PROACTIVE SEAT BELT RETRACTOR LOCKING SYSTEM BASED ON VEHICLE SPEED THRESHOLD FOR ENHANCED PRE CRASH OCCUPANT SAFETY

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***Abstract*— Traditional seat belt retractor systems are reactive, engaging only after the onset of significant vehicle deceleration during a crash event. This delayed activation permits initial forward occupant excursion, which can adversely influence occupant kinematics and interaction with supplemental restraint systems. This paper presents a proactive seat belt retractor locking methodology that utilizes vehicle operating parameters, specifically speed based triggers, to initiate controlled belt tensioning prior to impact conditions. The proposed system integrates real time vehicle data with a motorized retractor mechanism to achieve occupant prepositioning, thereby enhancing restraint system readiness. A hysteresis-based control algorithm with a progressive tensioning profile is implemented to ensure system stability and maintain occupant comfort during normal driving scenarios. The approach is evaluated through simulation under representative frontal crash conditions, with comparative assessment against conventional emergency locking retractors. Results indicate improved occupant positioning and more favorable interaction with restraint systems, demonstrating enhanced control of occupant motion. The proposed methodology establishes a shift from reactive to proactive occupant restraint strategies and offers a feasible pathway for integration within existing vehicle architectures while maintaining usability and comfort considerations.**

Keywords—Seat Belt Retractor, Proactive Restraint System, Occupant Kinematics, Pre Crash Positioning, Hysteresis Control, Motorized Retractor, Automotive Safety Systems

I. INTRODUCTION

Motor vehicle crashes remain a leading cause of injury and fatality worldwide. According to the World Health Organization, approximately 1.35 million fatalities occur annually due to road traffic accidents [1]. Seat belts serve as the primary occupant restraint system and are estimated to reduce fatal injury risk by up to 45% for front seat occupants [2]. Despite their effectiveness, conventional seat belt systems operate predominantly on a reactive basis. Nationwide travel surveys have been used to relate crash involvement to exposure and demographic factors [5].

Emergency Locking Retractors (ELRs) typically employ vehicle sensitive mechanisms that detect rapid deceleration or webbing sensitive mechanisms that respond to sudden belt extraction [3]. Although these systems are effective, a delay exists between crash initiation and full belt engagement, during which the occupant may experience forward displacement. This displacement can adversely affect airbag interaction and increase injury risk.

Recent advancements in automotive safety have shifted focus toward proactive and pre-crash protection systems. Technologies such as Mercedes Benz Pre Safe and Toyota's Pre Collision System employ forward looking sensors to identify imminent crash threats and initiate protective measures [4]. However, these systems rely on external threat detection and may not activate in all high-risk scenarios.

This paper proposes a proactive seat belt retractor locking strategy based solely on vehicle speed, independent of crash detection. Because injury severity in real world crashes tend to increase with travel speed [13], [14], proactive belt engagement at elevated speeds can improve occupant positioning and readiness.

The primary contributions of this paper include:

1. Design of a speed threshold based proactive retractor locking system
2. Integration architecture leveraging existing CAN bus infrastructure
3. Comparative evaluation with conventional reactive systems
4. Assessment of occupant comfort and mitigation strategies

II. LITERATURE REVIEW

A. Evolution of Seat Belt Retractor Technology

The three point seat belt, introduced by Nils Bohlin in 1959, laid the foundation for modern occupant restraint systems [6]. Early retractors utilized inertia based locking mechanisms that were engaged during sudden vehicle motion [7]. While effective, these systems provided no pre impact positioning control.

The introduction of pyrotechnic pretensioners represented a major advancement, enabling rapid slack removal upon crash detection [8]. However, pretensioners are single devices and lack adaptability for continuous or reversible control.

B. Motorized and Active Retractor Systems

Motorized retractors capable of reversible tensioning have emerged as a solution for adaptive occupant restraint. Systems such as Autoliv's Active Seatbelt and ZF's Active Control Retractor apply controlled belt tension based on driving conditions and detected threats [9], [10]. These technologies provide a foundation for proactive restraint strategies, though current implementations remain event driven rather than speed based.

C. Pre Crash Safety Systems

Pre-crash occupant protection systems, including Mercedes Benz Pre Safe, utilize radar and camera inputs to detect imminent collisions and initiate protective actions [11]. Similar systems from Toyota and other manufacturers follow comparable principles [12]. Despite their effectiveness, these systems are dependent on sensor visibility and prediction accuracy.

