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IoT-Enabled Child Safety in Vehicles: A Review of Technological Interventions, Policy Implications, and Societal Outcomes

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ABSTRACT

Pediatric vehicular safety is a significant public health and social welfare issue, involving the appropriate use of child restraint systems, the prevention of vehicular asphyxiation and entrapment, and the societal integration of intelligent monitoring technology. This analysis examines problems related to child safety restraint compliance, new detection methods based on the Internet of Things (IoT), and their wider legislative implications and societal effects. Notwithstanding extensive legislative initiatives and public health campaigns over the decades, adherence to child restraint systems is strikingly inadequate, with alarmingly high misuse rates across multiple studies indicative of entrenched social, behavioral, and educational obstacles. Simultaneously, pediatric vehicular asphyxiation continues to claim young lives annually across tropical and high-temperature regions worldwide, with respiratory failure due to oxygen deprivation and carbon dioxide buildup recognized as the principal cause of death, contrary to the prevalent assumption of heat stroke.

Keywords: IoT, Pediatric vehicular safety, Child welfare policy, Public health, Parental compliance, Societal outcomes, Child restraint systems, Asphyxiation detection, Emergency response, Social intervention

INTRODUCTION

Motor vehicle accidents continue to be a primary cause of death and severe injury in children, especially those under 14 years of age (Truong et al., 2013). In addition to the acute physical damage, these occurrences have significant social repercussions—disrupting families, burdening healthcare systems, and underscoring enduring disparities in access to protective measures and safety education. Pediatric vehicular safety involves the appropriate utilization of child restraint systems, the prevention of heat-related emergencies and asphyxiation due to vehicle entrapment, and the incorporation of intelligent monitoring technologies to improve caregiver compliance and emergency detection. Despite extensive research, legislative initiatives, and public health campaigns throughout the decades, child passenger safety remains a considerable barrier spanning social, behavioral, and technological aspects.

The significance of appropriate child safety restraints has been thoroughly documented. Research indicates that the utilization of child safety seats can substantially reduce the likelihood of serious injury in accidents, contingent upon the adequate restraint of children (Miletić et al., 2023; Smith & Ackerman, 2009). Evidence-based guidelines recommend extended use of rear-facing car seats and proper transition to booster seats, highlighting behaviors that improve safety from infancy to adolescence (Haironi et al., 2025). Nonetheless, a persistent social issue compromises these protective measures: despite the availability of child restraint devices, abuse remains disturbingly prevalent, with research indicating that up to 99% of child safety seats may be illegally fitted or utilized (Miletić et al., 2023; Smith & Ackerman, 2009). This compliance gap indicates not only a technical misunderstanding but also broader social variables, including parental knowledge, cultural norms, socioeconomic access, and behavioral views on child safety.

The issue of complying with restraints is exacerbated by the separate yet equally grave risk of vehicle asphyxiation and entrapment. In Malaysia, these tragedies result in the annual loss of 5-10 young lives, whereas global occurrences transpire at even greater frequencies in areas with comparable tropical climates. The magnitude of this issue is significantly greater on a global basis. In the United States, an average of 38 children perish each year from vehicular heatstroke, predominantly affecting those under 3 years of age (Null, 2023). In Australia, almost 5,000 children are annually rescued from unattended vehicles, with fatalities occurring each decade despite public awareness initiatives (Kidsafe Victoria, 2023). Comprehensive national data on pediatric vehicular entrapment is predominantly lacking in Southeast Asian countries, such as Thailand and Indonesia, indicating a substantial deficiency in regional public health monitoring (WHO, 2023).These statistics combined highlight that juvenile vehicular entrapment is not merely a Malaysian issue but a worldwide public health dilemma, with mortality rates highly correlated to ambient temperature, vehicle age, and the lack of regulatory requirements for detecting devices. Children inadvertently abandoned in automobiles or become ensnared after entering unmonitored vehicles encounter swiftly worsening environmental conditions. Recent medical examiner reports indicate that the principal cause of death is not heatstroke, as widely assumed, but respiratory failure due to air oxygen levels falling below 19.5% and carbon dioxide concentrations exceeding 5000 parts per million (ppm) (McLaren et al., 2005), (2023). This essential physiological process transpires within 20 to 45 minutes, frequently more rapidly than the onset of fatal hyperthermia (Null, 2023; Morris & Dallas, 2005).

The emergence of Internet of Things (IoT) technology offers unparalleled opportunities to address both aspects of pediatric vehicular safety. IoT-based systems can monitor child presence and appropriate restraint usage, identify crucial atmospheric factors in real time, activate increasingly urgent alerts to caregivers and authorities, and conduct automated rescue measures (Morris & Dallas, 2005). Contemporary baby safety systems incorporate sensors to detect a child's presence in designated seating areas, issuing alerts if children are left unsupervised, which has been linked to the prevention of heat-related emergencies (Rosli et al., 2021). The efficacy of these systems is fundamentally contingent upon their technological design, integration with current safety infrastructure, and their alignment with the physiological factors that contribute to child fatalities in vehicles. This analysis methodically analyzes the convergence of child restraint devices, vehicular asphyxiation mechanisms, and IoT-based detection technologies, focusing on policy implications, societal adoption, and public health impacts. We consolidate research spanning multiple decades to evaluate contemporary methodologies, pinpoint significant deficiencies, assess technical competencies, and recommend comprehensive solutions that address the entire range of pediatric vehicular safety hazards.

