From Hazard Analysis to Hazard Mitigation Planning: The Automated Driving Case*

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Abstract. Vehicle safety depends on (a) the range of identified hazards and (b) the operational situations for which mitigations of these hazards are acceptably decreasing risk. Moreover, with an increasing degree of autonomy, risk ownership is likely to increase for vendors towards regulatory certification. Hence, highly automated vehicles have to be equipped with verified controllers capable of reliably identifying and mitigating hazards in all possible operational situations. To this end, available methods for the design and verification of automated vehicle controllers have to be supported by models for hazard analysis and mitigation.

In this paper, we describe (1) a framework for the analysis and design of planners (i.e., high-level controllers) capable of run-time hazard identification and mitigation, (2) an incremental algorithm for constructing planning models from hazard analysis, and (3) an exemplary application to the design of a fail-operational controller based on a given control system architecture. Our approach equips the safety engineer with concepts and steps to (2a) elaborate scenarios of endangerment and (2b) design operational strategies for mitigating such scenarios.

Keywords: risk analysis, hazard mitigation, safe state, controller design, autonomous vehicle, automotive system, modeling, planning

1 Challenges, Background, and Contribution

Automated and autonomous vehicles (AV) are responsible for avoiding mishaps and even for mitigating hazardous situations in as many operational situations as possible. Hence, AVs are examples of systems where the identification (2a) and mitigation (2b) of hazards have to be highly automated. This circumstance makes these systems even more complex and difficult to design. Thus, safety engineers require specific models and methods for risk analysis and mitigation.

As an example, we consider manned road vehicles in road traffic with an autopilot (AP) feature. Such vehicles are able to automatically conduct a ride only given some valid target and minimizing human intervention. The following AV-level (S)afety (G)oal specifies the problem we want to focus on in this paper:

SG: The AV can always reach a safest possible state $\sigma$ wrt. the hazards identified and present in a specific operational situation $os$.

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Table 1: Examples of endangerment scenarios and mitigation strategies.

| Scenario of Endangerment | Possible Mitigation Strategy |
|--------------------------|-----------------------------|
| Vehicle subsystem fault  | Vehicle dependability pattern | Driver controlled shutdown | RoadEnv car2x.com., digital road signs |
| Driver maloperation      | Vehicle emergency braking assistant | RoadEnv braking or circumvention | IT attack x2car.com. |
| RoadEnv unforeseen obstacle | RoadEnv security pattern | RoadEnv safe reaction (if controllable) |

Background. Adopted from [4,9], we give a brief overview of terms used in this paper: We perceive a mishap as an event of harm, injury, damage, or loss. A hazard (or hazardous state) is an event that can lead to a mishap. We consider hazards to be factorable. Hence, a hazard can play the role of a causal factor of another hazard or a mishap. We denote causal factors, hazards, and mishaps—i.e., the elements of a causal (event) chain—by the term safety risk (risk state or risk for short). We perceive the part of a causal chain increasing risk as an endangerment scenario, and the part of a causal chain decreasing risk as a mitigation strategy. Table 1 exemplifies different endangerment scenarios and how these can be mitigated using corresponding strategies.

Mitigation strategies can be seen as specific system-level safety requirements implemented by a given control system architecture. We assume that a control system architecture consists of features deployed on sensors, actuators, and software components running on networked computing units (cf. Fig. 4a). By traditional driver assistance (TDA), we refer to driver assistance features already in the field, e.g. adaptive cruise control (ACC) and lane keeping assistance (LKA).

We distinguish between the domains vehicle, driver, and road environment. For highly and fully automated driving, not all domains have to be considered. For example, in full automation (e.g. level 5 in [12]), the vehicle has to operate under all road and environmental conditions manageable by a human driver and therefore a driver does not have to be taken into account.

Contribution. Elaborating on previous work in [5,6], we contribute

1. a framework for modeling, analysis, and design of planners (i.e., high-level controllers) capable of run-time hazard identification and mitigation, and
2. a procedure for constructing planning models from hazard analysis.

