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Digital Thread Governance for Traceable ADAS and Restraint Engineering Change Management

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ABSTRACT
There is now data sharing of sensing data, the decision logic, and calibration values among advanced driver assistance system and occupant restraint systems. One domain can impact the other in terms of safety behaviors but most of the programs use individual documents and tools to deal with a change. In this paper, a digital thread governance framework is proposed which provides a connection between requirements, hazard records, simulation models, test evidence, and release packages into a single traceable chain. The framework uses definite guidelines to impact analysis, coverage of the verification, and approval. The analysed evidence demonstrates that the practice of traceability remains incomplete in the automotive industry, change diffusion studies have not yet identified restraints that are specific to a case, and that the performance of ADAS highly depends on situation and velocity. The framework is subsequently tested in a simulated reenactment of 240 engineering change requests on ADAS software, sensor hardware, restraint hardware and restraint control. Each request was executed on a document-based foundation and the controlled model. The level of completeness of trace links increased from 68.3% to 94.0%. The mean change lead time was reduced to 10.9 days from 17.6 days. The rate of impact recall improved to 92.6% from 71.2%. There was a reduction of 31 to 11 escaped change defects. The governance preparedness index increased to 0.906 from 0.634. The greatest cross domain exposure with the best benefit was restraint control changes.

Keywords: *ADAS; Digital thread; Engineering Change Management; ISO 26262; Occupant Restraint Systems; Product Lifecycle Management; Safety Governance; Traceability*

INTRODUCTION

The surface control chain of modern vehicles combines both active and passive safety. The risk is detected by a radar or a camera. The ADAS operates the brakes or steers. In case a crash occurs, there is a setting of belt tension and airbag timing by the restraint system. The shared signals and shared calibration data are used by these functions. Any slight modification in one area can change the outcomes in another.

These links are still addressed with scattered files in programs. According to Mies and colleagues, digital thread is a method of measuring and analyzing data throughout the product lifecycle in order to reduce cost and lead time [1]. In their review, they noted that four out of ten manufacturers with whom they surveyed cited uncertain product quality as one of the barriers to additive manufacturing. It also details a materials schema that comprises of over 800 attributes in 21 tables. Data mapping method review indicates that, standards vary in terms of design, manufacturing, and inspection, and that there is a need to map methods to attain lifecycle interoperability [2]. A summary of some of the percentages in the studies in this paper can be seen in Figure 1.

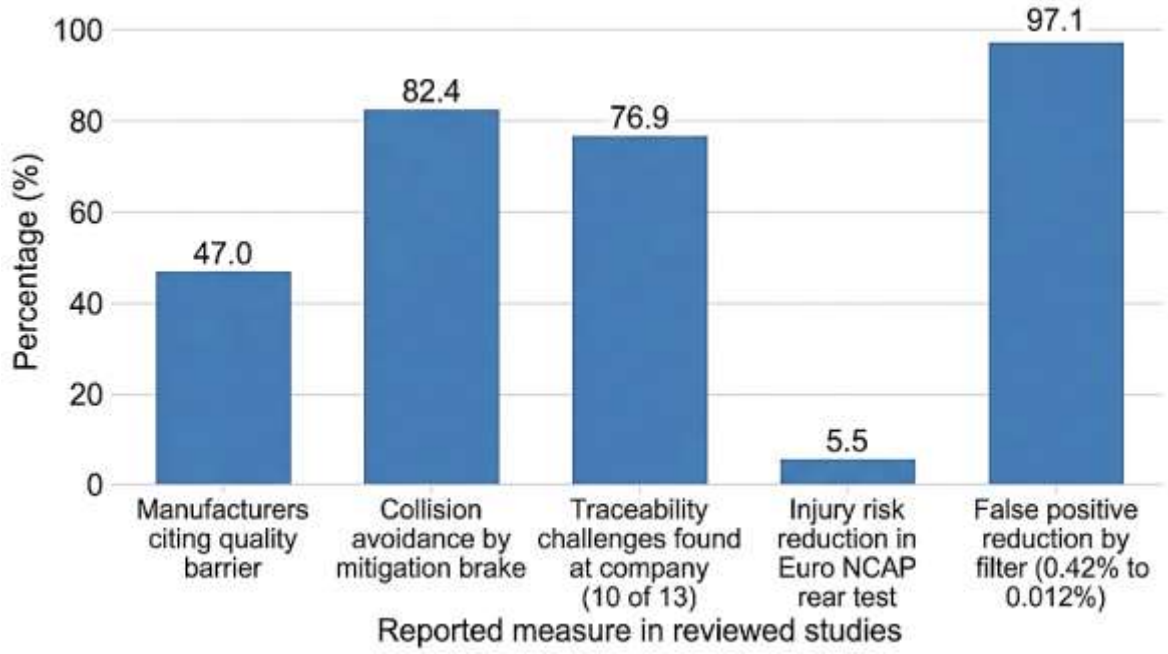

Figure 1. Individual percentage values which were described in the reviewed studies including quality barriers, ADAS effectiveness, traceability issues, injury reduction and false positive reduction