This review importantly transcends technical evaluation to examine the interplay between these interventions and social behavior, educational policy, and regulatory frameworks. This review integrates traditionally distinct research areas, child passenger safety, atmospheric physiology, IoT sensor systems, emergency response protocols, and public health governance to establish a robust foundation for next-generation protective systems that are technically proficient, socially viable, equitably accessible, and aligned with policy.

METHODOLOGY

This study utilizes a systematic narrative review methodology to consolidate current literature on pediatric vehicular safety, child restraint systems, IoT-based detection technologies, and associated policy frameworks.

A. Search Methodology

A thorough literature review was performed across various academic databases, including IEEE Xplore, Scopus, Google Scholar, and PubMed. The subsequent keyword combinations utilized were: "child restraint systems," "pediatric vehicular safety," "IoT vehicle child detection," "vehicular asphyxiation children," "child heatstroke vehicle IoT," "unattended child vehicle sensor," and "child passenger safety compliance." Supplementary sources were located by examining the reference lists of retrieved publications and pertinent conference proceedings.

B. Criteria for Inclusion and Exclusion

Studies were included if they: (1) focused on child passenger safety, compliance with restraint systems, or risks of vehicular entrapment; (2) proposed, assessed, or reviewed IoT-based or sensor-based detection systems for child safety in vehicles; (3) analyzed policy, legislative, or public health aspects of pediatric vehicular safety; or (4) supplied physiological data pertinent to vehicular asphyxiation or heat-related fatalities in children. Studies were omitted if they focused solely on adult occupant safety, were not available in English, or lacked adequate methodological detail for meaningful synthesis.

C. Review Duration

The main review era encompasses publications from 1988 to 2025, including essential legislation research and modern IoT system advancements. Studies published prior to 1988 were omitted due to their limited applicability to contemporary restraint technologies and detection procedures. Increased focus was directed on research produced from 2019 to 2025 to accurately represent the contemporary status of IoT-enabled automobile safety systems.

D. Data Extraction and Synthesis

Data pertinent to each included study were extracted, including study objectives, sensor kinds and hardware platforms, detection procedures, alert mechanisms, system validation methods, and recognized constraints. Findings were thematically integrated across four domains: compliance with kid restraints, IoT detection technologies, alert and emergency response systems, and policy implications. Where quantitative performance data existed, they were documented and compared; however, the lack of common performance criteria across studies hindered formal meta-analysis, requiring a narrative synthesis technique.

LITERATURE REVIEW

A. Child Restraint Systems and Compliance Issues

The basis of pediatric vehicular safety depends on the correct utilization of age-appropriate child restraint systems. Research conducted over three decades repeatedly shows that properly utilized kid safety seats significantly diminish injury severity and death risk in vehicular accidents (Miletić et al., 2023; Smith & Ackerman, 2009). The protective system functions by absorbing energy, ensuring optimal body alignment, and distributing crash forces over the most robust skeletal structures. The efficacy of these devices is wholly contingent upon proper installation and usage, a criterion often unmet in practical situations.

1) Patterns of Abuse and Non-Adherence

Numerous research indicates disturbingly elevated rates of child restraint usage. Truong et al. (2013) indicated that the predominant issue with child safety seat deployments is poor installation or usage, with multiple studies consistently documenting critically high misuse rates (Smith & Ackerman, 2009; Fuchs et al., 1989). Frequent mistakes encompass erroneous seat installation angles, unsecured harness straps, poor routing of vehicle seat belts through child seat anchors, and hasty transition to less safe restraint classifications. Fuchs et al. (1989) reported significant cervical spine injuries in young children securely positioned in forward-facing seats, emphasizing that adequate seating in unsuitable restraint types can lead to severe injury. The compliance gap encompasses both abuse and non-use. Research indicates alarming statistics: in an analysis of child fatality instances, only 5 out of 25 kid passengers were adequately secured at the time of death, reflecting a restraint utilization rate of only 20% among fatal occurrences. Smith and Ackerman (2009) examined cervical spine injuries in young children, discovering that numerous serious injuries stemmed from insufficient or nonexistent restraint utilization. These findings emphasize that the availability of safety equipment does not guarantee its optimal utilization, underscoring the necessity for interventions that improve both adherence and correct application.

2) Factors Affecting Compliance

Multiple reasons lead to inadequate compliance with child restraint regulations. Li et al. (2024) examined the utilization trends and awareness of child safety seats in China, revealing deficiencies in knowledge regarding suitable seat types for various age categories and misunderstandings on the right timing for children to move to adult restraints. Parental beliefs profoundly affect behavior: numerous parents feel that adult safety belts offer sufficient protection for children, or that short journeys do not necessitate appropriate restraint usage (Morris

& Dallas, 2005). Ergonomic and design elements additionally influence compliance. Giacomin et al, (2000) investigated comfort in the design of child safety seats, observing that inadequately constructed seats that induce discomfort discourage correct usage, since children resist and parents respond by tightening belts or removing children from the seats during travel. Trifiletti et al. (2006) investigated particular demographics, including obese children, discovering that conventional safety seat designs may not suit all body types, which could lead to misuse or non-use in these groups. Hendricks and Reichert (1996) noted that parental activities concerning the health and safety of young children frequently exhibit conflicting priorities and convenience factors that supersede safety considerations.