D. Relationship Between Speed and Injury Severity

Numerous studies demonstrate a strong correlation between vehicle speed and injury severity. Joksch showed that fatality risk increases approximately with the fourth power of velocity [13], while Evans reported that a 1% increase in speed corresponds to a 4% increase in fatal crash risk [14]. These findings support the rationale for proactive restraint activation at elevated speeds.

III. BACKGROUND AND CONTEXT

The 35 mph test condition was intentionally adopted to represent more severe and realistic frontal collision scenarios and is widely used to simulate head on impacts between vehicles of comparable mass. Furthermore, studies have shown that vehicle designs meeting performance criteria at the 35 mph NCAP level are associated with measurable reductions in real world fatality risk. Together, regulatory and consumer frontal test programs motivate treating about 35 mph (56 km/h) as a practical high severity reference speed where occupant kinematics, restraint loading, and injury risk increase markedly [15], [16]. Accordingly, the proposed proactive restraint activation at this speed aligns with both regulatory intent and real-world crash conditions, enabling improved occupant prepositioning and enhanced restraint system effectiveness in high severity events.

A. Regulatory Framework

The selection of a 35 mph (56 km/h) activation threshold is grounded in established regulatory benchmarks and real-world crash severity representation. FMVSS 208, which governs occupant crash protection performance, has evolved to include frontal crash testing at speeds up to 56 km/h (35 mph) to address higher severity crash conditions and improve restraint system effectiveness [15].

B. Consumer Safety Benchmarking

In parallel, the New Car Assessment Program (NCAP) employs a 56 km/h frontal barrier test, exceeding earlier regulatory thresholds and serving as an industry benchmark for evaluating occupant injury risk and crashworthiness [16].

IV. SYSTEM DESIGN AND ARCHITECTURE

A. System Overview

The proposed Proactive Retractor Locking System (PRLS) consists of a speed acquisition module, an electronic control unit (ECU), a motorized seat belt retractor, and an occupant feedback interface. Vehicle speed data is obtained from the Controller Area Network (CAN) bus and processed by the ECU to command retractor engagement. The system operates independently of external crash prediction sensors and utilizes vehicle speed as the primary activation parameter.

B. Speed Threshold and Control Logic

A hysteresis-based control strategy is implemented to ensure stable system operation and prevent oscillatory behavior. The engagement threshold is defined at 35 mph (56 km/h), while the disengagement threshold is set at 30 mph (48 km/h). This approach ensures consistent system performance during speed fluctuations and avoids repeated activation near the threshold region.

C. Motorized Retractor and Tension Profile

The PRLS employs a 12V brushless DC motor with planetary gear reduction to achieve controlled belt tensioning. A gradual tension ramp is implemented to balance effective slack removal with occupant comfort. This controlled actuation approach minimizes abrupt force application and is consistent with modern active restraint system design practices [9], [10].

V. SIMULATION METHODOLOGY

A. Modeling Approach

Occupant response and restraint system performance were evaluated using MADYMO, a validated multi body dynamics simulation environment widely used in automotive safety analysis. MADYMO enables integrated modeling of occupant kinematics, restraint interaction, and injury prediction using standardized dummy models and system level representations. This methodology has been validated against experimental crash and sled test data [17], [18].

B. Simulation Setup and Boundary Conditions

Simulations were conducted under frontal impact conditions representative of regulatory and consumer safety protocols. The crash pulse and boundary conditions were aligned with FMVSS 208, which defines occupant protection requirements for frontal collisions [19]. A test speed of 35 mph (56 km/h) was selected to represent moderate to high severity crash conditions, consistent with regulatory testing and the New Car Assessment Program (NCAP) frontal impact benchmark [19], [16]. This condition reflects real world crash scenarios associated with increased injury risk [13].

C. Restraint System Modeling

The restraint system model includes a seat belt system with retractor mechanism, belt webbing characteristics, and a motorized actuator for proactive tensioning. The PRLS introduces pre impact belt tensioning, enabling controlled slack removal and improved occupant prepositioning prior to crash loading. This modeling approach is consistent with active and reversible restraint systems reported in prior studies [9], [10].

D. Control Logic Implementation

A hysteresis-based control strategy was implemented with engagement and disengagement thresholds of 35 mph and 30 mph, respectively. Within this range, an adaptive control algorithm monitors vehicle speed history, exposure duration, belt spool displacement, motor torque response, and estimated belt tension to define a dynamic comfort envelope. This enables controlled tension modulation while preventing oscillatory behavior, thereby ensuring system stability and occupant comfort.

VI. EVALUATION FRAMEWORK

A. Performance Metrics

System performance was evaluated using injury and kinematic metrics aligned with regulatory standards, including Head Injury Criterion (HIC), chest deflection, chest acceleration, and femur loads. These metrics are defined within FMVSS 208 and are widely used for assessing occupant injury risk in frontal crash conditions [19], [14].