The 13 traceability challenges in the literature were discovered during a case study plus a tertiary investigation on a big automobile supplier. Four remained unresolved despite being provided solutions to in literature [3]. Eight themes were obtained as a result of interviews with 19 professionals working in five companies. Teams had challenges in dividing the requirements of machine learning perception, operating domains, and edge cases, and traceability.

Second level is change management. Developed around 143 publications on change propagation is a framework which classifies 50 concepts into seven categories. It remarks poor reporting of product family and effects of production [4]. A modular impact viewpoint on factory systems suggests that the dissemination of changes takes the form of networks of factors, and therefore every situation requires its own evaluation design [5]. All these studies do not consider ADAS and restraint systems as a single system.

This gap is filled by this paper. It offers a digital thread framework of governance of ADAS and restraint change control. It is a test of the framework that simulates 240 change requests. It contributes in three ways. It establishes governance controls of various lifecycle stages. It provides eight traceability, eight impact, lead time, risk and readiness equations. It gives a report of quantitative results of a learning experiment.

LITERATURE REVIEW

2.1 Digital Thread and Traceability

Table 1 cross tabulates the six themes with the concepts added to the framework by each theme.

Table 1. Literature to Concept Map Indicating the Six Themes, the Number of the Themes that the Literature Includes in the Framework, and the Concepts Each Themes adds to the Framework

Theme	Sources (n)	Contributed concepts
Digital thread and data exchange	5	Lifecycle information capture, format mapping, variant management, provenance
Traceability and requirements	4	Recovery of links, and requirement decompositions, and perception requirements, and open challenges
Engineering change management	2	Propagation of changes, impact analysis, functional analysis
ADAS safety and validation	7	Scenario testing, data on accidents, safety cases, measures of performance
Restraint system engineering	7	Airbag optimisation, belt management, occupancy mismatch, pre impact sensing
Security and software updates	3	Cybersecurity process, type approval rules, update assurance

Note. The number of sources sums up to 28. Source. Derived based on reviews of the studies.

The study of traceability has shifted focus to learned links as opposed to manual links. A deep learning analysis involved semantic word representations to generate trace links between software artefacts and outperformed traditional retrieval techniques [6]. Total variant management reveals that variants in products must be represented in explicit product design data models [7]. Safety requirement decomposition work reveals how teams are divided in terms of requirements influences their ability to test them in the future [8].

The thread audit value is provided by data provenance. To provide provenance, chain of custody, and traceability across organizations, a design science study created an Ethereum smart contract with certificate authentication to provide provenance [9]. In a survey of 187 auto companies, blockchain implementation increased the integration in supply chain by a coefficient of 0.329, and the model was able to account 39% sustainable performance variance [10].

2.2 ADAS Validation and Assurance

ADAS evidence is based on scenario, speed and quality of data. The Chinese accident statistics available over 17 years were analyzed, ten scenarios (which cover more than 80 percent of accidents) were selected and 353 cases were reconstructed. In 176 simulations of collisions a collision mitigation brake achieved 82.4% collision avoidance [11]. Another analysis approximated the KIDAS accident database safety benefit of automatic emergency braking [12]. CMI Vr is a technique that dissociates the speed of closing and impact eccentricity. It claimed a reduction in injury risk in hypothetical Euro NCAP rear test, (5.5 percent) and injury risk decreased about 15 times at 60km/h when compared to injury risk at 30km/h [13].

An overview of perception testing concludes that test requirements, situations and reference data are still unresolved as a pertinent issue in ensuring safety [14]. The artefacts of evidence in a safety case of a pedestrian braking demonstrator had 34 items. The system previously achieved non-collision in 23 out of 25 pedestrian test conditions and an out of distribution filter reduced false

positives per image from 0.42% to 0.012% [15]. Two other publications contend that machine learning elements require formalized safety reasons and particular guarantees [16], [17].

