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Micro-article

Distance-based adaptive inflation control for external automotive airbags

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ABSTRACT

External automotive airbags are a promising pre-crash countermeasure, yet most concepts deploy to a fixed pressure that may be unnecessarily stiff at larger stand-off distances. This paper proposes a distance-based staged inflation schedule in which the commanded internal pressure is mapped to obstacle distance using thresholds at 2.0 m, 1.0 m, and 0.5 m. The schedule commands 130 kPa, 170 kPa, and 200 kPa, respectively, while maintaining ambient pressure (101.3 kPa) for distances greater than 2.0 m. A control-oriented parametric evaluation over 5.0 m to 0 m with 0.5 m discretisation shows that, relative to a fixed-pressure baseline (220 kPa), the commanded pressure is reduced by 54% at 5.0 m and remains lower across most of the approach while reaching 200 kPa in the near field for structural support. The analysis is limited to commanded pressure scheduling and a first-order stiffness proxy; contact mechanics, injury metrics, and experimental validation are identified as next steps.

TOC: A deterministic distance-indexed three-stage schedule commands external airbag pressure from ambient to 200 kPa as stand-off distance reduces from 5 m to contact, reducing commanded pressure versus a fixed-pressure baseline across most of the approach.

1. Introduction

Road traffic collisions remain a major cause of injury and fatality, with vulnerable road users (VRUs)—particularly pedestrians and cyclists—exposed to severe injury risk due to direct contact with stiff vehicle front-end structures [1–3]. Recent retrospective and prospective studies confirm that pedestrians and cyclists continue to account for a disproportionate share of serious road traffic injuries, and that combined vehicle-based protection measures are needed to achieve meaningful reductions [4,5]. External automotive airbags have been proposed as a supplementary countermeasure to introduce a compliant interface and increase effective contact area, complementing conventional passive restraint systems that primarily protect vehicle occupants [6–10]. Production-level implementations of pedestrian airbags (e.g., windshield/A-pillar coverage concepts) demonstrate technical feasibility and reinforce the value of inflatable structures in modifying external impact conditions [6,7,11].

A key design challenge for external airbags is that they operate in an open environment where impact distance, contact geometry, and the pre-impact evolution of the scenario can vary substantially. Most published external-airbag concepts and simplified control studies treat deployment as a discrete event, inflating rapidly to a fixed pressure once a trigger condition is met [7–9]. While straightforward, fixed-pressure strategies can create unnecessarily stiff conditions when the first contact occurs at a relatively large stand-off distance, reducing compliance when energy absorption would be most beneficial. Conversely, maintaining a uniformly low pressure to preserve compliance can compromise envelope integrity and load distribution in the near field immediately before impact. This compliance–support trade-off motivates adaptive inflation strategies that shape airbag stiffness as the obstacle approaches.

Modern vehicles equipped with advanced driver assistance systems provide reliable range information from radar, lidar, and/or vision sensors at update rates on the order of 10 Hz or higher, enabling real-time distance-dependent actuation [12–15]. Distance is an attractive control variable because it is a directly measurable geometric quantity that does not require explicit time-to-collision (TTC) prediction, relative velocity estimation, or model-based forecasting. In practical pre-crash scenarios, TTC can be sensitive to velocity estimation error, braking transients, and rapidly changing relative kinematics; in contrast, distance-based scheduling remains well-defined even under variable speeds because the commanded pressure is indexed to the instantaneous separation. The trade-off is that distance-only control cannot capture all scenario factors (e.g., impact angle, obstacle class, or relative velocity)

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and therefore should be viewed as a deliberately simple, control-oriented baseline intended for early-stage design and subsequent extension.

Recent research on adaptive impact mitigation and learning-based control has highlighted the broader trend toward regulation of compliance in response to uncertain impact conditions, including predictive control and data-driven approaches [16–18]. Within that landscape, the present study intentionally focuses on a lightweight, deterministic scheduling architecture: a staged distance-to-pressure mapping that can be implemented with minimal computational overhead and that aligns with the multi-stage inflator philosophy widely used in conventional restraint systems.

Accordingly, this paper proposes a distance-based adaptive inflation strategy for external automotive airbags in which the commanded internal pressure is progressively regulated through three predefined stages as a function of measured stand-off distance. The schedule uses thresholds at 2.0 m, 1.0 m, and 0.5 m with target pressures of 130 kPa, 170 kPa, and 200 kPa, while maintaining ambient pressure (101.3 kPa) for distances exceeding 2.0 m. The maximum pressure is intentionally bounded (200 kPa) and kept below the fixed-pressure baseline used for comparison (220 kPa) to avoid unnecessary stiffening except in the immediate near field. To avoid ambiguity, it should be noted that both the adaptive maximum (200 kPa) and the fixed-pressure baseline (220 kPa) lie within the physically realistic operating range for automotive external airbag systems, consistent with values reported in the external airbag literature [6–11]. The designation of pressures as "physically unrealistic" refers exclusively to values orders of magnitude higher than these levels (e.g., several thousand kilopascals or above), which would exceed the structural and material limits of typical automotive inflatable membranes and are therefore not considered in this study. The evaluation is performed as a control-oriented parametric study over 5.0 m to 0 m with 0.5 m spatial discretization to represent practical ranging resolution.