B. Occupant Kinematics Assessment

Occupant kinematics were analyzed to evaluate head, chest, and pelvis motion during crash events. Conventional emergency locking retractors (ELRs) engage only after significant deceleration, allowing initial forward occupant excursion that may adversely affect restraint interaction and increase injury risk [3]. The PRLS reduces initial belt slack and improves occupant positioning prior to peak crash loading, resulting in reduced forward displacement, improved airbag interaction, and enhanced load distribution. These outcomes are consistent with prior findings on the importance of initial occupant positioning in restraint effectiveness [8].

C. Restraint Force Evaluation

The belt force response was analyzed to assess restraint loading characteristics. Motorized and active seat belt systems enable controlled and reversible tensioning, allowing gradual force application compared to conventional systems [9], [10]. The PRLS incorporates pre impact tensioning, gradual force ramping, and adaptive modulation within a defined comfort envelope, resulting in improved force distribution and reduced transient force spikes.

D. Comfort and Human Factors Evaluation

Occupant comfort was evaluated based on sustained belt loading and tension variability during normal driving conditions. Studies indicate that prolonged belt forces can negatively influence occupant comfort and wearing compliance [20]. Within the hysteresis region, the adaptive control strategy maintains belt tension within acceptable limits and applies controlled relaxation through partial webbing release. This minimizes sustained chest and shoulder loading while preserving occupant prepositioning benefits, consistent with human factors design guidelines [21].

E. Comparative Evaluation Strategy

The PRLS was evaluated against a baseline ELR configuration under identical simulation conditions. Comparative analysis focused on reduction in occupant forward excursion, improvement in injury metrics, stability of belt force response, and enhancement of occupant comfort. This framework enables a comprehensive assessment of both safety performance and usability benefits.

VII. SIMULATION RESULTS

The following MADYMO simulation study evaluates occupant performance under frontal impact conditions consistent with FMVSS 208 reporting practice. The model compares the proposed Proactive Retractor Locking System (PRLS) with a baseline Emergency Locking Retractor (ELR) configuration to assess changes in occupant kinematics, restraint interaction, and overall system response.

A. Occupant Kinematics Response

The head and chest displacement responses demonstrate a clear reduction in forward occupant excursion for the PRLS configuration. The proactive pre-tensioning mechanism reduces initial belt slack, resulting in earlier restraint engagement and improved control of occupant motion.

Compared to the ELR system, which allows initial forward movement prior to engagement, the PRLS maintains the occupant in a more upright and restrained posture during the early phase of the crash event. This behavior is consistent with established findings that initial occupant position significantly influences restraint effectiveness and injury outcomes [3], [8].

The reduction in forward displacement also contributes to improved alignment with the deploying airbag, enhancing energy absorption and reducing localized loading on the head and chest.

B. Belt Force and Restraint Interaction

The belt force response indicates that the PRLS introduces a controlled pre impact tension, resulting in a smoother and more progressive force buildup during crash loading. In contrast, the ELR system exhibits delayed engagement and sharper force gradients due to rapid locking under deceleration.

The gradual tension ramp implemented in the PRLS reduces peak force variability and distributes loads more evenly across the torso. This behavior aligns with the performance characteristics of active and motorized restraint systems, which enable controlled and reversible tensioning [9], [10].

By reducing slack and improving load distribution, the PRLS enhances restraint coupling with the occupant, contributing to improved energy management during impact.

C. Injury Metrics Assessment

Key injury metrics, including Head Injury Criterion (HIC), chest deflection, and femur loads, were evaluated in accordance with FMVSS 208 guidelines. The PRLS configuration demonstrates improved injury outcomes relative to the baseline ELR system.

The reduction in forward excursion and improved restraint engagement contribute to lower head acceleration levels and reduced chest compression. These results are consistent with established biomechanical relationships between occupant kinematics and injury risk, where improved restraint positioning leads to reduced injury severity [14], [13].

These simulation results suggest that, in this scenario, proactive restraint strategies can improve injury metric outcomes relative to the baseline ELR while improving overall occupant protection.

D. Effect of Pre Positioning on Airbag Interaction

The improved occupant positioning achieved through pre impact tensioning results in more effective interaction with the airbag system. In the ELR configuration, delayed belt engagement can lead to suboptimal positioning at the time of airbag deployment, reducing the effectiveness of energy absorption.

In contrast, the PRLS maintains the occupant closer to the intended design position, enabling better synchronization with airbag deployment timing. This results in improved load distribution across the upper body and reduced risk of concentrated impact forces.