2.3 Restraint Engineering, Security, and Updates

The design of restraint is based on tuning and simulation. A kriging surrogate model and tabu search were applied in an optimization study to be able to tune an airbag and load limiter in frontal impact [18]. An investigation into airbag parameter that corresponds to tuned behavior during crash simulation [19]. In another study, they developed a frontal passenger prototype with which they correlated a crash test and compared male with female protection due to regulation based on the 50th percentile male dummy [20]. The concepts of adaptive restraint vary the protection to the occupant and simulation studies have included reversible belt pretensioners [21], [22]. The design of a new inflator was capable of filling a 50L airbag, in 30-40 ms and pulled approximately three quarters of cabin air gas [23]. Before impact, ADAS is connected to restraint control, sensor tolerance studies indicate that real world situations exert this connection [24].

Other gate is provided by security rules. Annex UNCE R155 and ISO/SAE 21434 are compared with each other to express the relationship between the regulation and the standard [25]. An overview of the car cybersecurity laws and standards also aligns with the opinion [26]. The recent research suggests assurance case templates that encompass both ISO 26262 and SAE J3061 since most frequently software does not succeed when it undergoes changes [27]. Table 2 summarizes the quantitative evidence that is utilized to design the experiment.

Table 2. Quantitative Evidence pulled out of the reviewed Literature, revealing the size of each study, the reported value and its relevance to the governance design

Study focus	Scale	Reported value	Design use
Digital thread in additive manufacturing	21 schema tables	47% quality barrier, 800 attributes	Data model size
Traceability-automotive supply	13 challenges	10 found at company, 4 unsolved	Control priorities
Perception requirements interviews	19 experts, 5 companies	8 themes	Requirement links
Change propagation concepts	143 publications	50 concepts, 7 categories	Impact rules
Collision mitigation brake	353 cases, 176 runs	82.4% avoidance	ADAS scale of effect
Braking safety case with pedestrians	34 artefacts	23 of 25 scenarios passed	Evidence volume
CMI Vr injury evaluation	Euro NCAP rear test	5.5% risk reduction, 15 times speed effect	Restraint link
Blockchain of auto companies	187 firms	Coefficient 0.329, 39% variance	Audit records
Aspirated airbag inflator	50 L bag	30 to 40 ms fill time	Restraint timing

Note. Values are as per the original studies. Source. Derived based on reviews of the studies.

METHODS

3.1 Framework Design

Each of the engineering artefacts is considered a node and each of the dependencies are a typed edge in the framework. Examples of artefacts are requirements, hazard records, simulation models, test cases, calibration files and release packages. The four layers are represented in figure 2. Artefacts are stored in their home tools in the data layer. Trace edges and version states are stored in the link layer. Approval, access and audit rules are implemented in the governance layer. Engineers are provided with a release gate and an impact view by the application layer.

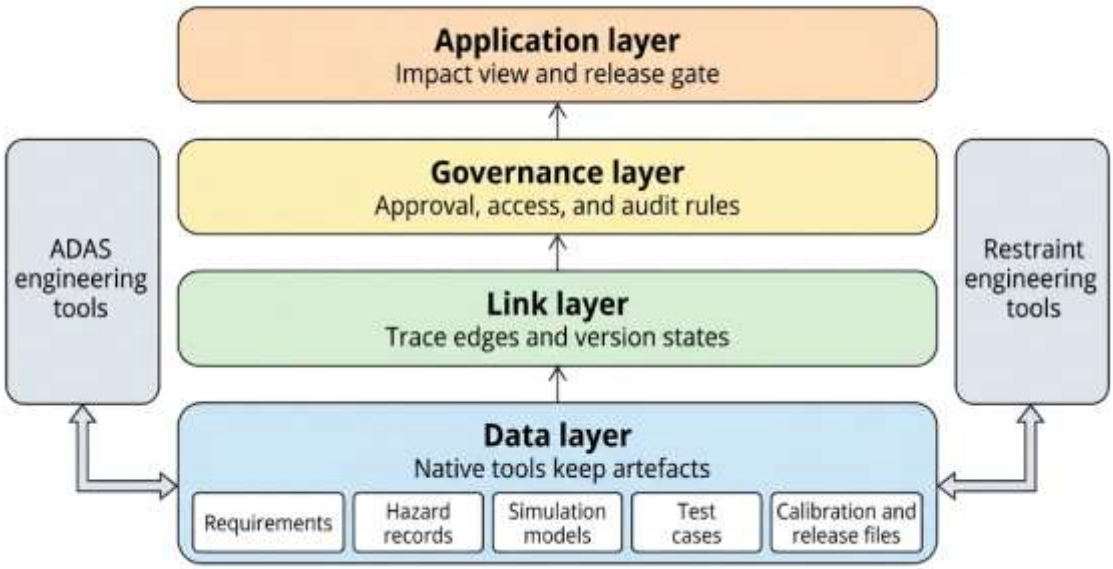

Figure 2. Digital thread governance framework layers architecture displaying ADAS and restraint engineering tools-related data and data, link, governance, and application layers

