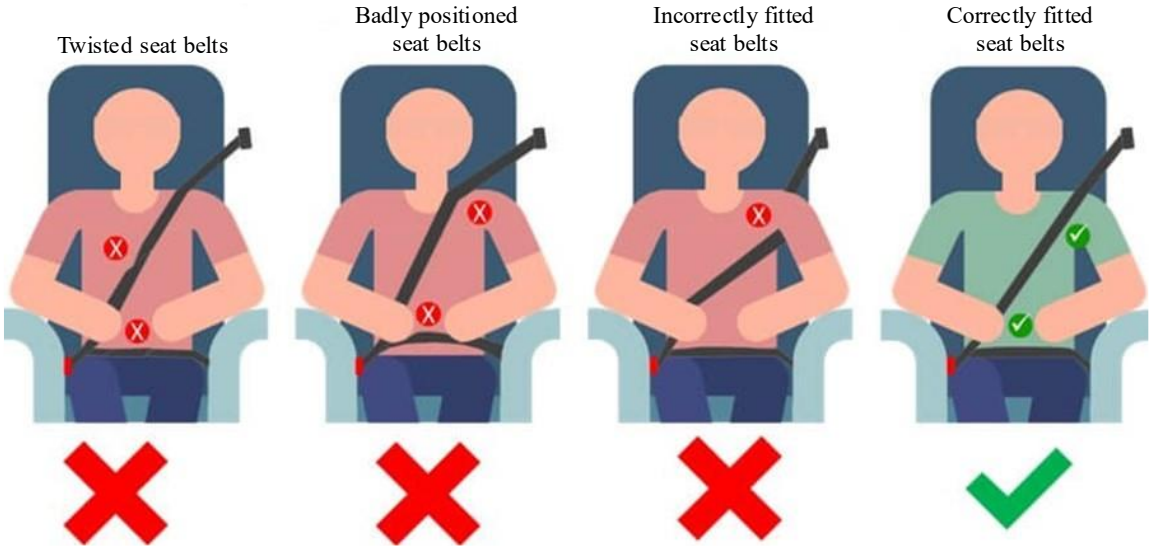

Figure 1. Mechanism to fasten the seat belt.

Figure 2. Seat belt malfunction injuries.

The objective for developing the anti-slip mechanism is mainly due to the factors such as safety, performance and cost. Slips, trips and falls are common occurrences that can happen at everyone's workplace, homestead or any other area which require safety precautions. Anti-slip technologies such as textures on the surface, matting, and special footwear prevent such mishaps hence safeguarding the sensitive groups and cutting on expenses on medical bills, insurance claims and downtimes. Also, these mechanisms facilitate effective operations in industries through avoiding slippage of equipment as well as promoting stability amongst workers. They also help save the expenses incurred over a long period since they slow the use of 'wear' on the material in areas that experience high traffic. Due to the present tendencies to introduce stricter safety standards and constant progress in materials sciences, the field of anti-slip products remains actively developing, thus remaining topical for more effective safety across various fields.

PROBLEM STATEMENT

Slippage in financial trading occurs when the actual trade price differs from the expected price, often in high-frequency or low-volume markets. Negative slippage, where trades execute at worse prices, is most common. It is caused by price volatility, limited stock availability, large orders, and system delays. In traditional markets, outdated matching engines and weak algorithms contribute, while in DeFi, smart contract delays, front running, and MEV worsen slippage. Real-time pricing issues and low liquidity also affect large or urgent trades. To reduce slippage, tools like limit orders, slippage tolerance, and advanced execution systems are used, though small investors remain more vulnerable (Figure 3).

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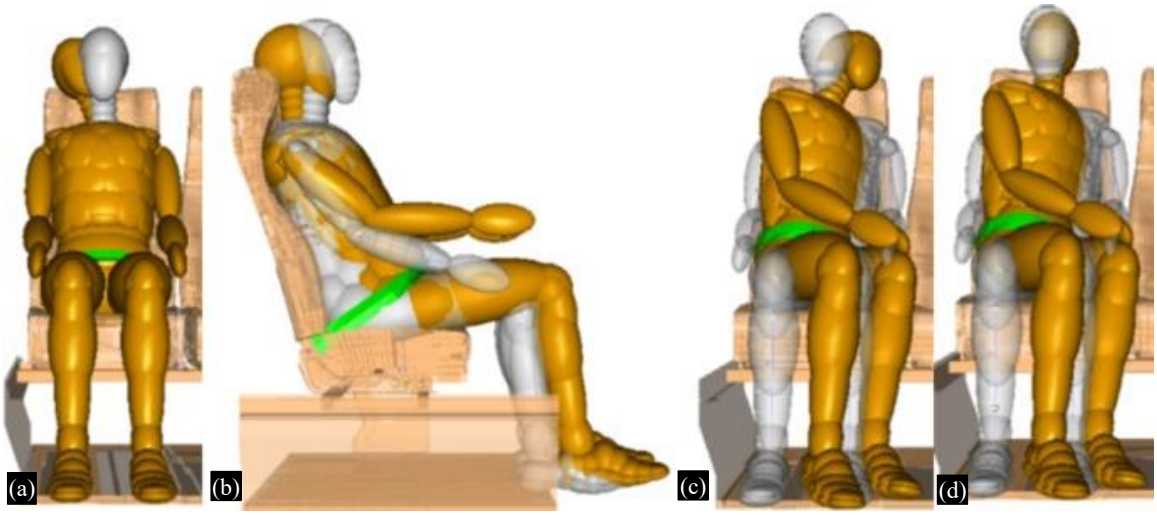

Figure 3. Need for anti-slip mechanism for enhanced seat belt safety.