For this, we formalize the core engineering steps necessary for (2a) the identification and analysis of scenarios of endangerment and (2b) the design of operational mitigation strategies. Using an exemplary AV, we incrementally build up a risk structure involving three hazards in the vehicle domain, as well as several strategies to reach safe states in presence of these hazards. We discuss approaches to model reduction suited for run-time hazard analysis and mitigation planning where efficient identification of operational situations and acting therein play a crucial role.

In this paper, we discuss related work in Section 2, our abstraction in Section 3, and our modeling framework in Section 4. Section 5 shows a procedure for building a
hazard mitigation planning model. We present an AV example in Section 6, discuss our approach in Section 7, and conclude in Section 8.

2 Related Work

Among the related formal methods available in robotics planning, embedded systems, and automated vehicle control, we only discuss a few more recent ones and highlight how we can improve over them.

Güdemann and Ortmeier [7] present a language for probabilistic system modeling for safety analysis. Formalized as M\textsc{ARKOV} decision processes (MDP), they propose two ways of failure mode modeling (i.e., per-time and per-demand failure modes), and two ways of deductive cause consequence reasoning (i.e., quantitative and qualitative). Their model and reasoning can extend our approach. However, our work (i) adds stronger guidelines on how to build planning models and (ii) puts hazard analysis into the context of autonomous systems and mitigation planning.

Eastwood et al. [3] present an algorithm for finding permissive robot action plans optimal w.r.t. to safety and performance. They employ partially observable MDPs (helpful in regarding uncertainty and robot limitations) to model robot behavior, and two abstractions from this model to capture a system’s modes and hazards. Our framework uses three layers of abstraction ($\Sigma^s$, $\Sigma^p$, $\Sigma$), operational situations to capture control modes, and a structure to capture hazards. While they directly encode hazard severity for plan selection, our framework allows the planner to calculate the risk priority based on a causal event tree towards mishaps. As opposed to complete behavioral planning, our approach focuses the construction of mitigation planning models. For example, for system faults we can plan mitigations by using adaptation mechanisms of a given control system architecture.

Jha and Raman [8] discuss the synthesis of vehicle trajectories from probabilistic temporal logic assertions. Synthesized trajectories take into account perception uncertainty through approximation of sensed obstacles by combining Gaussian polytopes. In a similar context, Rizaldi and Althoff [10] formalize safe driving policies to derive safe control strategies implementing worst-case braking scenarios in autonomous driving. They apply a hybrid-trace-based formalization of physics required for model checking of recorded [10] and planned [11] strategies. [8,10,11] discuss low-level control for a specific class of driving scenarios, whereas our approach provides for (i) the investigation and combination of many related operational situations, thus, forming a more comprehensive perspective of driving safety, (ii) regarding various kinds of hazards that might play a role in high- and low-level control beyond safe and optimal trajectory planning and collision avoidance.

Wei et al. [14] describe an autonomous driving platform, capable of bringing vehicles to a safe state and stop, i.e., activating a fail-operational mode on critical failure, and a limp-home mode on less critical failure. These are mitigation strategies we can assess in our framework. Their work elaborates on designing a specific class of architectures. Additionally, we provide an approach to systematically evaluate risks and, consequently, derive an architecture design.

Babin et al. [1] propose a system reconfiguration approach developed with the Event-B method in a correct-by-construction fashion using a behavior pattern similar to
Fig. 1: Abstractions for state and predicate modeling, and for hazard analysis.

our approach (particularly, Fig. 2b). Reconfiguration as one way to mitigate faults is discussed in this work. Wardziński [13] discusses hazard identification and mitigation for autonomous vehicles by predetermined risk assessment (i.e., with safety barriers) and dynamic risk assessment. For both, he provides argumentation patterns for creating AV safety cases. In addition to his work, the abstraction and the method we propose covers both paradigms in one framework. We provide formal notions of all core concepts.

3 Abstraction for Run-time Hazard Mitigation

Fig. 1 depicts three abstractions—\( \Sigma^s \), \( \Sigma^p \), and \( \Sigma \)—for run-time hazard mitigation in AVs. The state space \( \Sigma^s \) pertains to the quantization of continuous signals from the physical world encompassing the driver (\( \text{drv} \)), the vehicle (\( \text{veh} \)), and the road environment (\( \text{renv} \)). For instance, the quantity speed is represented by the discrete state variable \( \text{veh}. \text{speed} \), which in turn is used to formulate predicates to obtain the abstract state space \( \Sigma^p \). For example, a predicate over sensor values \( \mathcal{p}(\text{veh}. \text{speed}, \text{veh}. \text{loc}, \text{renv}. \text{map}) \) can encode \text{exitTunnel}, an invariant constraining the activity of leaving a tunnel. We describe this two-staged abstraction in more detail in [6].