The controls are in accordance with the ISO 26262 functional safety. Table 3 indicates the control that was used to each stage of the lifecycle in each domain. The above can be regarded as the safety and security view and the update controls also adhere to this view.

Table 3. Governance Control Matrix relating each lifecycle stage to the ADAS artefact, the restraint artefact, and Control that is applied before approval

Lifecycle stage	ADAS artefact	Restraint artefact	Governance control
Requirements and hazards	Definition of functions, Hazard log	Targets of injuries, load cases	All the requirements are associated with a hazard and a test case
System design	Sensor architecture and function architecture	Pretensioner, load limiter design	Sharing a signal change is agreed to by interface owners
Simulation	Perception models, scenario sets	Occupant and crash models	Single version of a model saved with each output

Verification	Track and scenario tests	Crash tests and Sled	The pieces of evidence should address all requirements that have been affected
Calibration	Braking and detection thresholds	Limits on deployment and belt forces	Joint domain inspection of common thresholds
Release and update	Software release package	Package of release process of control units	Safety and security

Note. Dual domain review refers to signing the change by the ADAS as well as the restraint owners. Source. Authors design.

Change workflow is indicated in Figure 3. A request comes into the system and the system identifies the affected nodes of the trace graph within the system. The impact and risk are scored in the system. A score high forwards the request to a joint review. An average score takes the average trajectory. The evidence of verification should be an area that is covered by the affected nodes prior to release.

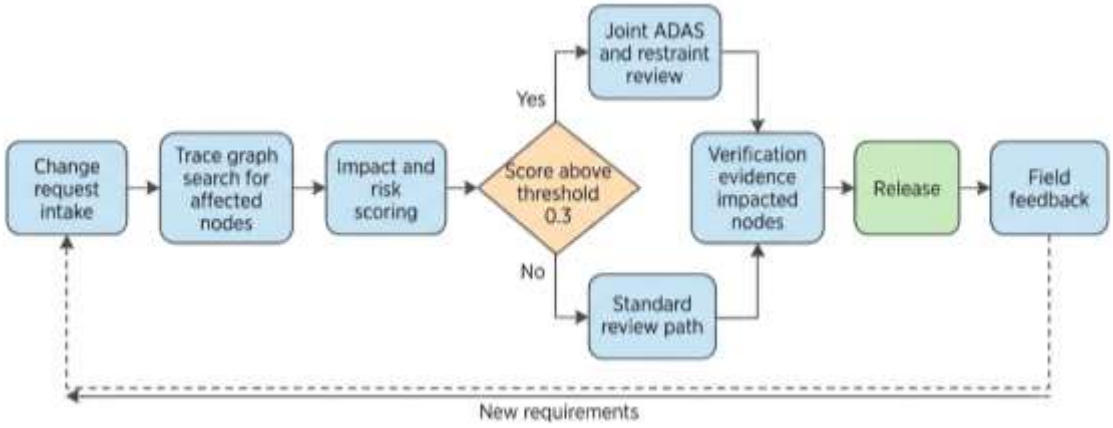

Figure 3. Flowchart of the controlled change process starting with request intake and ending with trace graph search, impact scoring, joint review, verification, release and field feedback

3.2 Metrics and Equations

Trace completeness quantifies the number of desired links and their validity. It is defined in equation (1) where L_v is the number of valid links, L_r is the number of required links.

$$TC = 100 \times \frac{L_v}{L_r} \tag{1}$$

The index of impact of a change c sums up the weighted probability of each neighbor node j being impacted. Equation (2) involves the weight w_j of node j, the propagation probability p_{cj} and the set of neighbors N_c. There is an increase in weights as the safety class increases.

$$I_c = \sum_{j \in N_c} w_j \times p_{cj} \tag{2}$$

The indirect effects require a search in the form of a graph. The reachability matrix is calculated using equation (3) in which A is the adjacency matrix, I is the identity matrix, and k is the search depth. K is 3 and Boolean arithmetic is employed in the experiment.

$$R = (I + A)^k \tag{3}$$

3.3 Simulated Experiment

It is a simulated replay experiment that is used in learning. It takes 240 engineering change requests that add 18 months in a single vehicle program which comprises AEB, lane keeping, airbags, belt pretensioners and load limiters. Each request was tested with less than two models. The manual links used are the documents and the manual basis model. The framework was employed by the governed model. The level of influence was 0.3. The orders were in realistic proportion. Maintenance of changes in ADAS was common since software updates are commonly furnished. The restraint alterations had fewer classes with more intense classes. Each request contained a list of actually affected artefacts and it was this list that was used to score recall in the study. The profile of the set is given in Table 4.