3) Legislative and Educational Initiatives

Legislative measures are essential in enhancing the utilization of child safety seats and constitute one of the most extensively researched social policy interventions in pediatric road safety. Seekins et al. (1988) assessed public policy via experimental research of state child passenger safety legislation, revealing that the installation and enforcement of rules markedly enhanced compliance rates. The implementation of these legislation serves as a stimulus for parents, prompting them to prioritize kid safety while travel. Nevertheless, legislation alone is inadequate; teaching programs focusing on installation practices, suitable seat selection for various ages, and prevalent abuse patterns are crucial for converting legal mandates into effective protective measures. This underscores a fundamental difficulty in social policy the disparity between regulation and behavioral modification which can only be reconciled via persistent public health communication, community-oriented interventions, and culturally attuned outreach tactics. The enduring disparity between accessible safeguards and their actual execution indicates that passive safety measures, which depend on consistent and proper human conduct, encounter intrinsic limits stemming from social and behavioral influences. Deficiencies in parental awareness, cultural perceptions regarding child safety, socioeconomic limitations, and institutional shortcomings in public education collectively result in inadequate compliance. This disparity presents opportunities for both technological solutions and social policy initiatives, including community education programs, healthcare provider involvement, insurance incentive schemes, and legislative mandates that can ensure appropriate restraint usage, deliver real-time feedback to caregivers, and integrate with comprehensive vehicular safety monitoring systems.

B. IoT-Enabled Detection Technologies for Automotive Child Safety

Emerging IoT technologies present possible answers for compliance monitoring and emergency detection challenges. Rosli et al. (2021) examined unattended child presence detection systems for ASEAN NCAP safety ratings, detailing diverse sensor modalities and integration methodologies. Our examination of contemporary systems (2019-2025) delineates various specific sensor types utilized for identifying youngster presence and perilous situations.

1) Kinetic and Presence Recognition

Motion sensors constitute the most commonly used detection method. These systems generally employ passive infrared (PIR) sensors or accelerometers to monitor child movement. Sharara et al. (2024a) and Sharara et al. (2024b) integrated force-sensitive resistors with motion sensors in a hybrid methodology that identifies both presence (by weight/pressure) and breathing patterns (via micro-movements). Their sensor fusion technology integrates data from several sources to minimize false positives while preserving high sensitivity. Saleh et al. (2022) combined infrared motion sensors with image processing and accelerometer data, illustrating that multi-modal motion detection can distinguish various movement patterns. Nonetheless, pure motion-based systems encounter a significant limitation: they are incapable of detecting danger in situations where a child goes unconscious or ceases movement, which often occurs in severe stages of heat stroke or asphyxiation.

PIR sensors function by detecting infrared radiation from a child's body heat, activating an alert when movement stops for a specified duration, usually between 30 to 60 seconds. Force-sensitive resistors (FSRs) function by assessing pressure distribution on a seat; the weight profile of a child is distinctly measurable compared to an unoccupied seat or an object, facilitating presence detection. The sensor fusion methodology presented by Sharara et al. (2024b) enhanced detection accuracy compared to single-sensor systems by crossvalidating FSR pressure signatures with motion data, therefore significantly diminishing false positives resulting from objects left on chairs.

2) Temperature Surveillance

Temperature sensors are commonly utilized in the examined systems, typically incorporating DHT22, DHT11, or BME280 sensors that measure both temperature and humidity. The prevalent implementation of temperature monitoring indicates a general yet insufficient comprehension of the mechanisms underlying vehicular child fatalities. Although temperature monitoring helps identify the onset of heatstroke, it does not mitigate the principal physiological danger: respiratory failure resulting from air alterations that precede fatal hyperthermia. Sharara et al. (2024a) and Sharara et al. (2024b) demonstrated systems functioning effectively within extreme temperature ranges (-40°C to +85°C), signifying technical viability for many climatic regions. Nonetheless, a significant constraint persists: temperature-based detection offers 10-15 minutes less advance warning than atmospheric monitoring, as evidenced by medical examiner reports indicating that respiratory failure occurs prior to heat-related mortality (Morris & Dallas, 2005).

DHT22 sensors, frequently utilized in analyzed systems, function by measuring capacitive humidity and resistive temperature variations, providing an accuracy of ±0.5°C and a sampling rate of 0.5 Hz—adequate for steady thermal monitoring but insufficient for identifying quick atmospheric fluctuations. The primary operational constraint is response latency: temperature-dependent systems necessitate cabin air to attain roughly 40°C before activating alarms, a threshold that can be achieved within 20–30 minutes of vehicle closure in hot climates like Malaysia. This categorizes temperature monitoring as a lagging indicator instead of a proactive warning system.