Here, we will work with the risk state space \( \Sigma \) whose concepts—actions, hazard phases, their composition and ordering—are discussed below:

Actions. Let \( \mathcal{A} \) be a set of actions. We abstract from control loop behaviors within and across operational situations by distinguishing four classes of actions: endangerments \( \mathcal{E} \), mitigations \( \mathcal{M} \) (see Fig. 2b), mishaps \( \mathcal{E}_m \), and ordinary actions \( \mathcal{A}_o \). Note that actions can take place in one or more out of the three domains, \( \text{drv}, \text{veh}, \text{renv} \), depending on the quantities they modify. We require \( \mathcal{E}, \mathcal{M}, \mathcal{A}_o, \mathcal{E}_m \subseteq \mathcal{A} \).

Definition 1 (Hazard Phases). Let \( \mathcal{H} \) be a set of hazards. Given \( h \in \mathcal{H} \), endangerment actions \( e^h \), \( e^h_m \in \mathcal{A} \), and \( n_h \in \mathbb{N}\setminus\{0\} \) mitigation actions \( m^h_j \in \mathcal{A} \), we define the phases of a hazard \( h \) as the set \( P_h = \{0, e^h, e^h_m \} \cup \{m^h_j \mid j \in \mathbb{N}\setminus\{0\} \land j \leq n_h \} \) whose elements denote the following:

- \( 0 \) hazard \( h \) is (inactive),
- \( e^h \) hazard \( h \) has been (act)ivated by an action \( e^h \),
- \( e^h_m \) (act)ivated hazard \( h \) has contributed to a mishap by an action \( e^h_m \), and
- \( m^h_j \) hazard \( h \) has been (mit)igated by an action \( m^h_j \).

For each hazard \( h \), Fig. 2a depicts \( P_h \) as a transition system where \( |P_h| = n_h + 3 \), the indices \( s, e, c, t_1, \ldots, t_{n} \leq n_h \), the state \( \text{mit} \) subsumes \( n_h - 1 \) phases, \( \text{act} \) subsumes phases \( e^h \) and \( e^h_m \). For example, in the vehicle domain, \( m^h \) can model degradation transitions and \( m^h \) or \( m^h \) can model repair transitions.

From all the sets of hazard phases, we compose a tuple space as follows:
Definition 2 (Risk State Space). Based on Definition 1, we define the risk state space $\Sigma$ as the set of $|H|$-tuples

$$\{(p_{h_1}, \ldots, p_{h_{|H|}}) \mid \forall i \in \{1, \ldots, |H|\} : h_i \in H \land p_{h_i} \in P_{h_i} \}.$$  

We call any subset of $\Sigma$ a region. Let $\sigma, \sigma' \in \Sigma$ with $\sigma = (p_{h_1}, \ldots, p_{h_{|H|}})$ and $\sigma' = (p'_{h_1}, \ldots, p'_{h_{|H|}})$. To quantify risk in scenarios of endangerment and mitigation strategies (Table 1), we define a partial order over $\Sigma$:

Definition 3 (Mitigation Order). Let $P_h$ be a set of phases for hazard $h$ (Definition 1) and $<_h = \{(e^h, 0), (e^h, m^h), (m_j^h, 0), (e^h, e^h) \mid m_j^h \in P_h\}$. By the reflexive transitive closure $\leq_m \subseteq \Sigma \times \Sigma$, for states $\sigma, \sigma' \in \Sigma$, we define the mitigation order $\leq_m \subseteq \Sigma \times \Sigma$, as follows:

$$\sigma \leq_m \sigma' \iff \forall i \in \{1, \ldots, |H|\} : p_{h_i} \leq m p'_{h_i}.$$  

Intuitively, $\sigma <_m \sigma'$ denotes "$\sigma'$ is better or further in mitigation than $\sigma".$