Table 4. The profile of the 240 simulated change requests by type, giving counts, shares, mean affected artefacts, and share that touched both the ADAS and restraint domains

Category	Requests	Share (%)	Mean affected artefacts	Cross domain share (%)
ADAS software	96	40.0	14.2	38
ADAS sensor hardware	48	20.0	11.6	31
Restraint hardware	60	25.0	9.8	27
Restraint control and calibration	36	15.0	12.4	58
Total	240	100.0	12.3 weighted	36.9 weighted

Note. The weighted means utilize the counts of requests. Source. Simulated dataset.

RESULTS AND DISCUSSION

4.1 Traceability and Lead Time

Table 5 is a comparison between the two models. The relative change is in equation (4) and is denoted as Δ, with D being the absolute difference between the governing value G and the baseline value B.

$$\Delta = 100 \times \frac{D}{B} \tag{4}$$

Table 5. Comparison between baseline and governed models of trace completeness, impact assessment time, lead time, impact recall and rework loops on 240 requests

Metric	Baseline	Governed	Change (%)
Trace completeness (%)	68.3	94.0	37.6 higher
Impact assessment time (hours)	31.5	12.8	59.4 lower
Total lead time (days)	17.6	10.9	38.1 lower
Impact recall (%)	71.2	92.6	30.1 higher
Rework loops per request	1.9	0.8	57.9 lower

Note. The values of change are according to Equation (4). Source. Simulated experiment.

Trace completeness by stage of the lifecycle can be seen in Figure 4. The weakest were field feedback and calibration whereby it was 54 and 58 in the baseline model. The model in charge had over 90 per cent of the stages. The greatest gain experienced in field feedback links which increased by 37 points. This is compatible with the interview result, traceability and data intensive verification were difficult to perception teams.

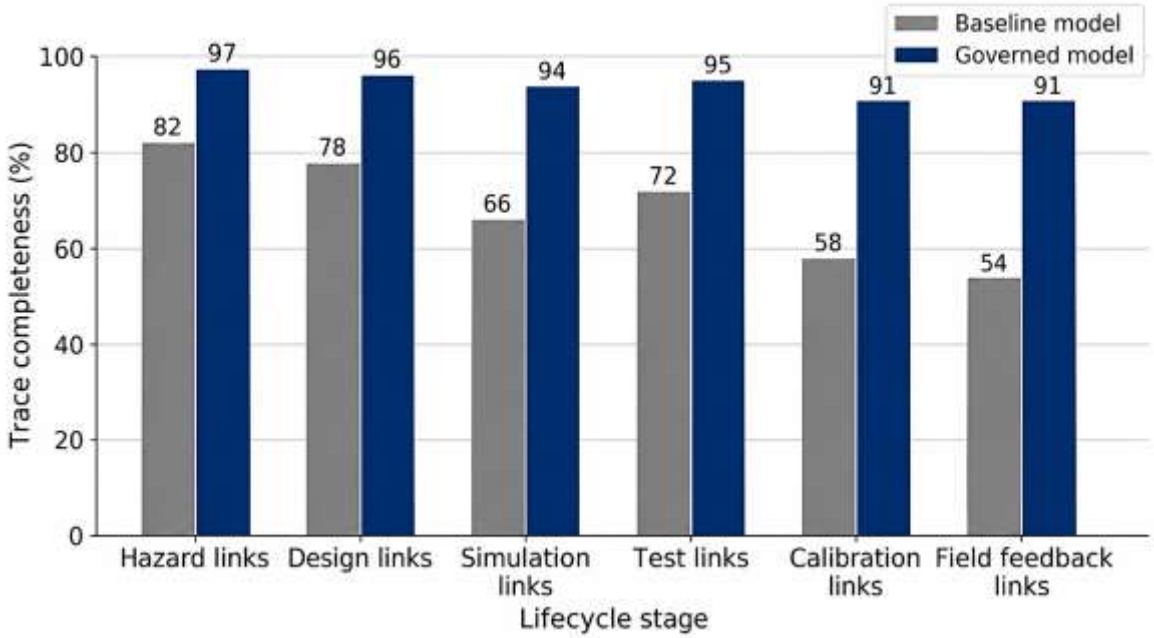

Figure 4. Lifelcycle-based trace completeness of the underlying model subjects to the baseline and controlled model, including the hazard, design, simulation process, test, calibration and field feedback connections