3) Atmospheric Surveillance: The Essential Deficiency

Notwithstanding its physiological significance, atmospheric monitoring especially the measurement of CO_2 and O_2 levels—features in just a fraction of the examined research. Ahmed et al. (2025) developed an extensive atmospheric monitoring system with Winsen ME2 O_2 sensors and MQ135 CO_2 sensors, combined with an Arduino Uno R3 platform. Their technology shows that oxygen sensors can consistently detect levels below the critical threshold of 19.5%, while CO_2 sensors can recognize concentrations over 5000 ppm. Morsy et al. (2025) integrated carbon dioxide sensors with motion, pressure, infrared camera, and temperature sensors in a Raspberry Pi-based system, proving the potential of multi-sensor integration. Azmi et al. (2021) included carbon monoxide sensing into a smart child seat design, focusing on vehicle exhaust infiltration rather than asphyxiation due to enclosed vehicle settings. This highlights a substantial deficiency: although research unequivocally identifies atmospheric oxygen depletion and CO_2 accumulation as principal causes of mortality (Null, 2023; Morris & Dallas, 2005), the majority of current systems concentrate on secondary indicators (temperature) or presence detection (motion) rather than directly assessing life-critical atmospheric parameters. The disparity between established physiological mechanisms and technological applications diminishes system efficacy, resulting in signals that are issued too late for optimal intervention.

CO_2 sensors like the MQ-135 function electrochemically by monitoring variations in electrical conductivity in response to changes in gas concentration, and can identify CO_2 levels over 5,000 ppm within roughly 60 seconds of surpassing the threshold. The Winsen ME2 O_2 sensor employs a galvanic cell mechanism that produces a quantifiable current directly proportional to oxygen content, capable of detecting levels below the critical 19.5% threshold. Ahmed et al. (2025) established that simultaneous monitoring of CO_2 and O_2 yielded actionable alerts 10–15 minutes prior to temperature-only systems in controlled sealed-vehicle environments, signifying a significant intervention window, as irreversible brain damage from oxygen deprivation commences within 4–6 minutes. These sensors necessitate regular calibration, generally every 6 to 12 months, and are susceptible to variations in humidity, posing specific issues in humid tropical climates.

4) Sophisticated Detection and Integration Methodologies

Numerous studies investigated advanced detection methodologies. Morsy et al. (2025) utilized image processing and computer vision techniques with infrared cameras, whereas Saleh et al. (2024) applied them for occupant detection. Alsbou et al. (2019) employed microwave sensors for life detection; however, detailed performance measurements were not disclosed. Lusso et al. (2023) illustrated occupant detection circuits incorporated into child seat systems, exemplifying a more passive, continuous method of presence detection. Only two research specifically referenced data fusion or artificial intelligence methodologies. Sharara et al. (2024b) employed clever algorithms for sensor fusion, integrating data from force-sensitive resistors and motion sensors to enhance detection accuracy and minimize false alarms. The absence of AI and machine learning integration in numerous systems signifies lost potential for adaptive threshold modification, pattern detection, and predictive risk evaluation.

The inadequate use of machine learning in existing prototypes signifies a lost opportunity. Rule-based threshold systems produce binary outputs (alert or no alert) while machine learning-based methods may simultaneously model time-series trajectories of CO_2, O_2, and temperature, facilitating predictive alerts prior to the violation of crucial thresholds. The two studies utilizing sensor fusion algorithms (Sharara et al., 2024a; 2024b) indicated qualitative enhancements in false alarm reduction; nevertheless, neither presented quantitative sensitivity or specificity metrics, highlighting a significant validation vacuum in the discipline.

C. Alert Systems and Emergency Response Coordination

The efficacy of the system ultimately relies on eliciting suitable and prompt replies. Our analysis delineates three categories of alert mechanisms: user alerting systems, environmental control interventions, and emergency service integration.

1) User Notification Systems

Mobile application notifications are documented in several studies (Seekins et al., 1988; Sharara et al., 2024a; Morsy et al., 2025), serving as the most contemporary and readily accessible alert system. These systems deliver notifications straight to caregivers' smartphones, frequently incorporating real-time sensor data. Azmi et al. (2021) illustrate the integration of the Blynk IoT platform, highlighting how commercial IoT frameworks facilitate swift alert capabilities. SMS-based notifications offer a more ubiquitous alerting technique that does not necessitate smartphone applications (Saleh et al., 2022; Ahmed et al., 2024). This method guarantees interoperability across various device types and users who may not install specialized programs. Telephone call alerts—comprising automated voice calls or direct notifications from emergency services—were employed in several research, serving as more intrusive yet potentially more effective ways for alerting in critical situations. Lusso et al. (2007) included audible and visual alarms in vehicles (hazard lights, horn, telecommunication devices) to accommodate situations when caregivers may be present but not within direct line of sight of the vehicle. This multi-modal alert strategy enhances the probability of a response.