4 Concepts for Run-time Hazard Mitigation

In this section, we explain the core concepts of deriving a risk structure for a specific operational situation. Using the risk state space $\Sigma$ and actions $A$, we define the notions of risk structure, risk region, and operational situation:

Definition 4 (Risk Structure). A risk structure is a weighted labeled transition system $(\Sigma, A, \Delta, W)$ with

\begin{itemize}
  \item a set $\Sigma$ called the risk state space (Definition 2),
  \item a set $A$ of actions used as transition labels,
  \item a relation $\Delta \subseteq \Sigma \times A \times \Sigma$ called labeled transition relation, and
  \item a set $W$ of partial functions $w : \Sigma \cup A \cup \Delta \to W$ called weights where the set $W$ can be, e.g. $\mathbb{N}, \mathbb{R}, [0, 1]$, or $\{m, c, f\}.$
\end{itemize}

\footnote{Here, for a relation $R$, $R^\circ$ represents the composition of relations.}

\footnote{We use the convention $\sigma <_m \sigma' \equiv \sigma \leq_m \sigma' \land \sigma \neq \sigma'.$}

\footnote{(m)arginal, (c)ritical, (f)atal; for other examples of severity scales, see [4].}
To capture the notions of endangerment scenario and mitigation strategy (Table 1) based on $\Delta$, we consider paths and strategies:

**Definition 5 (Paths, Strategies, and Reachability).** By convention, we write $\sigma \xrightarrow{a} \sigma'$ for $(\sigma, a, \sigma') \in \Delta$. Then, for $a, l \in \mathbb{N} \setminus \{0\}$, a path is a sequence $\sigma_0 \xrightarrow{a_0} \ldots \xrightarrow{a_{n-1}} \sigma_n$. By $\Delta^l$ we denote the set of all paths of length $l$ and by $\Delta^\omega = \bigcup_{l \geq 0} \Delta^l$ all paths over $\Delta$. Furthermore, we call a set $S \subseteq \Delta^\omega$ a strategy. By $\text{reach}_\Delta : \Sigma \to 2^{\Delta^\omega}$ with $\text{reach}_\Delta(\sigma) = \{\sigma \cup \{\sigma' \in \Sigma \mid \exists \sigma \xrightarrow{a} \ldots \xrightarrow{a'} \sigma' \in \Delta^\omega\}\}$, we denote the set of states reachable in $\Delta$ from a state $\sigma$.

**Endangerments.** We consider an action $a \in A$ as an endangerment, i.e., $a \in \mathcal{E}$, if $\sigma \succ_m \sigma'$ for a transition $(\sigma, a, \sigma') \in \Delta$. The class $\mathcal{E}$ models steps of endangerment scenarios. For example, $a$ can stem from faults in $\text{drv}$, $\text{veh}$, and $\text{renv}$.

**Mitigations.** We consider an action $a \in A$ as a mitigation, i.e., $a \in \mathcal{M}$, if $\sigma \prec_m \sigma'$ for a transition $(\sigma, a, \sigma') \in \Delta$. The class $\mathcal{M}$ models steps of mitigation strategies. One objective of a good mitigation strategy is to achieve a stable safe state.

**Operational Situations.** States and regions in $\Sigma$ both correspond to subsets of $\Sigma^n$ (Section 3). To limit the scope of a risk analysis, we use an operational situation which combines an initial region with a (reasonably weak) invariant holding along the driving scenarios in a specific road environment.

**Definition 6 (Operational Situation).** An operational situation is a tuple $(\Sigma_0, \{\sigma \in \Sigma^n \mid p(\sigma)\})$ where $\Sigma_0 \subseteq \Sigma$ and $p$ is an invariant over $\Sigma^n$ including all representations of $\Sigma_0$ in $\Sigma^n$. Let $\mathcal{O}$ be the set of all operational situations.

Below, we will work with a risk structure $\mathcal{R}_{\text{os}} = (\Sigma, \mathcal{A}, \Delta, \mathcal{W})$ and assume a fixed operational situation $\text{os} \in \mathcal{O}$ associated with $\mathcal{R}_{\text{os}}$. Hence, we use $\mathcal{R}$ solely.