Lead-time is derived through Equation (5) with the T_a being the assessment time, T_P being approval time, T_v being verification time and T_w the rework time.

$$T = T_a + T_p + T_v + T_w \tag{5}$$

Figure 5 is a mean lead time by category. In both of the models, sensor hardware change was the longest with both 20.8 days at baseline and 13.0 days governed. The restraint control changes dropped to 8.4 days as compared to 13.6 days. The majority of savings was achieved through T_a and T_w, as engineers realized that the impacted nodes responded quicker and reverted to fewer unsuccessful inspection.

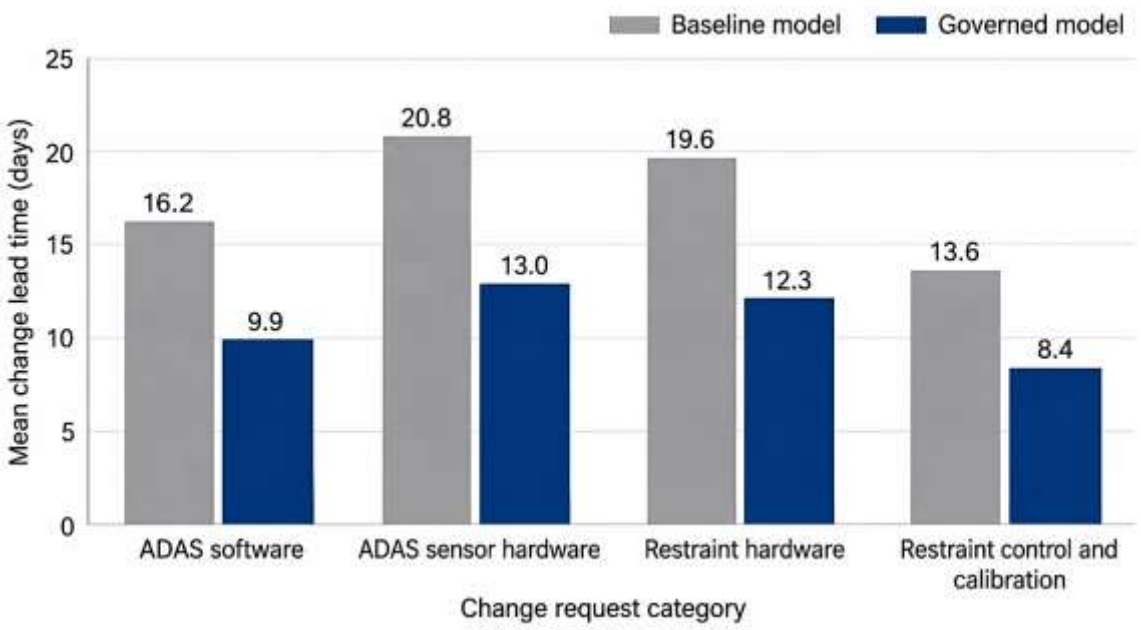

Figure 5. Mean change lead time in days in each category, between the governed and the baseline model

4.2 Escaped Defects

An escaped defect is a bug discovered after a release of the change. The number of escaped defects divided by the number of requests is the escaped defect rate as provided in equation (6) where D_e is the escaped defects and N is the number of requests.

$$E = 100 \times \frac{D_e}{N} \tag{6}$$

The counts and rates are indicated in table 6. Baseline model had a release rate of 12.9 releasing escapes of 31 defects. The managed model issued out 11, at 4.6 percent. This comprises a 64.5% cut. The highest rate of restraint control was 22.2%. It was reduced by the model being ruled to 8.3%.

Table 6. Listing counts and rates per category request group, escaped change defects by category by the baseline and governed models

Category	Baseline defects	Baseline rate (%)	Governed defects	Governed rate (%)
ADAS software	12	12.5	4	4.2
ADAS sensor hardware	5	10.4	2	4.2
Restraint hardware	6	10.0	2	3.3
Restraint control and calibration	8	22.2	3	8.3
Total	31	12.9	11	4.6

Note. Rates are based on the number of requests in Table 4. Source. Simulated experiment.