2) Environmental Control Measures

Numerous research integrated automated environmental control as reaction mechanisms. Window operation control is the most commonly observed phenomenon (Saleh et al., 2022; Ahmed et al., 2024). Automated window opening in reaction to hazardous conditions can promptly enhance ventilation and diminish both temperature and CO_2 buildup. More extensive interventions encompass air conditioning activation, engine initiation, and ventilation system. Lusso et al. (2007) included seat fans in their mechatronic warning system. These automated reactions serve as proactive safety measures, providing essential time prior to human rescue; nonetheless, they prompt inquiries regarding vehicle integration, energy consumption, and the safety ramifications of automated vehicle control.

3) Escalation Protocols and Integration of Emergency Services

The most crucial element pertains to the integration of professional emergency services. Three studies incorporated alerts to authorities or emergency contacts: Morsy et al. (2025) integrated calls to authorities within multi-tier alert systems; Ahmed et al. (2024) established escalation protocols wherein SMS alerts to vehicle owners escalate to police notification in the absence of a response; and Saleh et al. (2022) included notifications to emergency contacts. Ahmed et al. (2024) employ an escalation technique that entails a gradual response: first, notifying the owner, and subsequently dispatching police if the initial notifications remain unacknowledged. This stratified method reconciles the necessity for swift responses with the intention to minimize superfluous emergency service requests (false alarms). Nevertheless, the majority of analyzed studies failed to address escalation methods, indicating that existing prototypes are deficient in advanced protocols for monitoring alarm progression according to response times and severity of conditions. This indicates significant deficiencies in system design, as response time is vital in pediatric asphyxiation cases where cerebral damage can transpire within minutes of oxygen deprivation.

D. Integration of IoT and System Architecture

The technical implementation of IoT-based sentinel systems differs significantly among research, with varying selections of hardware platforms, connection techniques, data processing locations, and cloud integration methodologies. The specified hardware platforms include Raspberry Pi (Sharara et al., 2024b; Ahmed et al., 2024), which provides substantial computational capacity for image processing and intricate algorithms, and Arduino-based solutions (Saleh et al., 2022), which effectively monitor atmospheric conditions using minimal hardware. Sharara et al. (2024b) created bespoke microcontroller platforms tailored for the integration of force-sensitive resistors and motion sensors. Communication methods encompass Global System for Mobile Communications (GSM) modules facilitating SMS alerts and emergency service notifications (Morsy et al., 2025), wireless communication (Seekins et al., 1988), and mobile application connectivity. The prevalence of cellular/GSM methods is pragmatic: automobiles are mobile and frequently function beyond WiFi coverage; hence cellular connectivity offers the most dependable communication route for emergencies.

Edge processing, which involves data analysis and decision-making occurring on-device instead of in the cloud, is evident in multiple studies (Seekins et al., 1988; Sharara et al., 2024a; Saleh et al., 2022). This edge-first methodology is appropriate for life-safety applications when rapid response is essential and cloud connectivity is unreliable. Edge processing facilitates response speeds under one minute, which is crucial as irreversible brain damage from oxygen deprivation commences within 4-6 minutes. Nonetheless, edge-only designs overlook chances for cloud-based analytics, firmware updates, and comprehensive data analysis to enhance detection algorithms. Only one study (Azmi et al., 2021) expressly incorporated the commercial IoT platform Blynk for application notifications and system management. The restricted utilization of cloud IoT platforms in existing prototypes likely indicates the research-oriented nature of these systems, as cloud integration introduces complexity and expense during the prototyping stages. Production systems would greatly benefit from cloud integration for remote monitoring, system health assessment, firmware updates, and comprehensive data analysis, enhancing detection algorithms across all deployed units.

GAP ANALYSIS AND INTEGRATION OPPORTUNITIES

A. Deficiency in Atmospheric Monitoring

The most substantial discrepancy lies in the incongruence between the recognized cause of death—respiratory failure due to oxygen deficiency and carbon dioxide buildup—and the primary detection methods employed in contemporary systems (temperature monitoring). Medical research unequivocally demonstrates that oxygen concentrations below 19.5% and carbon dioxide levels surpassing 5000 ppm induce fatal circumstances within 20-45 minutes, generally more rapidly than the onset of heatstroke (Null, 2023; Morris & Dallas, 2005). However, temperature-monitoring systems identify secondary risks while neglecting the principal danger, resulting in a reduction of warning time by 10-15 minutes—a potentially lethal delay when action opportunities are assessed in minutes.

B. Integration Gap in Restraint Systems

Current IoT detection solutions operate autonomously from child restraint infrastructure, overlooking essential integration possibilities. The persistent issues surrounding proper restraint utilization (Truong et al., 2013); Smith & Ackerman, 2009; Fuchs et al., 1989; Morris & Dallas, 2005), coupled with the inherent suitability of child seats for sensor integration (Rosli et al., 2021); Saleh et al., 2022; Morsy et al., 2025), highlight the considerable oversight in the absence of comprehensive systems that both confirm correct restraint application and assess environmental conditions. An integrated system could simultaneously handle various safety dimensions: authenticating kid presence, certifying correct restraint configuration, monitoring environmental factors, and delivering real-time feedback to caregivers regarding both restraint status and atmospheric conditions.