**Risk Regions.** We consider specific subsets of $\Sigma$ called risk regions, particularly, the safe region $\text{saf}$, the hazardous region $\text{haz}$, and the mishap region $\text{mis}$ (see Fig. 2b). Safety engineers aim at the design of mitigations which (i) avoid $\text{mis}$ and (ii) react to endangerments as early and effectively as possible. Then, $\mathcal{E}_m$ reduces to unavoidable actions from so-called near-mishaps still in $\text{haz}$ towards $\text{mis}$. For example, we consider a successfully deployed airbag to be in $\mathcal{M}$ such that $\text{mis}$ is not reached in such an accident (more in Section 7).

Our definitions of risk regions depend on $\mathcal{R}$: First, $\text{mis} = \{(p_h, \ldots, p_{h|\mathcal{R}|}) \in \Sigma \mid \exists i \in \{1, \ldots, |\mathcal{R}|\} : p_i = e^h_m\}$. We require mishaps to be final, i.e., $\forall \sigma \in \text{mis} : \text{reach}_\Delta(\sigma) = \{\sigma\}$. Second, $\text{saf}$ and $\text{haz}$ vary with a given operational situation. Moreover, they can be defined based on, e.g., weights and equivalences. However, $(\text{0}, \ldots, 0) \in \text{saf}$ and, for an $\text{os}$, we start in the safe region iff $\Sigma_0 \subseteq \text{saf}$.

**Weights.** By associating weights with elements of $\mathcal{R}$, we quantify further details on the physical phenomena of the controlled process relevant for risk analysis.

For example, given $\delta = (\sigma, e^h_j, \sigma') \in \Delta$ with $e^h_j \in \mathcal{E}$, the probability of endangerment $\text{pr}(\delta) \in [0, 1]$ yields the probability that hazard $h$ gets activated in $\sigma'$ by performing $e^h$ in $\sigma$. Furthermore, given $\delta = (\sigma, m^j_i, \sigma') \in \Delta$ with $m^j_i \in \mathcal{M}$,
the probability of mitigation $\Pr(\delta) \in [0, 1]$ yields the probability that hazard $h$ gets mitigated in $\sigma'$ by performing $m^b_h$ in $\sigma$.

- the cost of mitigation $cs(\delta) \in \mathbb{N}$ yields the potential effort (i.e., time, energy, other resources) of performing the mitigation $m^b_h$.

For any mishap $\sigma \in mis$, $sv(\sigma) \in \{m, c, f\}$ specifies its severity. Depending on the abstraction, we can use qualitative (as shown above) or quantitative scales for $sv$ and $cs$. Anyway, we assume to have operators for abstraction, we can use qualitative (as shown above) or quantitative scales for $sv$ and $cs$. We speak of hazard (or fault) equivalence $\sigma \approx_{\text{h}} \sigma'$, iff $\sigma \leq_{\text{h}} \sigma'$ and both states share the same set of hazardous features $\sigma_{\text{h}}$. Furthermore, we speak of degradation equivalence $\sigma \approx_{\text{d}} \sigma'$, iff $\sigma \leq_{\text{d}} \sigma'$ and both states share the same set of degraded features. For simplification of complex risk structures $\mathcal{R}$, we can construct equivalence classes over states. From the structure of states in $\Sigma^s$, the dynamics in $\Sigma^e$, and the elements of the control system architecture (Section 1), we give a brief informal overview of equivalences over $\Sigma$ to be considered:

We speak of feature equivalence, $\sigma \approx_{f} \sigma'$, iff both, $\sigma$ and $\sigma'$ map to the same set of active features of the control system, i.e., in-the-loop no matter whether they are fully operational, faulty, or degraded. Note that out-of-the-loop features can be faulty, deactivated, or in standby mode. Next, we speak of degradation equivalence, $\sigma \approx_{d} \sigma'$, iff $\sigma \leq_{d} \sigma'$ and both states share the same set of degraded features. Furthermore, we speak of hazard (or fault) equivalence, $\sigma \approx_{h} \sigma'$, iff $\forall i \in \{1, \ldots, |\Omega|\} : p_{hi} \in P_{hi} \setminus \{0\} \quad p'_{hi} \in P_{hi} \setminus \{0\}$, and, particularly, of mishap equivalence, $\sigma \approx_{\text{ms}} \sigma'$, iff $\forall i \in \{1, \ldots, |\Omega|\} : p_{hi} = c_{ih} \iff p'_{hi} = c_{ih}$. Based on $\approx_{h}$, we finally define:

**Definition 7 (Mitigation Equivalence).** Based on Definition 3, two states $\sigma, \sigma' \in \Sigma$ are mitigation equivalent, written $\sigma \approx_{m} \sigma'$, iff

$$\sigma \approx_{h} \sigma' \land \forall i \in \{1, \ldots, |\Omega|\} : p_{hi} \geq_{h} e_{hi} \iff p'_{hi} \geq_{h} e_{hi}.$$
(a) The operators \(=_{w}, <_{w}, >_{w}\) and \(\geq_{w}\) where \(\geq_{w} \equiv =_{w} \land >_{w}\).

(b) Scheme for incremental construction of \(\mathcal{R}\) by constructRS.

Fig. 3: Operators and scheme

5 Construction of Risk Structures

In this section, we describe an incremental and forward\(^5\) reasoning approach to building a risk structure \(\mathcal{R}\).

Identification of Hazards. Throughout the construction of \(\mathcal{R}\), we assume to have a procedure hazId for the identification of a set of hazards \(\mathcal{H}\) based on a fixed control loop design \(\mathcal{L}\) of a class of AVs and their environments, and a fixed set \(\mathcal{O}' \subset \mathcal{O}\) of operational situations (Definition 6). Failure mode effects and fault-tree analysis (see, e.g. [4]) incorporate widely practiced schemes for hazId.

Building the Risk Structure. Fig. 3b shows the main steps of a procedure constructRS which, given a set \(\mathcal{H}\) and after termination, returns all elements of a complete risk structure \(\mathcal{R}\). Here, completeness is relative to \(\mathcal{H}\) and means that \(\mathcal{R}\) can no more be extended by (i) states which are reachable by existing actions in \(\mathcal{A}\), (ii) actions which allow reaching non-visited states in \(\Sigma\), (iii) transitions in \(\Delta\) which are technically possible and probable, and (iv) further knowledge by extending the domains of weights. Based on Fig. 3b, Algorithm 1 refines constructRS for a control loop \(\mathcal{L}\) and an operational situation \(\mathcal{O}'\). The while-loop (cf. line 2) accounts for the alternation between adding endangerments and mitigations. By using the maps \(r_{v}\) and \(r_{m}\) (cf. lines 2, 3, 14, 17, 26), the algorithm keeps track of the endangerment- and mitigation-coverage of visited states, i.e., for which hazards \(\sigma\) has already been visited.

We assume to have (i) a function \(\text{estimate}_{\mathcal{L}, \mathcal{O}}\) (cf. lines 9, 11, 22, 23) which acts as an oracle for weights (Section 4) depending on \((\mathcal{L}, \mathcal{O})\), and (ii) a function poss (cf. lines 6, 20) which acts as an oracle for determining the technical possibility of newly identified transitions.

The first for-loop checks for the addition of new transitions to \(\Delta\) (cf. line 7). The transition constructor activate returns a state with the given hazard or mishap activated

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\(^5\) See, e.g. [2] for details about probabilistic temporal logic and reasoning.

\(^6\) For generation of \(\mathcal{R}\), backward reasoning is the alternative not shown here.
Algorithm 1 \text{constructRS}(\mathcal{L}, os)