Slippage during vehicle collisions poses a serious threat to the effectiveness of restraint systems like seat belts and airbags. It refers to the unwanted movement of the occupant due to worn belts, smooth seats, poor positioning, or crash forces. A severe form is submarining, where the pelvis slides under the lap belt, causing the belt to press into the abdomen, risking internal injuries. Slippage disrupts crash force distribution, increasing harm to sensitive areas like the spine or neck and reducing airbag effectiveness. To prevent this, modern cars use anti-submarining designs, seatbelt pretensioners, load limiters, and high-friction seats to keep occupants securely in place during impact.

Need For a Reliable, Cost-Effective Solution

A proper, long-term solution must be safe, reliable, affordable, and suitable for all business sectors, especially where resources are limited. In such contexts, costly systems are often impractical. A cost-effective solution is not only affordable to acquire but also cheap to operate and maintain. Reliability—consistent performance under varied conditions—is crucial, particularly in critical areas like healthcare, transport, and safety. For example, low-cost yet efficient anti-submarining seats in cars can enhance safety without increasing production costs. Ultimately, solutions that balance affordability and reliability offer wider adoption, scalability, and meaningful improvements in both economics and quality of life.

LITERATURE REVIEW

Security belt systems are one of the most basic elements of vehicles that are worn to protect the occupants in the event of an accident and greatly decrease chances of the occupant's fatalities. It comprises a webbing material that is typically a powerfully woven fabric material polyester or nylon which is buckled across the lap and chest of the occupant. This almost always employs a lap belt which encircles the waist around the pelvis and a shoulder belt that diagonally crosses the chest and shoulder. These two components are usually integrated with a retractor system, which enables the belt to either be drawn out or wind up for the purpose of accommodating the occupant. When an accident occurs, the retractor keeps the belt tightened so that it does not allow the occupant to move forward or get thrown out of the car. They also consist of a chunk and clasp system that enables the occupant to release and adjust the belt. In an attempt to improve the performance of these systems, some new features have been introduced into the market like the pre tensioners that ratchet the seat belt to help remove slack in case of an accident limiters that enable the belt to extend a little in the case of extreme force to minimize harm to occupants. Although currently available seat belt systems are very popular and well established with a proven capability of preventing fatalities and death, their efficiency is limited by factors such as size and position of the occupant and the intensity of the crash. Enhancements in vehicle safety have therefore seen traditional types of seat belts mounted in tandem with other technologies including air bags and the automated restraint systems. Traditional countermeasures addressing the problem mainly involve increasing the immobilization of the seat belt during an accident to minimize chances of its

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shifting. The first approach is that the main elements of the protection – the seat belt – has the anti-slip material applied to the webbing to prevent the belt from slipping out of place due to slippage: The webbing can be coated with special textures or rubber inlays. First, seat belt positioners are installed to keep the shoulder belt of the concerned occupant well positioned against the chest of the concerned occupant while pre-tensioners tighten the seat belt from slack that it might allow during a crash. Many cars also contain load-limiters that regulates the pressure applied on a belt so that it cannot harm or slip off during an accident. Some of these are even incorporated in our today's seating positions to ensure that such belts remain in position during an accident. Thus, there are still some shortcomings regarding existing solutions, even if further development was observed in seat belt technologies. One is that it may not fit all users well since some may be uncomfortable to wear the belt or may be positioned in a way that will be less effective in the case of an accident. However, with the anti-slip materials put in place, it is still possible to slip especially in extreme situations or in event of a severe impact. There are other types of shortcomings, which prevent some systems from being altered dynamically, such as seat belts that might not be sensitive to movements or changes in occupant position or seats' positions. However, drivers and front passengers will continue to be at somewhat of a decreased risk, while rear-seat occupants, who do not use seat belts correctly most of the time, may be also at an increased risk because current technologies are oriented mainly to protecting front-seat passengers. Nonetheless, these gaps address the importance of more individualized, flexible and broader restraint systems that should be established to improve the safety of all the passengers. FMVSS 208 (Federal Motor Vehicle Safety Standard) in the United States; ECE R16 (Economic Commission for Europe Regulation 16) set vital standards for the seat belts to provide occupant safety. FMVSS 208 established the requirements for force limits and the geometry of the seat belt since people are at potential for risk of injuries in case of a crash. Likewise, ECE R16 deals with the strength and proper functioning of the seat belts where it outlines the requirement of the seat belt Webbing, Retractor and Buckle. These two standards make sure that they adequately restrain the occupants in the case of an impact, prevent their ejection from the vehicle, and restrict the amount of force that is experienced by the parts of the body by regulating the distribution of force. These safety regulations are crucial in the elimination of deaths and improvement of vehicle occupants' safety globally.

DESIGN AND DEVELOPMENT

The anti-slip mechanism aims to enhance occupant safety during crashes by preventing slippage, especially submarining, where the pelvis slides under the lap belt. It uses a contoured seat pan with a raised front to support the thighs and stop forward pelvic movement. High-friction seat fabrics help reduce sliding, while energy-absorbing materials and structural reinforcements keep occupants upright. By maintaining the correct occupant position throughout a crash, the mechanism improves the performance of seat belts and airbags, reducing the risk of serious injuries in frontal collisions (Figure 4).