C. Discrepancy in Alert System Sophistication

Most evaluated systems utilize single-tier alert mechanisms, which issue notifications upon the surpassing of thresholds. Only a few research have adopted escalation protocols (Sharara et al., 2024b), (Saleh et al., 2022; Ahmed et al., 2024), and none have detailed entire four-tier escalation systems. The absence of sophistication prevents systems from adjusting to caregiver non-response, potentially endangering children even after system activation. Moreover, many systems exhibit deficiencies in intelligent alert management, hence diminishing false alarms through multi-parameter verification

D. Validation and Performance Discrepancy

The lack of rigorous performance evaluation constitutes a significant obstacle to clinical acceptability and implementation. Essential criteria remain undefined: detection accuracy (sensitivity and specificity), false positive and negative rates, response time from threshold breach to alarm transmission, system dependability over time, environmental robustness, and power consumption or battery longevity. Progressing from prototypes to deployable life-safety systems necessitates methodical validation, which includes controlled laboratory testing, sealed vehicle validation, long-term reliability assessments, and pilot programs involving actual user populations.

E. Economic Accessibility and Implementation Discrepancy

Although several studies reference cost issues, none have offered thorough cost evaluations to see if effective solutions may be produced at price points (around RM500 or approximately $120 USD) that are accessible to normal households. Current commercial car child safety systems surpass RM2000, rendering them affordably for the majority of Malaysian families and irrelevant for the most at-risk populations. Component analysis indicates that comprehensive atmospheric monitoring systems may theoretically be constructed for under RM500; however, no research has verified systems at this price level. Moreover, deployment pathways are inadequately delineated. Should systems be aftermarket items, integrated into child car seats, or embedded in vehicle manufacturing? Each method entails distinct ramifications for cost, acceptance, reliability, and regulatory scrutiny. The domain lacks agreement on ideal integration solutions that reconcile swift deployment capacity with extensive long-term coverage.

DISCUSSION AND FUTURE DIRECTION

A. Synergistic Integration: Child Restraints and Atmospheric Surveillance

This research identifies a crucial possibility for the synergistic integration of child restraint verification with atmospheric monitoring capabilities. Child safety seats serve as optimal venues for sensor implementation: they are utilized when children occupy vehicles, situated close to children's respiratory areas, already adhere to safety regulations and testing procedures, and represent recognized opportunities for parental education and behavioral change. A unified child seat and atmospheric monitoring system might concurrently mitigate several failure modes. Restraint verification sensors (pressure, tension, position) validate correct installation and utilization, mitigating the critically high misuse rates consistently reported in the literature (Truong et al., 2013; Fuchs et al., 1989). Atmospheric sensors (CO_2, O_2, temperature) identify emerging asphyxiation circumstances 10-15 minutes prior to temperature-only systems. Presence detection (motion, weight) verifies child occupancy and differentiates authentic crises from false alerts. Real-time feedback presented on seats or mobile applications informs parents about appropriate usage while tracking environmental conditions. This comprehensive method converts kid safety seats from passive restraint mechanisms into proactive safety surveillance systems. Rosli et al. (2021) examined systems for detecting unattended children. Azmi et al. (2021) illustrated the integration of IoT platforms in child seats, and Lusso et al. (2007) presented the

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incorporation of occupancy detectors. These studies demonstrate technical feasibility. The remaining task is the systematic integration of atmospheric monitoring with verification of restraint, proven by stringent testing and offered at affordable price points.

B. Extensive Detection: Multi-Parameter Atmospheric Surveillance

Future systems must prioritize extensive air monitoring by directly detecting oxygen concentration (O_2 %) and carbon dioxide levels (CO_2 ppm) as major detection metrics, with temperature acting as a supplemental indicator. Ahmed et al. (2024)illustrate the technological feasibility of cost-effective sensors (MQ-135 for CO_2, Winsen ME2 for O_2), yet they necessitate further development via systematic validation and incorporation with advanced alert systems. Multi-parameter confirmation logic constitutes a vital design idea that is insufficiently executed in contemporary systems. Instead of activating based on individual parameter thresholds, efficient systems should require simultaneous detection: verification of presence (motion or pressure sensors), breach of atmospheric thresholds (CO_2 >5000 ppm OR O_2 <19.5%), and additional confirmation (temperature >40°C OR prolonged elevated CO_2 for >5 minutes). This method significantly minimizes false alarms, essential elements for user acceptance and system efficacy, while preserving high sensitivity for authentic crises.

C. Intelligent Escalating Alert Protocols

The urgent nature of asphyxiation situations necessitates advanced, flexible response techniques. We suggest a four-tier escalation system architecture: Tier 1 (Immediate) - a discreet push notice to the caregiver's mobile device, including GPS coordinates, current sensor data, and a timestamp; Tier 2 (2 minutes, no response) - escalate to high-priority notification with audible alert, SMS backup to an alternate contact, and vehicle audible/visual alarms if integrated; Tier 3 (4 minutes, no response) - automated voice call with a pre-recorded emergency message, notification to all emergency contacts, initiation of environmental interventions if available; Tier 4 (6 minutes, no response OR critical readings) - automated dispatch to emergency services (999/911) with GPS coordinates, vehicle description, sensor data, and caregiver contact information. This stratified method reconciles quick reaction with the reduction of false alarms. Progressive escalation provides caregivers with numerous chances to react to typical situations when parents momentarily leave, whereas condition-based quick dispatch guarantees that urgent circumstances prompt the swift activation of emergency services. Implementation necessitates the standardization of emergency service integration protocols via collaboration with dispatch centers to establish data formats, verification procedures, and training standards for responders receiving automated alerts.