Figure 6 graphs escaped defects monthly, relative to month of request arrival. The upper and lower limits in the baseline series were maintained at 1-3 defects/month. The duration of the series of rules under control did not exceed 1 defect per month. There were seven months under control without escapes.

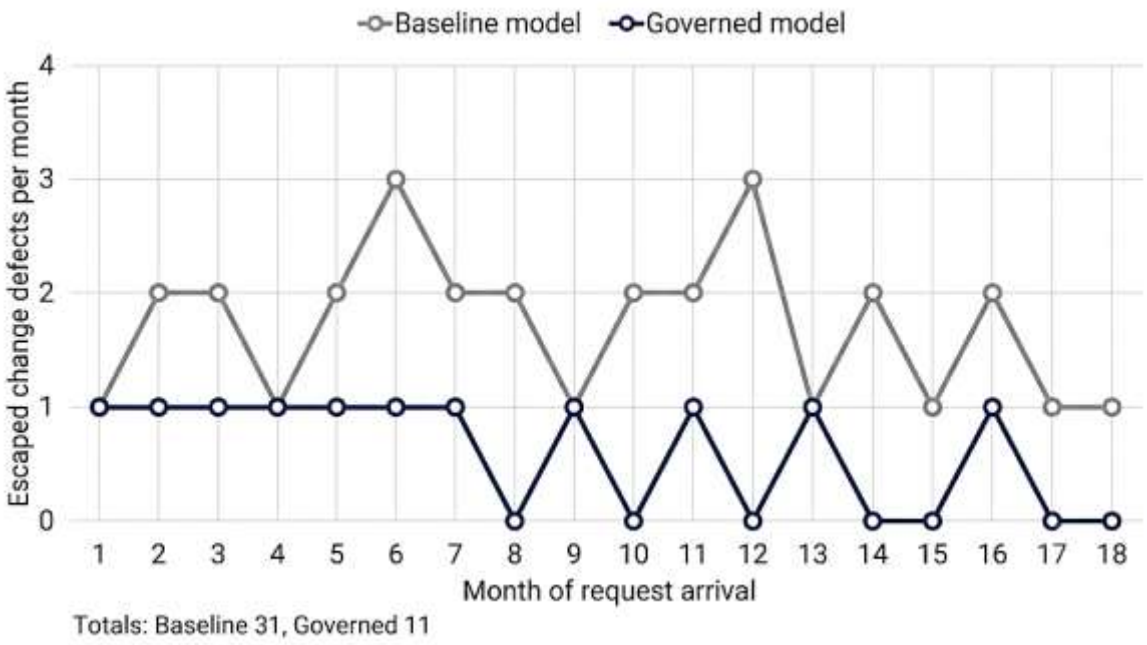

Figure 6. Baseline model and the governed model and number of defects on change that escaped per month in 18 months

4.3 Risk and Readiness

The findings are in line with the evidence in the literature. Collision reduction research demonstrates significant impacts in the appropriate situations, and speed has a profound impact on injury. Any change which causes a shift in a braking threshold, can thus change the crash speed which the restraint system must contain. The highest cross domain share of 58 was in restraint control changes and the highest gain of the defect rate was found there.

Risk requires a single number which can be ranked by engineers. The risk score would be calculated by Equation (7) as follows, with S_c being the severity class factor and U_c being the portion of impacted nodes that is not currently verifiable.

$$R_c = I_c \times S_c \times U_c \tag{7}$$

The score increases as there are impact, severity and missing evidence. When there is no missing evidence, it can be rated as zero and it will pass without any additional examination. The method also conforms to the safety case perspective that all claims should have up-to-date demonstrations.

There are six dimensions in the case of preparedness. The governance readiness index defined by equation (8) includes m_i which is the score of dimensions i and ω_i is the weight of that dimension. The weights sum up to 1.

$$\text{GRI} = \sum_i \omega_i \times m_i \tag{8}$$

The scores are provided in table 7. The balance index was 0.634 and the regulated index was 0.906, representing a 42.9% gain as per Equation (4). The greatest increase was recorded by interoperability, which increased from 0.52 to 0.85. This is congruent with data mapping review, where format differences are pointed out to be a key obstacle.