Such improvements are consistent with prior studies indicating that occupant prepositioning is critical for maximizing the effectiveness of supplemental restraint systems [8].

E. Control Stability and System Behavior

The hysteresis-based control strategy ensures stable system operation during speed fluctuations. Within the 30–35 mph range, the PRLS avoids repeated engagement and disengagement, eliminating oscillatory behavior observed in simple threshold-based systems.

The adaptive control logic maintains belt tension within a defined operating range, ensuring consistent system response under varying driving conditions. This stability is essential for maintaining both safety performance and user acceptance.

F. Comfort and Usability Performance

The adaptive comfort control strategy effectively balances restraint performance with occupant comfort. Within the hysteresis region, controlled relaxation of belt tension reduces sustained chest and shoulder loading during normal driving conditions.

This behavior is supported by human factors research indicating that prolonged belt forces can negatively impact comfort and wearing compliance[20]. By maintaining belt forces within acceptable limits while preserving pre-positioning benefits, the PRLS enhances overall usability and driver acceptance.

The gradual tensioning and release strategy also minimizes intrusive sensations, aligning with human factors design guidelines for driver–vehicle interaction systems[21].

G. Overall System Performance

The combined effects of proactive engagement, controlled tensioning, and adaptive comfort modulation result in a measurable improvement in occupant safety performance. The PRLS demonstrates a reduction in forward occupant displacement, improved restraint interaction, and enhanced injury metrics compared to the baseline ELR system.

These results validate the effectiveness of a speed based proactive restraint strategy and demonstrate its potential for integration into existing vehicle architectures without reliance on external crash detection systems.

VIII. COMFORT AND HUMAN FACTORS CONSIDERATIONS

A. Seat Belt Comfort and Wearing Compliance

The hysteresis region between 30 mph and 35 mph is utilized as an adaptive comfort control zone. Sustained belt loading during normal driving conditions can influence occupant comfort and wearing compliance[20]. Within this region, the controller monitors system parameters and defines a dynamic comfort envelope, enabling controlled relaxation through partial webbing release.

B. Adaptive Restraint Control Strategy

The proposed approach aligns with modern reversible restraint systems, where low force modulation balances occupant positioning and comfort [9], [10]. Controlled pre tensioning reduces belt slack and limits forward excursion while minimizing intrusive loading perception. By enabling gradual tension reduction prior to full disengagement, the system mitigates sustained chest and shoulder loading while maintaining improved occupant positioning. This dual function strategy enhances both control stability and occupant acceptance. **Figure 1.** below gives an overview of the proposed approach.

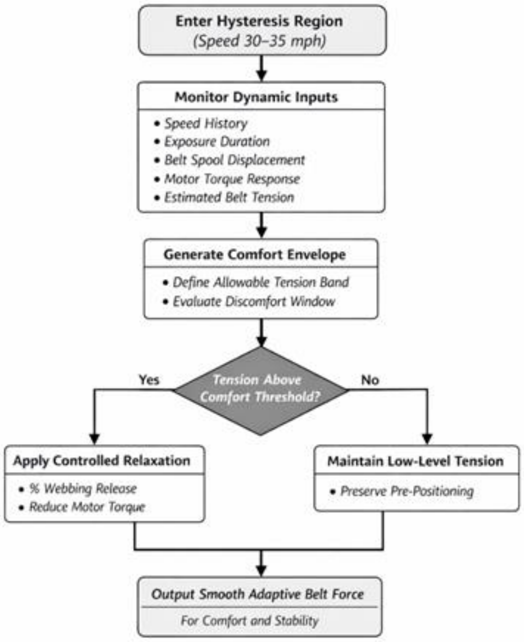

Figure 1. Overview of the proposed approach used to determine belt force.

IX. REGULATORY CONSIDERATIONS

The proposed system is designed to comply with FMVSS 208, FMVSS 209, and FMVSS 210, as well as UN Regulation No. 16. The PRLS supplements conventional ELR functionality without replacing mandatory regulatory mechanisms.

X. FUTURE WORK

Future work will focus on integration with advanced driver assistance systems (ADAS), adaptive threshold strategies, machine learning based personalization, and real-world validation through fleet testing.

XI. CONCLUSION

This paper presented a proactive seat belt retractor locking system based on vehicle speed thresholds. In the reported MADYMO study, the PRLS configuration showed improved occupant kinematics and restraint system effectiveness compared with a conventional reactive ELR baseline under the stated boundary conditions. The proposed approach represents a shift toward proactive occupant protection and can be implemented using existing vehicle architecture while maintaining occupant comfort and usability.

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