1: $\Sigma = \Sigma_0$, $\forall \sigma \in \Sigma_0: rv_m(\sigma) = rv_e(\sigma) = \emptyset$
2: while $\mathcal{H} = \text{hazard}(\mathcal{L}, os)$ and $\exists \sigma \in \Sigma:\text{mis} : \mathcal{H}(rv_e(\sigma) \cup rv_m(\sigma)) \neq \emptyset$ do
3:   for all $\sigma \in \Sigma:\text{mis} \text{ and } \mathcal{H}' \subseteq \mathcal{H}(rv_m(\sigma))$ do
4:     if $(\sigma', e_j^{H'}) \leftarrow \text{activate}(\sigma, \mathcal{H}')$ then // state/jth action estab. $\mathcal{H}'$ or mishap
5:       $\delta \leftarrow (\sigma, e_j^{H'}, \sigma')$
6:       if $\text{poss}(\delta)$ then // add endangerment?
7:         $(\Sigma, \mathcal{E}, \Delta, rv_e(\sigma')) \leftarrow (\Sigma \cup \{\sigma'\}, \mathcal{E} \cup \{e_j^{H'}\}, \Delta \cup \{\delta\}, \emptyset)$
8:       if $\sigma' \in \text{mis}$ then
9:         $sv(\sigma') \leftarrow \text{estimate}_{\Sigma, os}(sv, \sigma')$ // severity of mishap
10:     end if
11:     end if
12:     else // activate returns empty tuple
13:       $pr(\delta) \leftarrow \text{estimate}_{\Sigma, os}(pr, \delta)$ // probability of endangerment
14:     end if
15:   end if
16: end for
17: for all $\sigma \in \Sigma:\text{mis}$ and $\mathcal{H}' \subseteq \mathcal{H}(rv_m(\sigma))$ do // extend mitigations
18:   if $(\sigma', m_j^{H'}) \leftarrow \text{mitigate}(\sigma, \mathcal{H}')$ then // state/jth action mitig. $\mathcal{H}'$ from $\sigma$
19:     $\delta \leftarrow (\sigma, m_j^{H'}, \sigma')$
20:   if $\text{poss}(\delta)$ then // add mitigation?
21:     $(\Sigma, \mathcal{M}, \Delta, rv_m(\sigma')) \leftarrow (\Sigma \cup \{\sigma'\}, \mathcal{M} \cup \{m_j^{H'}\}, \Delta \cup \{\delta\}, \emptyset)$
22:     $\text{cs}(\delta) \leftarrow \text{estimate}_{\Sigma, os}(cs, \delta)$ // cost of mitigation
23:   end if
24:   else // mitigate returns empty tuple
25:     $rv_m(\sigma) \leftarrow rv_m(\sigma) \cup \mathcal{H}'$ // i.e., all options for $\mathcal{H}'$ are checked
26:   end if
27: end for
28: $\Sigma \leftarrow \Sigma \setminus \{\sigma \in \Sigma \mid \sigma \notin \bigcup_{\sigma_0 \in \Sigma_0} \text{reach}_{\Delta}(\sigma_0)\}$ // removing unreachable states
29: ... // further simplifications
30: return $(\Sigma, \mathcal{E} \cup \mathcal{M}, \Delta, \{sv, pr, cs\})$

(i.e., phases $e_h$ or $e_h^m$). Note that activate can generate $\sigma' \in \text{mis}$ reachable via $e_j^{H'} \in \mathcal{E}_m$.

The second for-loop checks for the addition of new transitions to $\Delta$ (cf. line 21). The transition constructor mitigate returns a state with the given hazards $\mathcal{H}'$ mitigated to a new phase $m_j^{H'} \in \mathcal{P}_h$ for each $h \in H'$.

Note that none of the constructors is idempotent, mitigate can construct several mitigation phases for each hazard (cf. lines 18, 26) and activate can construct two activation phases, $e_h$ and $e_h^m$, both with the corresponding actions (cf. lines 4, 14).

**Model Reduction.** To keep reasoning efficient, we have to apply reachability-preserving simplifications to $\mathcal{R}$ (cf. lines 29f), e.g. equivalences such as in Definition 7. The mitigation order (Definition 3) helps in reducing the state space and in merging actions modifying phases of the same hazards (i.e., by hazard equivalence).
**Abstraction from Control System Architecture.** In both stages of Algorithm 1, we need to analyze the given or envisaged architecture and to identify state variables, e.g. for software modules, at an appropriate level of granularity.

In the endangerment stage (lines 3ff), we can perform dependability analyses to identify events that can activate causal factors. Off-line, we then design specific measures to reach the safe region again, and, on-line, we design generic measures to be refined at run-time.

Moreover, the mitigation stage (lines 17ff) helps to revise a control system architecture, e.g. by adding redundant execution units and degradation paths. Moreover, we can pursue off-line synthesis of respective parts of the control system architecture.