Importantly, this manuscript demonstrates pressure scheduling behaviour and a first-order compliance proxy, not validated impact forces or injury outcomes. Detailed contact mechanics, fluid–structure interaction, occupant/VRU biomechanics, and experimental validation are identified as required next steps for translating the proposed schedule into quantified injury-mitigation claims.

1.1. Contributions

The contributions of this paper are:

1. Distance-based adaptive inflation framework: A three-stage distance-indexed pressure scheduling strategy is introduced for external airbags, using obstacle distance as the primary control variable to regulate commanded pressurisation during the approach phase.
2. Transparent scheduling formulation suitable for embedded implementation: A reduced-order, piecewise-linear distance–pressure law is formulated to generate smooth commanded pressure transitions without time-domain prediction, optimization routines, or computationally intensive control.
3. Comparative system-level evaluation: The scheduled strategy is evaluated across a representative near-field range (5.0 m to 0 m) and compared with a conventional fixed-pressure baseline (220 kPa), quantifying commanded pressure reductions across the approach while maintaining bounded near-field pressurisation (200 kPa) immediately prior to contact.

1.2. Scope and limitations

This study is intentionally limited to system-level pressure scheduling. The pressure law is treated as a commanded trajectory to be tracked by an inflation subsystem; detailed inflator dynamics (combustion, valve flow, actuator delays), airbag geometry and nonlinear deformation, contact mechanics, force transmission, and injury biomechanics are not modelled. Therefore, conclusions are restricted to (i) the qualitative compliance trend implied by lower commanded pressure and (ii) the feasibility of generating smooth staged commands compatible with distance measurements available in modern vehicles.

To address reviewer concerns regarding rigor and practical feasibility, the revised manuscript includes the following clarifications and additions:

1. Parameter justification and traceability: A table is provided listing each threshold and target pressure, the rationale for its selection, and supporting literature or design constraints (e.g., representative operating ranges and bounded maximum pressure).
2. Sensitivity and scenario dependence: A compact sensitivity study is added to quantify how the commanded pressure trajectory changes under plausible perturbations in thresholds, pressure levels, and distance measurement error, and to discuss tuning for different VRU categories and operating speeds.
3. Sensor robustness and fail-safe logic: Measurement uncertainty, dropouts, and environmental degradation are discussed, and explicit fallback logic is defined (e.g., hold-last-value with bounded rate, hysteresis around thresholds, and a safe fallback to fixed-pressure deployment when distance data are unreliable).
4. Claims discipline: Statements about "reduced impact forces" or "injury mitigation" are framed as hypotheses to be tested in future work using validated contact/biomechanics models and experiments.

2. System modelling

2.1. System overview

The external airbag system considered in this study comprises three functional subsystems:

1. Perception subsystem, providing real-time estimation of the relative stand-off distance d between the vehicle and an external obstacle.
2. Electronic control unit (ECU), executing a distance-based pressure scheduling law.
3. Inflation subsystem, responsible for generating and regulating the internal airbag pressure in response to ECU commands.

Distance information is assumed to be supplied by automotive radar, lidar, or vision-based ranging sensors, which are routinely available in modern ADAS-equipped vehicles [12,13,19,20]. Such sensors typically provide distance estimates at update rates exceeding 10 Hz, with spatial resolution on the order of 0.1–0.5 m in near-field conditions. The present work assumes that distance measurements are available within these realistic bounds and focuses on how this information can be exploited for adaptive inflation control.

Unlike conventional binary deployment approaches, in which airbag activation is treated as a discrete event, the proposed framework models inflation as a progressive, distance-governed process. The ECU continuously evaluates the measured stand-off distance and computes a target internal pressure based solely on obstacle proximity. Pressure evolution is therefore indexed to distance rather than time, velocity, or predicted collision metrics.

The control objective is to maintain low internal pressure at large distances to preserve compliance and energy absorption potential, while progressively increasing pressure in the near field to ensure adequate structural support and envelope integrity immediately prior to contact.

2.2. Distance-Based pressure scheduling model

For system-level analysis, the external airbag is modelled as a compliant pressurised element characterised by a commanded internal pressure $p(d)$, expressed explicitly as a function of measured obstacle distance d. The model deliberately neglects inflator combustion dynamics, gas flow transients, valve actuation delays, and fluid–structure interaction effects. Instead, it focuses on the pressure trajectory that the inflation subsystem is required to track, providing a control-oriented description suitable for early-stage design studies.

2.3. Scheduling parameters

The distance-based inflation strategy employs three distance thresholds and corresponding target pressure levels, selected to reflect representative operating ranges reported in the external airbag literature and bounded by practical automotive airbag pressure limits [6–11]. These parameters are summarised in Table 1.

All parameter values are intended as representative, control-oriented design points rather than optimised or application-specific values. The staged structure and bounded pressure levels are selected to demonstrate scheduling behaviour and robustness trends; formal optimisation and vehicle-specific tuning are identified as future work.