The proposed anti-slip mechanism enhances occupant stability with minimal design changes. It includes high-density polyurethane foam cushions that resist compression and absorb crash energy, along with high-friction seat coverings like textured fabric or rubber around key areas such as the thighs and pelvis. The seat structure uses reinforced steel or aluminium with shock absorbers to reduce impact force. A dynamic lock (mechanical ramp or cushion lock) activates during crashes to prevent forward pelvic movement and reduce submarining. Contoured seats with side supports work alongside pre-tensioned seat belts and proper anchoring to maintain occupant position. The design is durable, comfortable, easy to install, and boosts overall vehicle safety.

Integrating a new seat belt system into existing vehicle setups aims to enhance safety while ensuring compatibility with current technologies like airbags, seat sensors, and crash detectors. Advanced features such as pretensioners, load limiters, and adjustable belts must work seamlessly with these systems for optimal protection. Key challenges include maintaining the original ASV design like anchor points and retractors while adding software to link the seat belt with crash detection and inflation systems. Adjustments in sensors and actuators are needed for adaptive responses to various crash scenarios. Rigorous testing and compliance with safety standards are essential to ensure reliability without compromising system simplicity (Figure 5).

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MATERIAL SELECTION

Material selection for seat belt systems is based on strength, friction coefficient, and durability. High-strength steel is used for retractors and buckles due to its crash resistance, while polyester and nylon webbing offer high tensile strength and minimal stretch. For smooth operation and slip prevention, components use materials like stainless steel, aluminium, and thermoplastic polymers with suitable friction properties. To ensure long-term performance, polyester, nylon, and corrosion-resistant metals are chosen for their resistance to UV, wear, and environmental conditions, making the system reliable and safe over time (Figure 6).

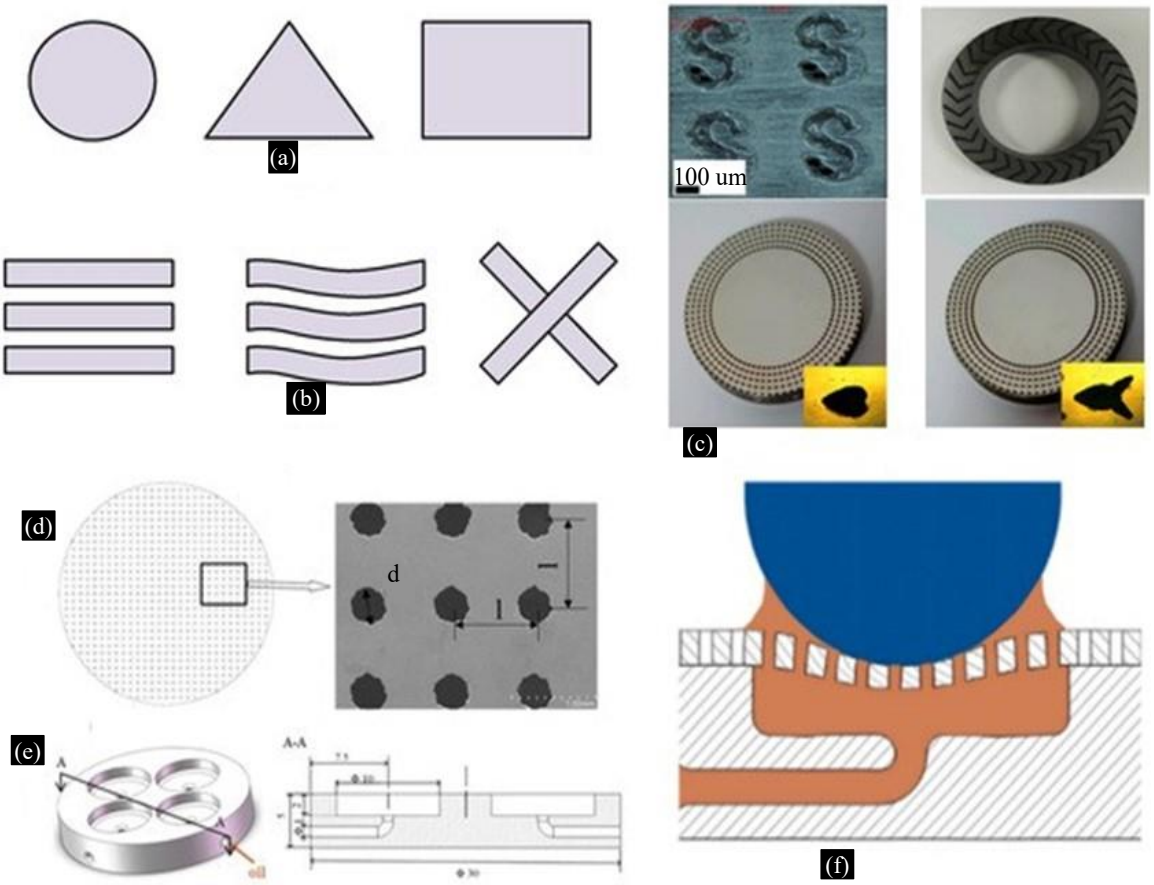

Figure 4. Design and development.