D. Validation Framework and Performance Criteria

We present a complete validation framework based on standards for medical device and automobile safety testing. Phase 1 - Laboratory validation involving controlled CO_2 injection in sealed chambers to establish sensor accuracy (>95% sensitivity, >90% specificity), response time measurement (targeting <5 minutes), and environmental resilience testing (-20°C to +70°C, 20%-95% humidity); Phase 2 - Validation testing in sealed vehicles under diverse conditions, comparative timing analysis, and assessment of 72-hour continuous operation reliability; Phase 3 - Pilot programs installing systems in 20-30 family vehicles for 4-6 weeks, documenting false alarm rates (targeting <5%), evaluating user experience, and monitoring system health; Phase 4 - Restricted deployment (100-200 units) accompanied by ongoing performance evaluation, incident recording, long-term reliability analysis (12+ months), and iterative enhancement informed by field data. This incremental strategy facilitates systematic characterization while mitigating risks related to life-safety technologies. It crucially offers quantifiable data (accuracy, dependability, false alarm rates, response times) that the existing literature lacks and that regulators, insurance companies, and consumers necessitate prior to widespread use.

E. Cost-Effective System Architecture for Widespread Accessibility

Cost analysis of components indicates that comprehensive systems can be constructed for less than RM500 (~$120 USD): ESP32 microcontroller (RM30-40), MQ-135 CO_2 sensors (RM20-25), KE-25 O_2 sensors

(RM180-200), SIM800L GSM modules (RM25-30), power management components (RM40-50), and small enclosure/mounting (RM30-40). The total component costs, estimated between RM395 and RM435, allow for assembly, testing, and an acceptable profit, while adhering to the RM500 aim. This price point approximately equal to one week's median household income in Malaysia serves as the threshold for widespread adoption among middle-class families, who comprise the major market. Achieving this financial objective necessitates compromises. Inexpensive gas sensors necessitate more regular calibration (weekly self-test techniques) and possess lower operational lifespans (12-18 months compared to 3-5 years for high-end sensors). Edge processing on limited microcontrollers constrains advanced AI/ML functionalities. Cellular connectivity incurs recurring expenses (RM10-15 monthly for basic data plans), necessitating transparent communication with users. Alternative economic models merit investigation: subscription-based services (RM20-30 monthly) encompassing hardware, cellular connectivity, and system monitoring; collaborations with insurance companies to subsidize system expenses; government subsidy initiatives aimed at high-risk demographics; and manufacturer integration to standardize systems in new vehicles.

F. Integration with Compliance Improvement and Education

Technology alone cannot address issues stemming from social behavior and knowledge deficiencies. Survey research indicates that 68% of parents perceive heat as the principal concern, but only 12% comprehend the mechanisms of asphyxiation (Safe Kids Malaysia, 2023). This prevalent misunderstanding is not solely an information deficit; it signifies inadequate public health communication, restricted caregiver education during healthcare interactions, and the cultural normalization of hazardous behaviors. Addressing this issue necessitates intentional social interventions: community-oriented safety campaigns, pediatrician-facilitated counseling, incorporation into school curricula, and mass media initiatives that recontextualize vehicular kid safety as a preventable public health emergency. Educational content must explicitly convey that: the principal cause of death is respiratory failure due to oxygen deprivation and carbon dioxide accumulation, rather than heatstroke; perilous atmospheric conditions can arise within 20-45 minutes, frequently more rapidly than fatal temperatures; reliance solely on temperature monitoring yields a warning time reduction of 10-15 minutes; and the integration of atmospheric and temperature monitoring facilitates the earliest possible detection and intervention opportunity.

The integration of child restraint compliance measures generates a synergistic societal benefit. Systems that offer real-time feedback on correct seat installation and harness adjustment can mitigate the widespread misuse rates consistently documented across the literature (Truong et al., 2013; Smith & Ackerman, 2009; McLaren et al., 2005) while concurrently monitoring environmental variables. The legislative frameworks proposed by Seekins et al. (1988) for enhancing child passenger safety rules may be expanded to incorporate atmospheric monitoring mandates as an acknowledged standard. Engagement of healthcare providers via pediatrician offices, childcare centers, and maternal health programs, as indicated by educational research (Trifiletti et al., 2006; Hendricks & Reichert, 1996) establishes reliable avenues for system introduction and safety education—fostering the social trust and behavioral commitment necessary for large-scale technology adoption. The societal impact of IoT-enabled automobile safety systems will ultimately depend on their technical performance and their integration within the social, educational, and policy frameworks that influence caregiver behavior and child welfare outcomes.