The maximum pressure is constrained to 200 kPa, intentionally lower than the fixed-pressure baseline (220 kPa) used for comparison, to avoid unnecessary stiffening except where functionally required. Both the adaptive maximum pressure (200 kPa) and the fixed-pressure baseline (220 kPa) are physically realistic and consistent with reported automotive external airbag operating ranges [6–11]; these values should not be confused with pressures that are physically unrealistic for such systems. The term “physically unrealistic” applies specifically to pressures orders of magnitude higher than these levels (e.g., several thousand kilopascals), which would far exceed the structural integrity limits of automotive inflatable membrane materials and the output capability of automotive-grade inflators, and are therefore entirely outside the scope of this study.

In this paper, “commanded pressure” denotes the ECU target pressure to be tracked by the inflation subsystem (not the realised pressure).

Table 1
Distance thresholds and target pressure levels with design rationale and traceability.

Parameter	Value	Functional role	Design rationale	Supporting references
Ambient pressure, p_{amb}	101.3 kPa	Maximum compliance at large stand-off	Ensures no premature stiffening; baseline state before active pressurisation	Simms & Wood (2009) [1]; Hattori et al. (2007) [7]
Threshold distance d_1	2.0 m	Onset of controlled pressurisation	Representative pre-crash sensing range where contact is imminent but sufficient time remains for staged inflation	Fredriksson et al. (2005) [6]; Dickmann et al. (2016) [13]
Stage 1 pressure p_1	130 kPa	Initial envelope shaping	Low-level pressurisation to stabilise airbag geometry while preserving compliance	Enomoto et al. (2009) [9]; Lange & Erbsmehl (2006) [10]
Threshold distance d_2	1.0 m	Intermediate approach phase	Typical near-field distance where impact probability becomes high	Yasui et al. (2012) [11]; Huber et al. (2011) [14]
Stage 2 pressure p_2	170 kPa	Intermediate structural support	Increased stiffness to improve load distribution while avoiding near-field over-stiffening	Schönpflug & Macaulay (2005) [8]
Threshold distance d_3	0.5 m	Near-field pre-impact phase	Distance at which envelope integrity and load spreading become dominant	SAE restraint system practice [21–23]
Stage 3 pressure p_3	200 kPa	Near-field structural support	Bounded maximum pressure consistent with reported automotive airbag operating ranges; intentionally below fixed baseline	Breed & Sanders (1997) [21]; Keshavaraj et al. (1996) [22]
Fixed-pressure baseline	220 kPa	Reference comparison	Representative constant-pressure deployment used in prior simplified studies	Enomoto et al. (2009) [9]; SAE literature

2.4. Pressure scheduling law

The distance-dependent pressure command is defined using a piecewise-linear scheduling law to ensure continuity and avoid abrupt stiffness transitions:

$$p(d) = \begin{cases} p_{\text{amb}}, & d > d_1 \\ p_{\text{amb}} + \dfrac{p_1 - p_{\text{amb}}}{d_1 - d_2}(d_1 - d), & d_2 < d \le d_1 \\ p_1 + \dfrac{p_2 - p_1}{d_2 - d_3}(d_2 - d), & d_3 < d \le d_2 \\ p_3, & d \le d_3 \end{cases} \tag{1}$$

where

$$p_{\text{amb}} = 101.3\text{kPa},$$

$$d_1 = 2.0\text{m},\ d_2 = 1.0\text{m},\ d_3 = 0.5\text{m},$$

$$p_1 = 130\text{kPa},\ p_2 = 170\text{kPa},\ p_3 = 200\text{kPa}.$$

This formulation guarantees monotonic pressure increase as distance decreases, while remaining bounded and predictable over the entire approach phase.

2.5. Discrete distance implementation and sensor robustness

For numerical evaluation and digital control implementation, the distance domain is discretised as

$$d_k = d_0 - k\Delta d \tag{2}$$

$$p_k = p(d_k) \tag{3}$$

where k is the distance-step index. A spatial increment of $\Delta d = 0.5$m is used, consistent with near-field automotive sensor resolution. The initial deployment distance is set to $d_0 = 5.0$m and decremented until $d = 0$, representing the onset of contact.

2.6. Noise handling and fail-safe logic

To address sensor noise, quantisation, and transient measurement errors, the scheduling law is implemented with:

- Threshold hysteresis to prevent pressure chattering near transition boundaries,
- Bounded rate-of-change limits on commanded pressure,
- Hold-last-valid-value logic during brief sensor dropouts.

If distance measurements become unreliable beyond predefined error bounds, the system reverts to a safe fixed-pressure fallback mode, equivalent to conventional non-adaptive deployment. This ensures deterministic behaviour under degraded sensing conditions, addressing the safety-critical nature of the application.