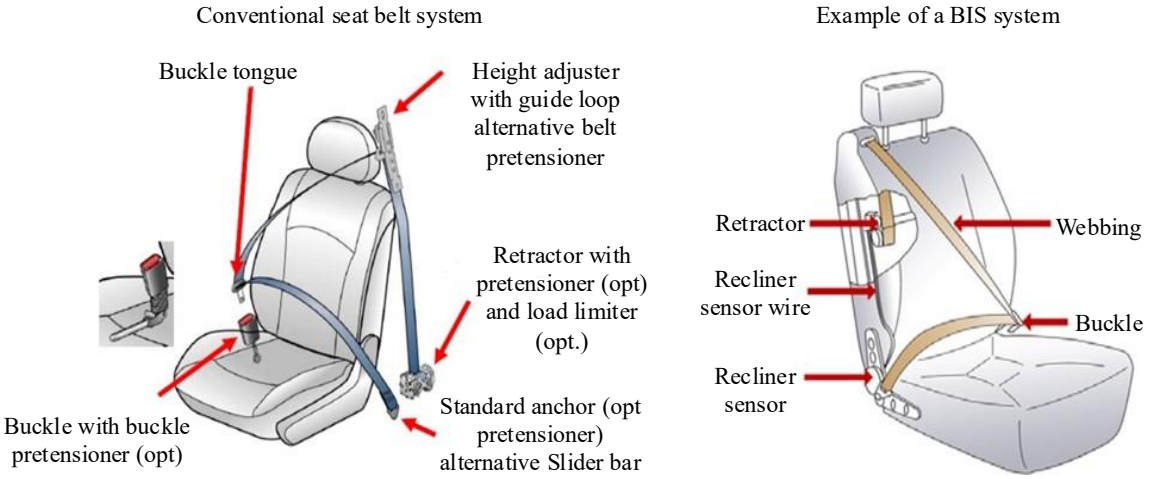

Figure 5. Integration method with existing seat belt systems.

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Figure 6. Materials chosen for the belt, locking unit, and friction layers.

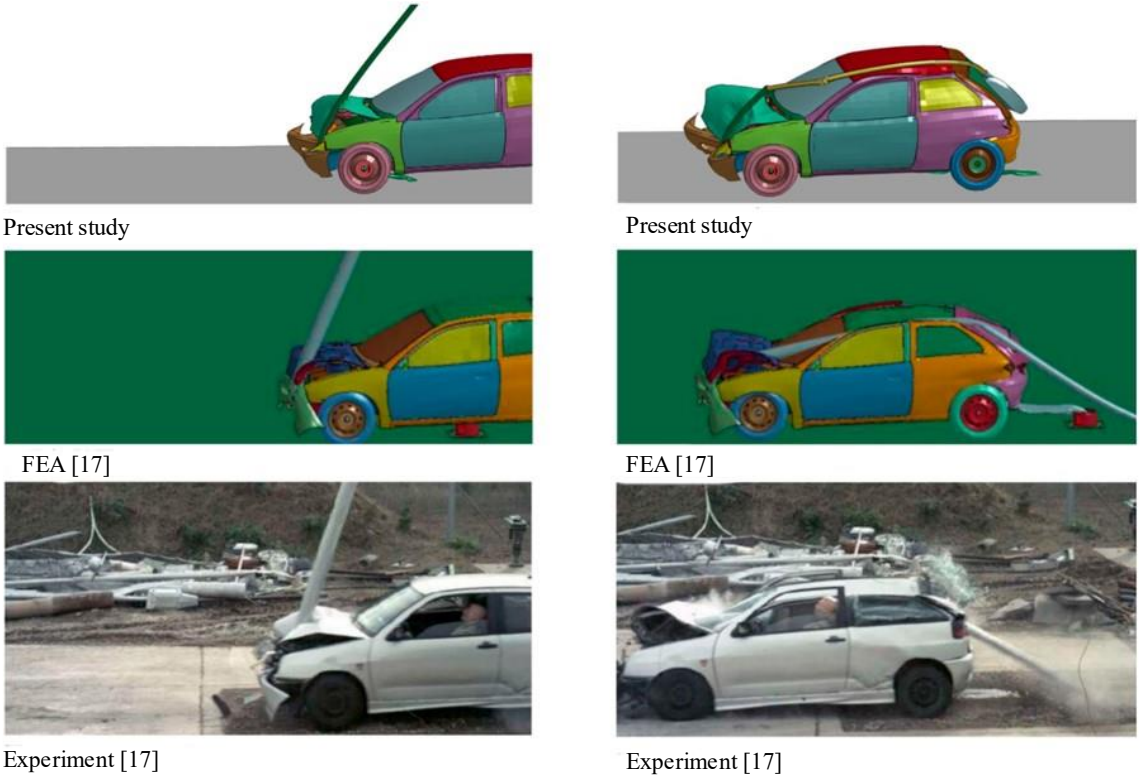

Figure 7. Test procedures: static load testing, dynamic testing (crash simulations).

The materials used in a seat belt system webbing, locking unit, and friction layers are carefully selected for safety, performance, and durability. Nylon and polyester are ideal for webbing due to their high tensile strength, low stretch, and resistance to abrasion and environmental damage, with polyester offering excellent UV and moisture resistance. High-strength steel is used in the locking unit for its ability to handle impact forces, while aluminium alloys provide a lighter alternative with good corrosion resistance. Thermoplastic polymers like polyurethane or polypropylene are used in friction layers for their durability, low wear, and stable friction properties ensuring smooth belt operation during normal use and firm locking during crashes. Each material plays a key role in ensuring occupant safety and system reliability over time.