Table 7. Governance Readiness Index by dimension of the baseline and governed models, displaying the weight and score of the six dimensions

Dimension	Weight	Baseline score	Governed score
Traceability coverage	0.25	0.68	0.94
Change impact analysis	0.20	0.71	0.93
Verification linkage	0.20	0.60	0.89
Data model interoperability	0.15	0.52	0.85
Access and security control	0.10	0.66	0.88
Audit and versioning	0.10	0.58	0.91
Index	1.00	0.634	0.906

Note. The index is the weighted sum of Equation (8). Source. Simulated experiment.

4.4 Sensitivity and Limits

There is trade-off between recall and precision based on the impact threshold. The result for the thresholds of 0.1 to 0.5 are displayed in figure 7. Recall fell from 0.98 to 0.76 and precision rose from 0.58 to 0.93. The selected value was 0.3 which recalls 0.926 with a precision of 0.81. A smaller threshold should be used in case of high severity changes, its reason being missed impacts are expensive compared to additional reviews.

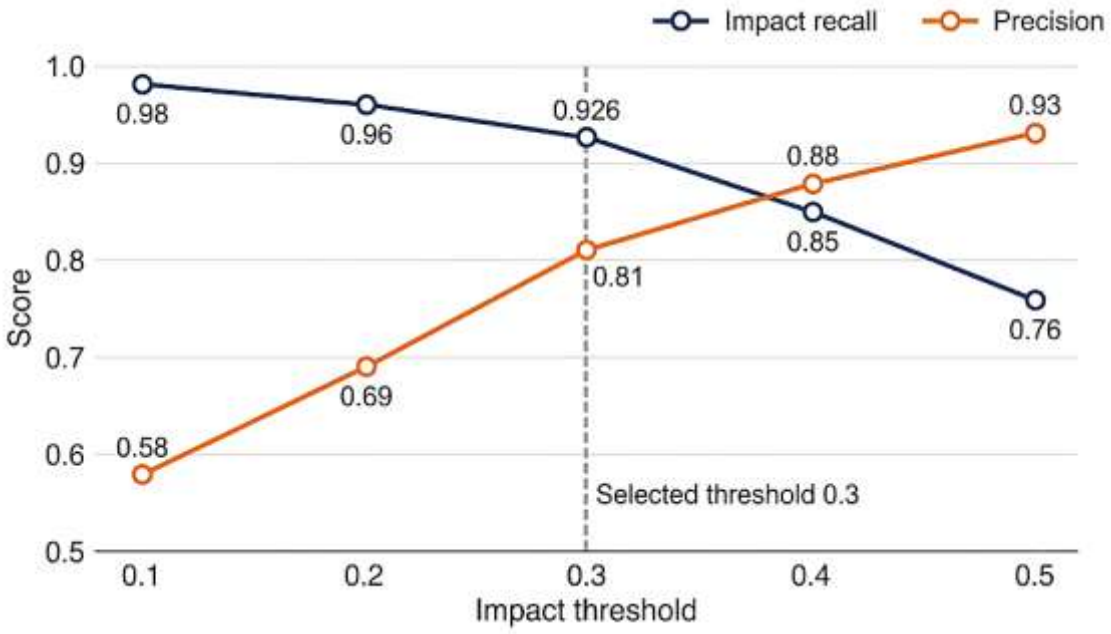

Figure 7. The ability to recall impact and to be precise at the impact threshold, 0.1 to 0.5 and the choice is 0.3

The framework is useful to the program teams. A release manager will be able to open up the view of impact and view what requirements, models and tests a change has an impact on. A

restraint engineer is able to observe when an ADAS threshold change is deployed to the deployment logic. The evidence in each claim can be read without needing to request new files, which is possible with a safety assessor. These applications reduce meeting time, and decrease the likelihood of unspoken modifications. Audits against rules of type approval also adopt the same records as the regulation anticipates managed cybersecurity process.

There are limitations of the research. The simulation is an experiment and therefore the values are of method behavior and do not demonstrate field results. This model employs a single program, and a single reviewer group. Security regulations are source of extra work and update assurance must have evidence of its own. The framework should be tested using a set of actual change logs through a field trial.

CONCLUSION

In this paper, a change management framework of the ADAS and restraint change governance was proposed as a digital thread framework. The reviewed 28 studies exhibit half-life traceability gaps, little work on propagation of change on restraint systems, and heavy reliance on safety outcomes on the situation and speed factor. The imitated execution of 240 requests increased trace completeness up to 94.0% and impact recall up to 92.6. It decreased lead time to 10.9 days and defects to 11. The index of readiness was 0.906. The highest profits were realized in changes in the restraint control where the ADAS and restraint data converge. Future research ought to experiment with the framework on actual change logs, and include automated link recovery.

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