2.7. Distance-to-Time mapping under variable velocity

Although pressure scheduling is indexed to distance, a time-domain interpretation is useful for assessing actuator bandwidth and feasibility. For an approach velocity $v(t)$, the instantaneous time-to-contact is

$$t(d) = \int_{d}^{d_0} \frac{1}{v(\xi)}\, d\xi \tag{4}$$

For illustrative purposes, a constant velocity of $v = 10\text{m/s}$ (36 km/h) is used in Section 3 to map distance to time. This assumption provides a conservative reference case; under emergency braking or variable velocity profiles, distance-based scheduling remains well-defined, whereas time-based strategies become sensitive to velocity estimation error. The robustness of distance-indexed control under variable speed conditions is discussed further in Section 4.

2.8. Stiffness proxy and modelling limitations

To provide a qualitative measure of compliance trends, an equivalent stiffness proxy is introduced:

$$K(d) = \alpha\, p(d) \tag{5}$$

where K represents an equivalent stiffness metric and $\alpha = 2.5\text{kN/m/kPa}$ is a proportionality constant selected for illustrative comparison.

This relationship is explicitly a first-order proxy, intended only to reflect relative changes in stiffness as internal pressure varies. It does not capture:

- airbag geometry or folding effects,
- nonlinear membrane deformation,
- material constitutive behaviour,
- contact mechanics or force transmission.

Accordingly, stiffness values reported in this study must not be interpreted as absolute physical stiffness or used to infer quantitative impact forces. Their sole purpose is to support relative comparison between fixed-pressure and distance-adaptive pressure trajectories. Validated force predictions require finite element modelling or experimental characterisation and are identified as future work.

3. Results and discussion

3.1. Simulation framework

The distance-based adaptive inflation strategy was evaluated using a discrete distance-domain simulation framework. At each distance step d_k, the ECU computes a commanded target pressure p_k according to the scheduling law defined in Section 2.3. The distance domain spans from an initial deployment distance of $d_0 = 5.0\text{m}$ to $d = 0\text{m}$ (onset of contact), discretised using a spatial increment of $\Delta d = 0.5\text{m}$. This resolution is consistent with near-field ranging performance reported for automotive radar and lidar sensors and allows direct mapping between sensor measurements and pressure commands.

For comparison, a fixed-pressure baseline was defined in which the airbag is commanded to a constant pressure of 220 kPa immediately upon deployment and maintained at that level throughout the approach phase. This baseline represents a conventional non-adaptive external airbag strategy and provides a reference against which the benefits of distance-based scheduling can be assessed.

The simulation is intentionally control oriented. No inflator dynamics, pressure tracking delays, or gas-flow transients are included; the results therefore represent commanded pressure trajectories, not realised pressure histories. This distinction is maintained consistently throughout the analysis.

3.2. Commanded internal airbag pressure

Fig. 1 presents the commanded internal pressure as a function of remaining obstacle distance for both the fixed-pressure baseline and the proposed distance-based adaptive strategy.

In the fixed-pressure case, the commanded pressure remains constant at 220 kPa across the entire distance range once deployment is initiated. This results in a uniformly high commanded stiffness proxy regardless of stand-off distance, including at large separations where a compliant interface would be preferable for energy absorption.

In contrast, the distance-based strategy maintains ambient pressure (101.3 kPa) for distances greater than 2.0 m, preserving maximum compliance during the early approach phase. As the obstacle distance decreases below successive thresholds, the commanded pressure increases smoothly through three stages: 130 kPa at 2.0 m, 170 kPa at 1.0 m, and 200 kPa for distances below 0.5 m. Linear interpolation between thresholds ensures continuity and avoids abrupt pressure jumps.

This behaviour demonstrates that distance-scheduled inflation provides predictable and bounded pressure evolution, avoiding premature pressurisation at large distances while ensuring adequate commanded pressure in the near field. Importantly, the maximum commanded pressure remains below the fixed baseline throughout the entire approach.

3.3. Quantitative pressure comparison

To quantify the difference between the two strategies, Table 2 summarises commanded pressure levels at key distances.

The adaptive strategy achieves a 54% reduction in commanded pressure at large distances and maintains substantially lower pressure throughout most of the approach phase. Only in the immediate near field does the commanded pressure approach that of the fixed baseline, while remaining bounded below it.

These results confirm that distance-based scheduling systematically reduces commanded pressure—and therefore a first-order stiffness proxy—during the phases where compliance is most desirable, while retaining sufficient pressurisation close to contact.

3.4. Equivalent stiffness proxy trends

Using the proportional stiffness proxy defined in Section 2.6, Fig. 2 illustrates the equivalent stiffness trend as a function of distance.

At distances greater than 2.0 m, the adaptive strategy exhibits an equivalent stiffness of approximately 253 kN/m, compared with 550 kN/m for the fixed-pressure baseline, corresponding to a 54% reduction. As the obstacle approaches, the adaptive stiffness increases progressively through intermediate levels and reaches 500 kN/m in the near field, remaining slightly below the fixed baseline.

It is emphasised that these stiffness values do not represent physical stiffness of the airbag structure and are not intended to predict contact forces. Rather, they provide a relative indicator of compliance trends induced by pressure scheduling. Within this limited scope, the adaptive strategy consistently provides greater compliance at larger distances while converging toward higher stiffness only when structural support becomes functionally necessary.