METHODOLOGY

Seat belt system prototype development follows a structured process to ensure functionality, vehicle compatibility, and safety. It begins with concept creation and 3D design using software like SolidWorks or CATIA, focusing on dimensions, attachment points, and layout. Material selection follows, considering tensile strength, friction, and wear resistance. Finite Element Analysis (FEA) tools like ANSYS or Abaqus are used to evaluate crash performance. Prototypes of components such as webbing,

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locks, and retractors are then manufactured and assembled. Tests assess retraction, locking, load capacity, and comfort. Real-world simulations with crash dummies and sled testing are performed. Based on results, the design is refined in an iterative cycle until all safety standards are met for production readiness (Figure 7).

As a key safety feature, seat belts undergo both static and dynamic testing. Static load testing evaluates the belt's strength by gradually applying tensile forces (typically 13–15 kN) to the webbing, buckles, and anchors to ensure they meet standards like FMVSS 209 or ECE R16. It verifies structural integrity under stress beyond typical use. In contrast, dynamic testing simulates real crash conditions using crash dummies and high-speed sleds to replicate impacts over 30 mph (48 km/h). This test measures belt effectiveness, dummy movement, retractor response, and injury metrics like HIC and chest deflection. Static tests validate design strength, while dynamic tests assess real-world crash performance and certification readiness (Figure 8).

Developing and testing a seat belt system involves a variety of tools to ensure accuracy, safety, and compliance. CAD software like SolidWorks and CATIA is used for 3D modeling, while FEA tools such as ANSYS or Abaqus simulate crash behavior. CNC machines, 3D printers, and laser cutters assist in prototype fabrication, and tools like torque wrenches and sewing machines are used for assembly. Universal Testing Machines (UTMs) evaluate static strength, while high-speed sled rigs, crash test dummies, sensors, and high-speed cameras are used for dynamic crash testing. DAQ systems collect test data, and climatic chambers and UV testers assess performance under environmental stress. Together, these tools ensure the seat belt system is safe, reliable, and production-ready.

Key parameters are analyzed during seat belt testing to assess performance in normal and crash conditions. Force is critical, measuring the seat belt’s ability to withstand crash loads on components like webbing, anchors, and retractors, typically in kilonewtons (kN) using load cells. Slippage evaluates how much the belt webbing moves through the buckle or retractor—excessive slippage reduces protection. Stretch of the webbing is measured as a percentage increase in length under load to ensure energy absorption without excessive forward movement. Locking response time indicates how quickly the retractor engages during rapid acceleration or deceleration, measured in milliseconds using high-speed sensors. These parameters ensure the belt system provides fast, firm restraint and minimizes injury risk during a crash.

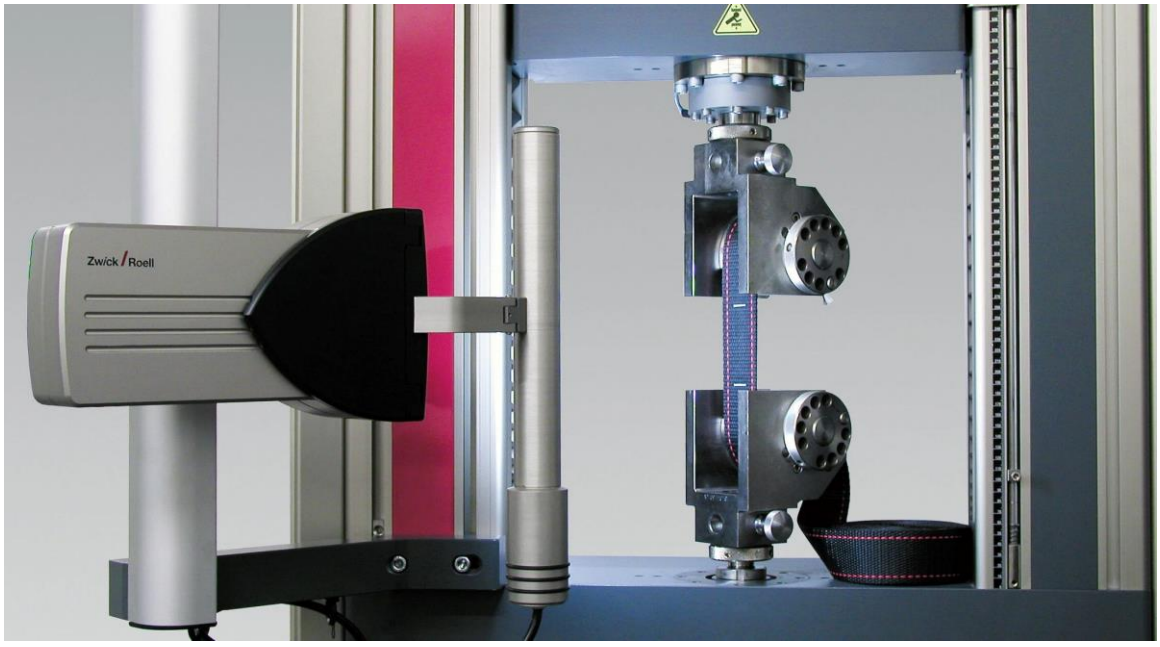

Figure 8. Tools and equipment use.