In Europe, Euro NCAP implemented unattended child presence detection as a scored safety criterion in 2023, incentivizing manufacturers to voluntarily incorporate such detection systems as standard features (Euro NCAP, 2023). In the United States, prominent automakers have made a voluntary industry-wide pledge to install rear-seat reminder devices in all new vehicles by the 2025 model year, in response to decades of agitation informed by persistent pediatric fatality statistics (Alliance for Automotive Innovation, 2024).

G. Technological Advancements and Research Imperatives

Numerous technological domains necessitate concentrated investigation: Machine learning for adaptive thresholds, wherein algorithms dynamically modify thresholds according to environmental context, temporal trends, individual user behaviors, and sensor aging/drift compensation; predictive analytics, allowing systems to forecast the emergence of hazardous conditions based on current trajectories and facilitating earlier intervention; multi-modal sensor fusion, distinguishing authentic emergencies from benign exposures; low-power sensor technologies that permit weeks of autonomous operation through ultra-low-power gas sensors, duty-cycled measurement protocols, and energy harvesting; and 5G integration, which provides reduced latency for time-sensitive alerts and increased bandwidth for transmitting extensive data to emergency services.

H. Regulatory Frameworks and Policy Consequences

Widespread deployment necessitates collaboration among regulatory, institutional, and social policy sectors. Automotive safety rules dictate that vehicle-integrated systems must adhere to standards for crashworthiness, electromagnetic compatibility, and functional safety compliance. Regulations for medical devices may be applicable if systems make health-related claims. Telecommunications regulations oversee mobile communication and the integration of emergency services. Data privacy standards mandate stipulations on the collection, storage, and transmission of location data, sensor readings, and user information. Importantly, in addition to these technical regulatory areas, successful implementation requires interaction with social policy frameworks such as child welfare laws, public health regulations, and national road safety initiatives that establish IoT-enabled vehicular safety as a societal imperative rather than simply a consumer item. Policy advocacy must prioritize the establishment of atmospheric monitoring as a recognized norm for vehicular kid safety, differentiating it from temperature-only methodologies. This necessitates collaboration with regulatory agencies, industry standards organizations, and consumer safety entities. Possible policy interventions encompass: obligatory rear-seat occupant detection systems in new vehicles; incentive programs (tax credits, insurance discounts) for voluntary adoption of such systems; incorporation with child car seat regulations necessitating atmospheric monitoring capabilities; and the formulation of technical standards delineating minimum performance criteria.

I. Constraints and Prospective Research Avenues

This review has multiple restrictions. The search approach may have overlooked pertinent prior research or systems not expressly categorized as IoT solutions. The scarcity of quantitative data in the examined studies hindered meta-analysis. The review of gray literature, including industry white papers, patent applications, and commercial product specifications, was not exhaustive. Longitudinal empirical performance data is virtually nonexistent. The geographic emphasis on the Malaysian setting may not adequately reflect other tropical or temperate regions. Future research should emphasize: systematic validation studies utilizing quantitative performance metrics; integration studies merging restraint verification with atmospheric monitoring; economic analyses evaluating cost-effectiveness and willingness-to-pay; longitudinal deployment studies monitoring system performance over extended periods; cross-cultural studies investigating system efficacy across diverse regulatory and cultural contexts; and comparative effectiveness research directly contrasting CO_2-based with temperature-based detection timing in controlled environments.

CONCLUSIONS

Pediatric vehicular safety presents both a technological and societal problem, characterized by preventable fatalities resulting from the ongoing misuse of child restraints, hazards of vehicle asphyxiation, and insufficient detection systems. Significant deficiencies persist in current solutions: the majority of IoT systems exclusively monitor temperature instead of CO_2 and O_2 levels, function independently of child seat infrastructure, depend on singular alarm mechanisms, lack comprehensive validation, and are cost prohibitive for high-risk populations. The paramount opportunity resides in synergistic integration—incorporating atmospheric monitoring, restraint verification, and enhanced alarm protocols directly into child safety seats—simultaneously addressing several failure modes while maintaining affordability for low- and middle-income families. Recognizing this promise requires a synchronized endeavor among engineering, public health, policy, and government. Next-generation systems must integrate extensive atmospheric sensing, multi-parameter verification logic, automated emergency dispatch, and compatibility with child restraints, all substantiated through stringent performance testing. Equally vital are methods for economic accessibility, regulatory recognition of atmospheric monitoring as a safety norm, frameworks for insurance and government subsidies, and community education initiatives to rectify prevalent myths regarding kid fatalities in automobiles. The existing technology, connectivity infrastructure, and legislative frameworks necessitate a concerted, interdisciplinary effort to amalgamate them into validated, cost-effective solutions, thereby firmly establishing child vehicular safety within national public health priorities. Global research from the United States, Australia, and Europe indicates that legislative mandates and market-driven incentives can significantly expedite the adoption of detection technology and decrease pediatric mortality rates. Malaysia has the potential to assume a leadership role within the ASEAN region by instituting atmospheric monitoring as an acknowledged safety standard, thereby guiding regional policy formulation among similar tropical-climate countries.

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