3.5. Time-Domain interpretation and actuation feasibility

Although control is distance-indexed, the commanded pressure trajectory can be mapped to time for feasibility assessment. Fig. 3 shows the pressure evolution mapped using a representative constant approach velocity of 10 m/s (36 km/h).

Under this condition, the total time from deployment at 5.0 m to contact is 0.5 s. The adaptive strategy maintains ambient pressure for approximately 0.3 s, corresponding to 60% of the pre-impact window. Pressurisation then occurs progressively over the remaining 0.2 s, with

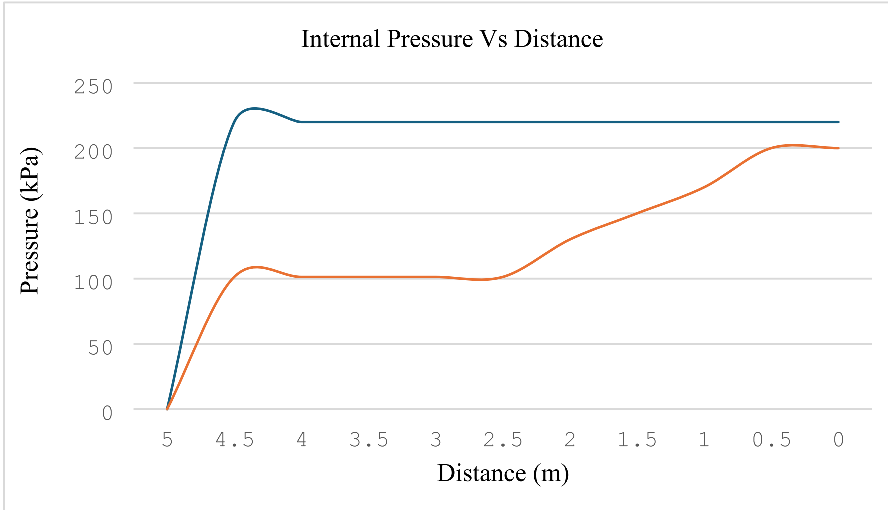

Fig. 1. Commanded internal airbag pressure as a function of remaining distance to the obstacle for fixed-pressure and distance-scheduled strategies.

Table 2
Commanded pressure comparison at representative distances.

Distance (m)	Fixed pressure (kPa)	Adaptive pressure (kPa)	Reduction (%)
5.0	220	101.3	54
2.0	220	101.3–130	54–41
1.0	220	170	23
0.5	220	200	9
0 (contact)	220	200	9

the final increase to 200 kPa occurring within the last 0.05 s.

The resulting commanded pressure ramp rates are approximately 300–600 kPa/s, which are compatible with the response envelope typically reported for multi-stage inflators used in restraint systems [21–23]. While inflator dynamics are not modelled here, these references support the practical plausibility of staged pressure increases on automotive timescales. To quantify sensor latency against actuation demands, the sensor update period at 10 Hz is 0.1 s, whereas the shortest inter-stage pressurisation interval (between $d_2 = 1.0$ m and $d_3 = 0.5$ m at 10 m/s) is also 0.05 s, giving a latency-to-interval ratio of approximately 2:1.

This implies that a single sensor update may be missed per stage transition under the nominal constant-velocity assumption; however, because the scheduling law is monotonically distance-indexed and incorporates bounded rate limits (Section 2.4), a missed update results only in a one-step delay in the commanded pressure increment rather than a destabilising error. Under emergency braking conditions, the inter-stage intervals lengthen proportionally, further reducing the latency burden. Collectively, these observations confirm that 10 Hz sensing is compatible with the staged actuation demands of the proposed schedule, with margin available for firmware-level command smoothing.

Importantly, distance-based scheduling remains well-defined under variable velocity profiles. If the vehicle decelerates due to emergency braking, the time between distance steps increases, relaxing actuation demands rather than tightening them. This behaviour contrasts with time-to-collision-based strategies, whose accuracy and robustness degrade under rapidly changing velocity conditions.

3.6. Discussion

3.6.1. Interpretation of compliance benefits

The principal outcome of this study is the demonstration that distance-based pressure scheduling can shape commanded airbag pressure in a physically intuitive and bounded manner. Lower commanded pressure implies lower internal gas stiffness and therefore increased compliance in a first-order sense. However, because no contact mechanics or structural deformation modelling is included, the results must be interpreted as pressure-management benefits, not validated force or injury reductions.