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RESULTS AND DISCUSSION

While comprehensive comparative data between conventional and anti-slip seat belts is limited, existing studies suggest that anti-slip belts featuring elements like pretensioners and optimized D-ring positions offer better occupant restraint by reducing slippage and lateral head movement during collisions. Although data on stretch and reaction time is sparse, pretensioners in anti-slip systems appear to enhance belt engagement speed and reduce slack. However, studies on systems like Seat Integrated Restraint Systems (SIRS) show no significant difference in injury or fatality rates compared to conventional belts under rollover conditions. Evaluating seat belt performance under varied angles and force conditions is critical, as factors like belt angle significantly influence injury patterns flat angles distribute pressure more evenly, while sharp angles may concentrate force and increase localized injury risk. Testing under real-world crash simulations through dynamic and static load assessments, dummy-based evaluations, and high-speed imaging helps assess kinematics such as head excursion, chest deflection, and neck forces. These tests also analyze components like pretensioners and load limiters to gauge their timing, load management, and safety effectiveness. Ultimately, multi-directional testing enables engineers to optimize seat belt design for enhanced safety across diverse crash scenarios (Figure 9).

Table 1 compares the seat belt's performance based on the angle of the seat belt, showing how varying the angle affects the force distribution, head excursion (forward movement), chest deflection, and the potential injury risk to the occupant. The higher the angle, the greater the potential for injury due to increased force on localized areas of the body.

Figure 10 would plot how head excursion increases as the force applied during a crash increases, showing the relationship between the forces on the seat belt and the occupant's movement.

As the force applied during a crash increases, head excursion (the forward movement of the occupant's head) also increases. The seatbelts performance is considered effective if the head excursion is minimized under higher forces.

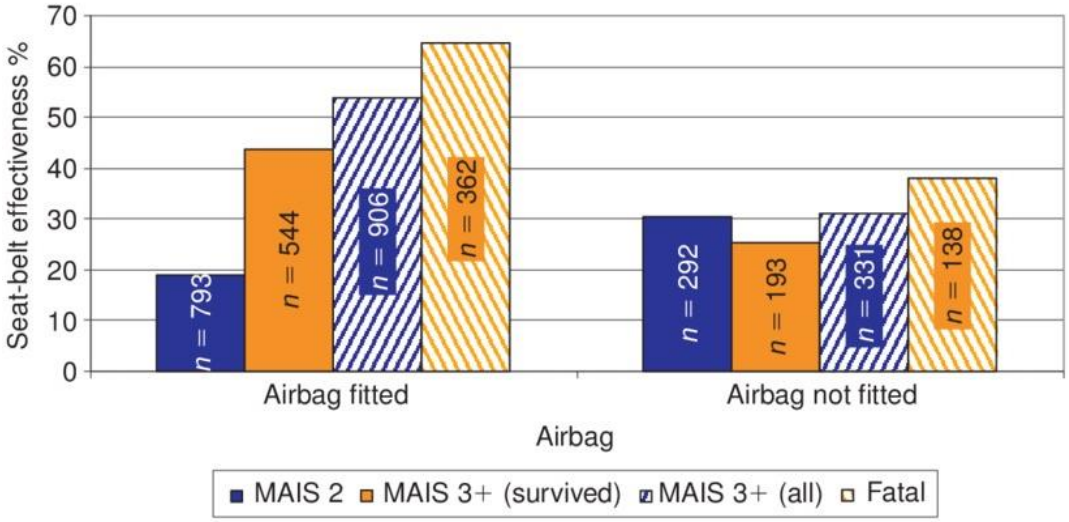

Figure 9. Data from testing: comparison between conventional vs. anti-slip belt.

Table 1. Comparison of seat belt performance at different angles.

Angle of seat belt	Force applied (kN)	Head excursion		Chest deflection (cm)	Injury risk
			(cm)		
0° (Flat)	12.5	24		22	Low
15° (Moderate)	10.3	28		25	Medium
30° (Sharp)	9.8	32		30	High

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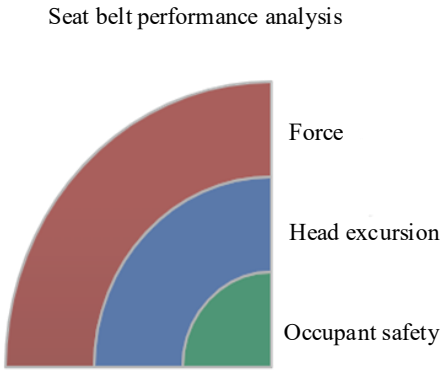

Figure 10. Seat belt performance analysis.

Table 2. Performance of seat belts with and without anti-slip features.

Feature	Force applied (kN)	Slippage (cm)	Stretch (%)	Reaction time (ms)	Effectiveness
Conventional seat belt	12.5	4.5	5%	150	Medium
Anti-slip seat belt	12.5	1.2	3%	120	High

Table 2 compares the performance of a conventional seat belt and an anti-slip seat belt under the same force. Anti-slip seat belts show lower slippage (less movement of the webbing through the retractor), less stretch (indicating better energy absorption), and faster reaction time. This leads to a more effective restraint during a crash (Figure 11).