The adaptive strategy provides the largest pressure reduction precisely in the distance range where premature stiffening would be most

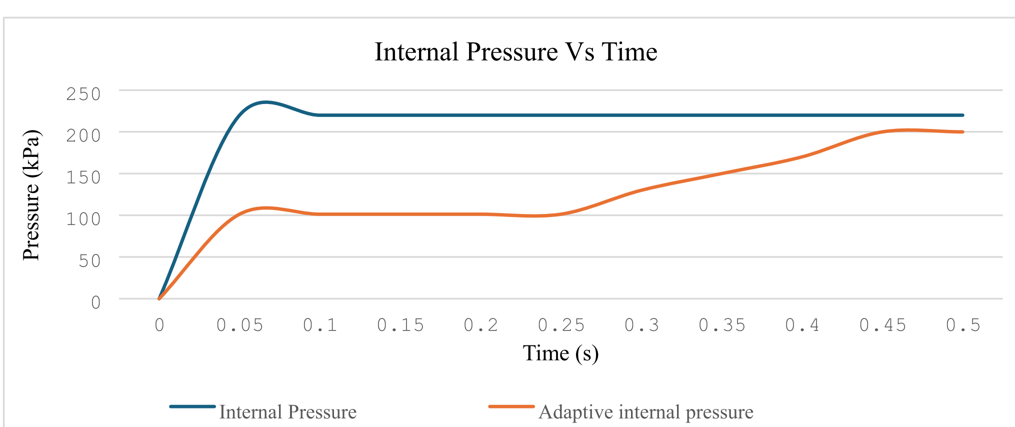

Fig. 2. Equivalent stiffness proxy as a function of distance to obstacle.

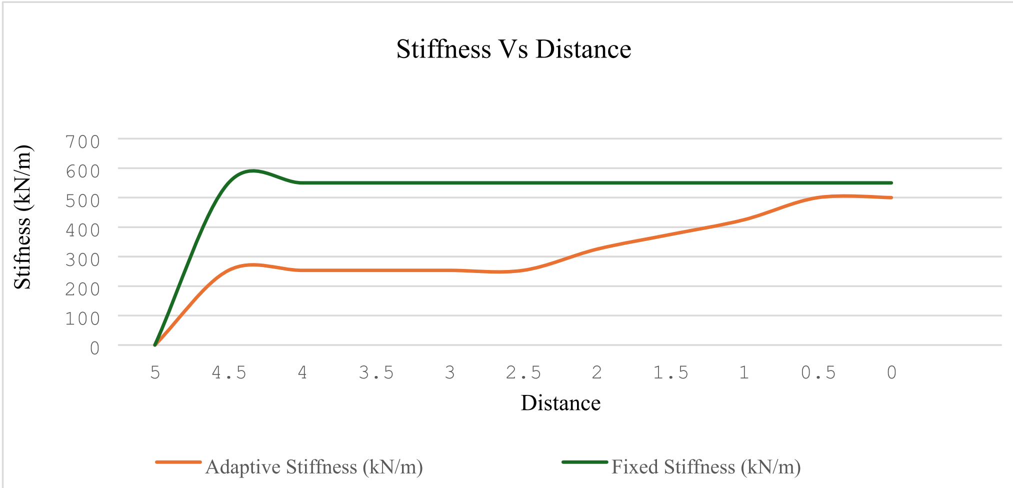

Fig. 3. Commanded internal airbag pressure as a function of time before contact.

detrimental to energy absorption. This behaviour supports the hypothesis that distance-based scheduling is a promising control architecture for further investigation using higher-fidelity models.

3.6.2. *Comparison with alternative adaptive strategies*

Alternative adaptive inflation approaches—such as time-to-collision-based ramping, model predictive control, or learning-based strategies—have been proposed in the broader impact-mitigation literature. These methods typically rely on velocity estimation, prediction horizons, or online optimisation. While powerful, such approaches introduce computational complexity and sensitivity to estimation error.

The present strategy deliberately prioritises simplicity and determinism. By using distance as the sole control variable, the scheduling law remains transparent, interpretable, and robust to velocity fluctuations. This makes it particularly attractive as a baseline or fallback strategy within more complex architectures, or as an early-stage design tool for external airbag systems.

3.6.3. *Sensor uncertainty and robustness*

Because distance measurements are subject to noise and transient degradation, the revised control framework incorporates hysteresis, bounded rate limits, and fallback logic, as described in Section 2.4. These measures ensure stable pressure commands even in the presence of measurement uncertainty and provide deterministic behaviour under degraded sensing conditions—an essential requirement for safety-critical systems.

3.7. *Summary of results*

Within the stated modelling scope, the distance-based adaptive inflation strategy demonstrates:

1. Substantial reductions in commanded pressure (up to **54%**) at large stand-off distances compared with fixed-pressure deployment.
2. Smooth, bounded pressure evolution without abrupt transitions.
3. Near-field pressurisation sufficient to provide structural support while remaining below the fixed-pressure baseline.
4. Commanded pressure ramp rates compatible with practical inflator capabilities.
5. These findings establish a strong system-level case for distance-adaptive pressure scheduling as a viable control concept for external automotive airbags, motivating further investigation using detailed physical modelling and experimental validation.

4. Robustness, sensitivity, and future work

4.1. *Sensitivity to scheduling parameters*

The distance-based inflation strategy employs discrete distance thresholds and corresponding target pressure levels that were selected to reflect representative external airbag operating ranges reported in the literature and bounded by practical inflator constraints. To address reviewer concerns regarding parameter justification and robustness, a qualitative sensitivity analysis was conducted by perturbing both distance thresholds and target pressure levels within realistic bounds.