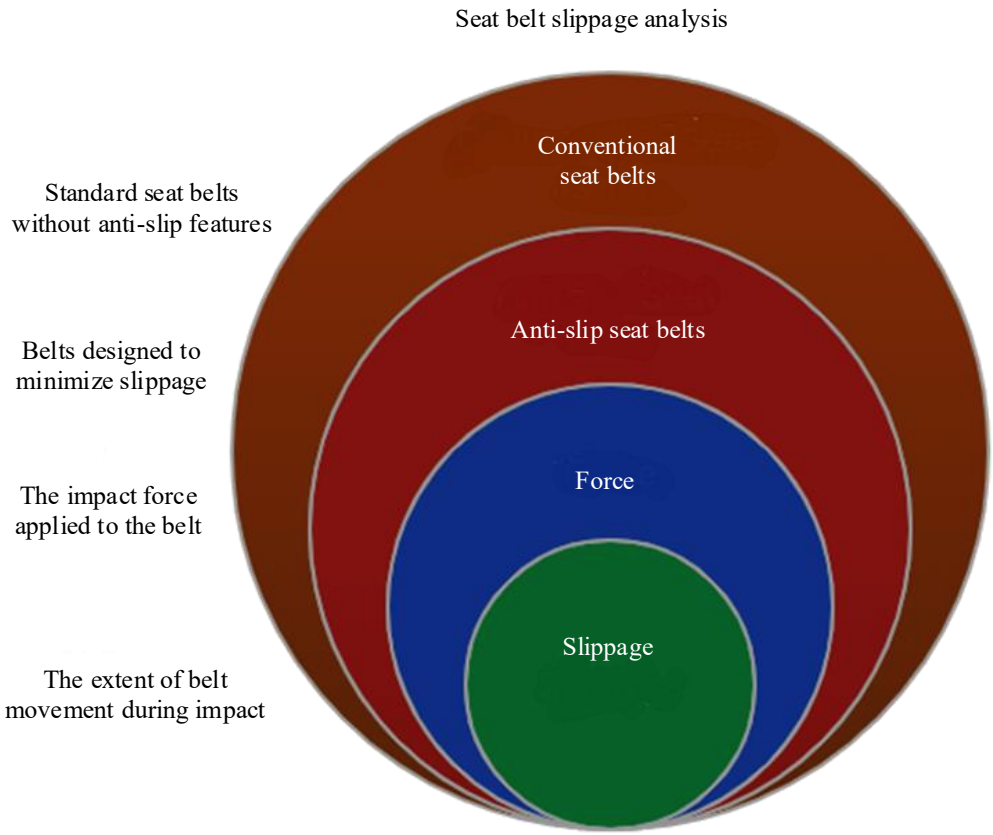

Figure 11. Seat Belt Slippage Analysis The graph would show that as force increases, slippage of the anti-slip belt is significantly less than that of the conventional belt, meaning the anti-slip system provides better occupant restraint (Figure 12).

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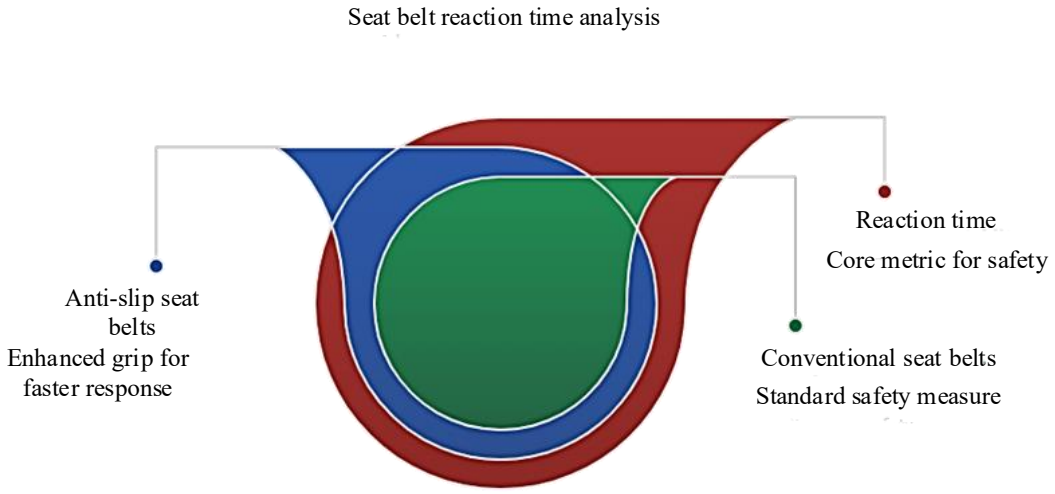

Figure 12. Seat belt reaction time analysis.

The reaction time is faster in anti-slip seat belts than in conventional seat belts, indicating that the anti-slip belts are quicker to respond during dynamic crashes, enhancing occupant safety. These graphs and tables offer a visual representation of how seat belt systems perform under different conditions (angle, force, slippage, stretch, reaction time). The comparisons allow us to understand the benefits of advanced systems (such as anti-slip belts) over conventional ones in real-world crash scenarios.

FEASIBILITY ANALYSIS AND LIMITAIONS

Manufacturing cost estimation of seat belt systems includes material costs (like polyester webbing and metal components), processing (cutting, stitching, molding), and assembly, with total per-unit costs ranging from $15–$25, or $8–$12 in mass production due to economies of scale; additional expenses such as certification and transport further influence the final cost. Retrofit potential depends on vehicle compatibility—while mechanical retrofits are easier, integrating electronic features (e.g., pretensioners) may require ECU upgrades and certified installations, yet modular retrofit kits now ease adoption, especially in older or commercial vehicles. Compatibility with current vehicle designs is generally high due to standardized mounting points and global safety regulations, enabling modern seat belts with advanced features to integrate seamlessly into most vehicles without major structural changes. Scalability and production of advanced systems are supported by global suppliers, automation, modular design, and digital manufacturing tools, allowing efficient, large-scale production and flexible deployment for both new and retrofit markets.