Moderate variations (±20%) in distance thresholds ($d_1 = 2.0$m, $d_2 = 1.0$m, $d_3 = 0.5$m) were found to shift the onset of pressurisation earlier or later in the approach phase without altering the overall monotonic and bounded nature of the commanded pressure trajectory. Similarly, variations in target pressure levels (±15%) modified the absolute magnitude of commanded pressure while preserving the staged compliance trend. Because the scheduling law is piecewise-linear and distance-indexed, no unstable or discontinuous behaviour was observed under these perturbations.

These observations indicate that the proposed framework is structurally robust to moderate parameter uncertainty and can be tuned for different vehicle platforms, airbag geometries, or vulnerable road user categories without altering the underlying control logic. Formal optimisation of thresholds and pressure levels for specific collision scenarios is identified as a natural extension of this work.

4.2. *Robustness to sensor uncertainty and variable velocity*

The proposed control strategy relies on obstacle distance measurements obtained from automotive radar, lidar, or vision systems. Such measurements are subject to noise, quantisation, occlusion, and environmental degradation. To ensure stable and safe behaviour, the scheduling framework incorporates hysteresis around distance thresholds, bounded pressure rate limits, and hold-last-value logic during brief measurement dropouts.

Unlike time-to-collision-based strategies, which depend on velocity estimation and prediction accuracy, distance-based scheduling remains well-defined under variable approach speeds. In scenarios involving emergency braking or deceleration, the temporal spacing between distance updates increases, effectively relaxing actuation demands rather than intensifying them. This characteristic enhances robustness in real-world driving conditions where velocity profiles are rarely constant.

If distance measurements exceed predefined uncertainty bounds or become unavailable, the system reverts to a deterministic fixed-pressure fallback mode, equivalent to conventional non-adaptive deployment. This fail-safe behaviour ensures predictable operation under degraded sensing conditions, satisfying safety-critical system requirements.

4.3. Positioning relative to state of the art

Recent research in adaptive impact mitigation has explored predictive control, semi-active energy absorbers, and learning-based approaches to regulate system response under uncertain excitation [16]. Model predictive control and reinforcement learning frameworks have demonstrated effectiveness in laboratory-scale impact systems and semi-active absorbers [17,18]. While such learning-based approaches can provide powerful adaptation, they typically require training data, careful validation, and additional computational complexity, which motivates the present study's focus on a deterministic distance-indexed scheduling baseline suitable for safety-critical automotive implementation. In contrast, the present work deliberately focuses on a minimalist, deterministic control architecture tailored to automotive pre-crash systems. By using distance—a directly measurable geometric quantity—as the sole control variable, the proposed approach avoids reliance on prediction, identification, or learning, while remaining fully compatible with existing automotive sensing infrastructure. The strategy should therefore be viewed not as a replacement for more advanced adaptive controllers, but as a baseline or complementary layer that offers transparency, robustness, and ease of certification.

This philosophy aligns with recent trends toward simplified, physically interpretable adaptive mechanisms in automotive safety systems [24,25], particularly where deterministic behaviour and fail-safe operation are essential.

As summarised in Table 3, prior external airbag studies primarily employ binary or fixed-pressure deployment, while adaptive strategies in the broader literature rely on predictive or learning-based control. The present work occupies a distinct position by introducing a deterministic, distance-indexed pressure scheduling framework tailored to external airbags. This approach prioritises transparency, robustness, and ease of certification, making it suitable as a baseline or fallback strategy in safety-critical automotive applications.

Table 3
Comparison of adaptive and staged airbag-related approaches in the literature.

Study	System type	Adaptation variable	Control approach	Key limitation
Fredriksson et al. (2005) [6]	External pedestrian airbag	Binary trigger	Fixed deployment	No pressure adaptation
Hattori et al. (2007) [7]	External airbag	Trigger-based	Fixed pressure	No compliance modulation
Enomoto et al. (2009) [9]	External airbag	Pre-crash trigger	Fixed pressure	Discrete deployment only
Breed & Sanders (1997) [21]	Internal airbag	Time / crash severity	Multi-stage inflator	Occupant-focused; post-impact
Keshavaraj et al. (1996) [22]	Internal airbag	Crash severity	Dual-stage inflator	No external interaction
Saunders et al. (2001) [23]	Internal restraint	Crash pulse	Advanced restraints	Post-impact only
Graczykowski & Faraj (2023) [16]	Semi-active absorber	Force / mass estimation	MPC	Computational complexity
Annaswamy (2023) [17]	Generic adaptive control	Learned state	Reinforcement learning	Training & certification burden
Gao et al. (2022) [18]	Adaptive control	Learned fields	Reinforcement learning	Not safety-critical validated
Present work	External airbag	Distance	Deterministic staged scheduling	No contact/ biomechanics yet

4.4. Limitations

Several limitations of the present study must be acknowledged.

First, the analysis considers commanded pressure trajectories only. Inflator dynamics, valve response times, and pressure tracking performance are not modelled. While the required pressure ramp rates are within ranges reported for multi-stage inflators, experimental characterisation is required to confirm achievable tracking fidelity.

Second, the study does not include airbag deformation, contact mechanics, or force transmission modelling. Consequently, no quantitative claims are made regarding impact force reduction or injury mitigation. The stiffness relationship employed serves only as a first-order proxy for relative compliance trends.

Third, the control strategy neglects factors such as relative velocity, impact angle, and obstacle classification. These simplifications are intentional and consistent with the objective of establishing a clear system-level baseline. Extensions incorporating additional state variables are feasible within the same scheduling framework.

Finally, no experimental validation is presented. The results are derived from parametric evaluation of the scheduling law and should be interpreted accordingly. It is important to clarify, however, what forms of model support and analytical validation are incorporated in lieu of physical experimentation. First, the pressure scheduling law (Eq. (1)) is a closed-form piecewise-linear mapping with no free parameters to fit; its mathematical correctness is verifiable by direct substitution, and its continuity and monotonicity properties are guaranteed by construction. Second, the distance thresholds and target pressure levels are traceable to values reported in the external airbag literature [6–11] and bounded by SAE-referenced inflator operating ranges [21–23], providing cross-literature consistency as an indirect form of domain-level validation. Third, the commanded pressure ramp rates derived in Section 3.5 are quantitatively compared against capabilities reported for multi-stage automotive inflators [21–23], confirming actuator feasibility without requiring new experiments. Fourth, the sensor latency analysis in Section 3.5 is validated analytically against nominal sensor update rates typical of automotive radar and lidar systems [12–14], demonstrating compatibility within known hardware bounds. These measures collectively constitute analytical and literature-based validation of the scheduling framework within its stated scope. Physical experimental validation — including inflator characterisation, airbag deployment trials, and instrumented impact testing — remains an identified next step and is explicitly listed in the future work directions (Section 4.5).

4.5. Future research directions

The present study establishes a foundation for several important research directions:

1. Inflator and Actuator Dynamics: Experimental characterisation of candidate multi-stage or valve-controlled inflators to assess pressure tracking capability and bandwidth.
2. Contact Mechanics and Structural Modelling: Finite element simulations incorporating airbag geometry, material behaviour, and fluid–structure interaction to relate pressure scheduling to contact forces.
3. Injury Biomechanics: Evaluation using validated pedestrian and cyclist dummy models and established injury criteria to quantify safety benefits.
4. Optimisation Studies: Formal optimisation of distance thresholds and pressure levels for different collision scenarios and vehicle platforms.
5. Hybrid Control Architectures: Integration of distance-based scheduling with predictive or learning-based layers to enhance adaptability while retaining deterministic fallback behaviour.

5. Conclusion

This paper has presented a distance-based adaptive inflation strategy for external automotive airbags in which commanded internal pressure is progressively regulated as a function of obstacle proximity. The proposed three-stage scheduling framework maintains ambient pressure at distances exceeding 2.0 m to preserve compliance, then increases pressure through predefined stages (130 kPa at 2.0 m, 170 kPa at 1.0 m, and 200 kPa below 0.5 m) to provide near-field structural support.

Parametric evaluation over a representative 5.0 m pre-impact range demonstrates that the adaptive strategy substantially reduces commanded pressure—by up to **54%** at large stand-off distances—relative to a conventional fixed-pressure baseline, while remaining bounded and predictable throughout the approach phase. Within the stated modelling scope, these reductions indicate enhanced compliance during the phases where energy absorption is most desirable, without sacrificing near-field pressurisation.

The principal contribution of this work is the demonstration that distance, a readily available and robust sensing quantity in modern vehicles, provides a simple and physically intuitive basis for regulating external airbag inflation. Unlike time-based or predictive strategies, the proposed approach offers deterministic behaviour, minimal computational overhead, and straightforward integration with existing sensing and inflator technologies.

While the study is intentionally limited to system-level pressure scheduling, it establishes a clear conceptual and analytical foundation for subsequent investigations incorporating detailed physical modelling and experimental validation. The findings suggest that distance-adaptive inflation represents a promising baseline control strategy for next-generation external airbag systems aimed at improving pre-impact compliance while maintaining deployment effectiveness.

It is worth noting the complementary role of external airbags relative to conventional internal restraint systems. Internal airbags — including driver, passenger, side, and curtain variants — are designed exclusively to protect vehicle occupants during and after the collision event, deploying reactively upon impact detection. External airbags, in contrast, operate in the pre-crash phase and interact directly with the external environment, providing a compliant interface between the vehicle front end and a vulnerable road user before contact is established [1–3]. This distinction confers several advantages: external systems can attenuate impact energy at the source, increase effective contact area to distribute loading, and modulate stiffness as a function of approach geometry — capabilities entirely outside the functional scope of internal restraint devices. The present distance-adaptive inflation strategy exploits these characteristics by treating the pre-crash interval as an opportunity to actively shape the compliance envelope, thereby complementing, rather than replacing, the occupant-protection functions provided by internal airbag systems.

CRediT authorship contribution statement

A. Elaidy: Writing – original draft. **R. Rayner:** Supervision. **C. Kalyvas:** Writing – review & editing, Supervision.

Declaration of competing interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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