- *Design constraints:* Seat belt design must meet safety standards, ergonomic needs, vehicle space limits, material and cost constraints, and manufacturing efficiency to ensure systems are safe, comfortable, and affordable (Figure 13).
- *Environmental or usage conditions that may affect performance:* Seat belt performance is affected by environmental and usage conditions such as temperature extremes, moisture, UV exposure, and corrosion, which can weaken materials and components. Frequent use, dirt, and improper handling can further degrade function. To ensure long-term safety, seat belts undergo rigorous testing for durability, thermal resistance, corrosion, and mechanical wear (Figure 14).
- *Maintenance or wear-and-tear issues:* Seat belts can degrade over time due to wear, environmental exposure, and misuse, leading to issues like frayed webbing, dirt buildup, corrosion of metal parts, and retractor spring fatigue. These problems can reduce belt strength, hinder retraction, or cause locking failures. Pretensioners may also silently fail if sensors degrade. Regular inspections—checking webbing, retraction, buckle function, and locking response—are vital, along with gentle cleaning and prompt replacement after a collision or significant damage to ensure continued safety and reliability.

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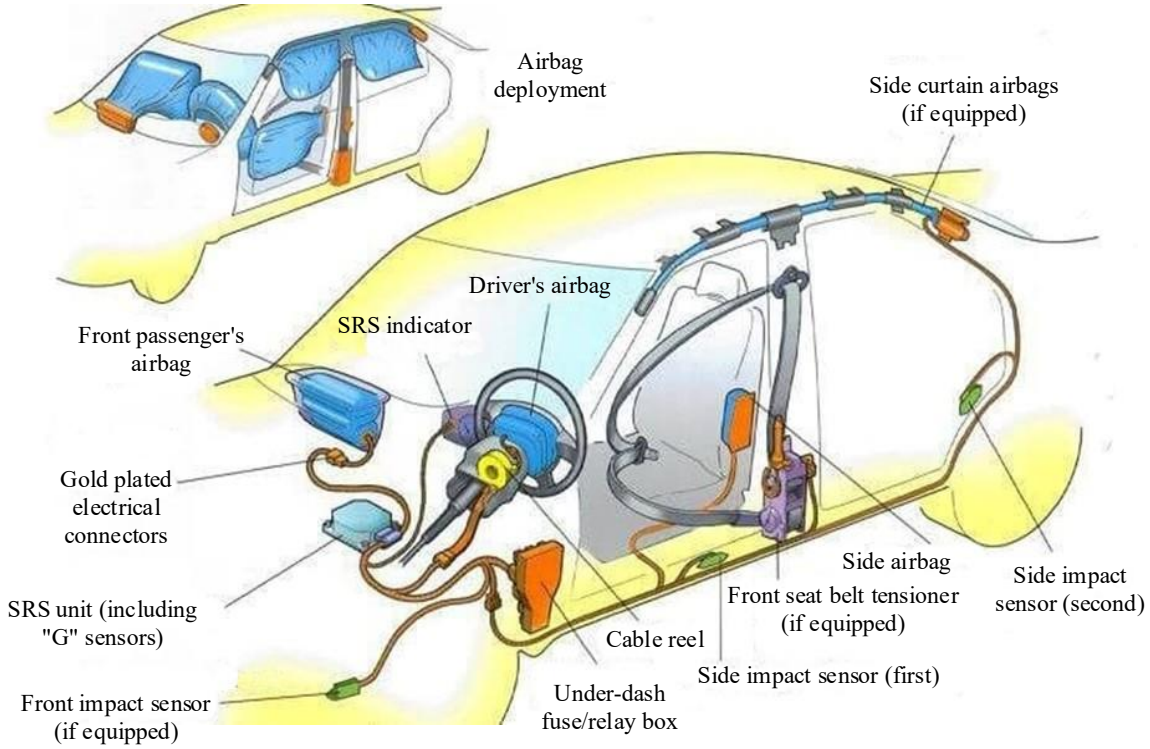

Figure 13. Design constraints.

Figure 14. Environmental or usage conditions that may affect performance.

CONCLUSION

- Modern seat belt systems integrate advanced technologies like pretensioners, load limiters, and anti-slip materials to significantly enhance occupant safety during various crash scenarios.

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- Design, material selection, and testing protocols are carefully aligned with global safety regulations and real-world conditions, ensuring durability, ergonomic fit, and consistent performance across diverse environments.
- Scalability and production of these systems are feasible due to modular designs and automated manufacturing, making them suitable for mass-market applications as well as specialized vehicles.
- Routine inspection and maintenance are essential, as wear-and-tear from environmental exposure and frequent use can compromise seat belt reliability over time.
- Seat belt innovation offers commercial opportunities across mainstream, luxury, autonomous, and retrofit vehicle markets, with potential to enhance occupant protection and differentiate vehicle brands.
- Future seat belts will evolve with smart sensors, real-time data feedback, and integration with other vehicle systems, enabling personalized restraint and improved safety for all occupant types and driving conditions.

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