**Hazard Mitigation Planning.** First, hazId is hybrid in the sense that it (i) performs the sensing of already known endangerment scenarios (e.g. near-collision detection, component fault diagnosis) on-line, and (ii) allows the addition of new scenarios from off-line hazard analysis.

Second, a simple planner would continuously perform shortest weighted path search in $\mathcal{R}$ to keep a list of all available lowest-risk mitigation paths (Definition 5) and coordinate optimized lower-level controllers.

Based on these two steps, we assume $\mathcal{R}$ to be continuously updated according to the available information (i.e., adding or modifying endangerments and mitigations according to known scenarios). It is important to have powerful and precise update mechanisms, highly responsive actuation, and short control loop delays. Main issues of signal processing are briefly mentioned in Section 7.

The notion of *safest possible state* ($\text{SG}$, Section 1) is governed by the accuracy of $\Sigma^*$ (Section 3), the completeness of the results of hazId, and the exhaustiveness of $\mathcal{R}$ for a fixed setting $L, os$. According to Definition 3, for a pair $(\sigma, \sigma') \in \Sigma \times \Sigma$, we might say that $\sigma'$ is the *safest possible state* iff we have

$$ \exists \sigma'' \in \text{reach}_{\Delta_M}(\sigma): \sigma' <_m \sigma'' $$

(2)

where $\Delta_M = \Delta \{ (\sigma_1, a, \sigma_2) \in \Sigma \mid a \in \mathcal{E} \}$. Any controller for $\text{SG}$ would have to find and completely conduct a shortest plan for $(\sigma, \sigma')$ to reach $\sigma'$.

**6 Example: Fail-operational Driver Assistance**

Elaborating on an example in [6], we apply our framework and algorithm to hazard analysis and elaboration of mitigation strategies. We use the abbreviations introduced in Section 1.

**Identifying an Operational Situation.** We consider the situation $os \in \mathcal{O}$: “AV is taking an exit in a tunnel, at a speed between 30 and 90 km/h, with the driver being properly seated, and the next road segments contain a crossing.” Fig. 4b depicts the corresponding street segment.
Modeling the Road Vehicle Domain. Fig. 4a shows a simplified control system architecture used for driver assistance systems. We model the relevant state information according to the abstractions described in Section 3. State variables commonly used for road vehicles are listed in Table 2. For $\Sigma_s$, we assume to have the variables (prefixed with their domains, in parentheses their types): $\text{veh}.\text{loc}$ (coordinate), $\text{veh}.\text{speedvec}$ (vector of floats), $\text{renv}.\text{map}$ (street map), and $\text{drv}.\text{pos}$ (enumeration). $\text{veh}$ denotes all variables of this domain. For $\Sigma_p$, we identify the following predicates:

$\text{exitTunnel} \equiv \text{veh}.\text{route} \subset \text{renv}.\text{map} \land (P_{\text{exit}} \cup P_{\text{tunnel}})$

$\text{crossingAhead} \equiv \text{veh}.\text{route} \cap (\text{renv}.\text{map} \cap P_{\text{crossing}}) \neq \emptyset$

$\text{drvSeated} \equiv \text{drv}.\text{pos} = \text{seated}$

Furthermore, we use unspecified predicates:

$\text{inTunnel} \equiv p_4(\text{veh}.\text{loc}, \text{renv}.\text{map})$

$L \equiv p_6(\text{veh}.\text{faults})$

$A \equiv p_9(\text{veh}.\text{faults})$

$R \equiv p_7(\text{drv}.\text{vigilance})$

$\text{inCrossing} \equiv p_2(\text{veh}.\text{loc}, \text{renv}.\text{map})$

$tunnelAhead \equiv p_8(\text{veh}.\text{loc}, \text{renv}.\text{map})$

The invariant for $os$ is $p_{os} = \text{exitTunnel} \land \text{drvSeated} \land \text{crossingAhead}$. Note that the AP is active in the initial state $\sigma_0$ associated with $os$.

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6 Variable types and usage depend on the AV sensors and car2X services through which they are measured. We assume individual error estimators for all variables.

7 With, e.g. topological coordinate system, information about tunneled parts.

8 Here, $P_x$ refers to a pattern for the street map element class $x$ which acts like a filter on the street map data type. For sake of brevity, we omit details of sensor fusion and street map calculations required for evaluating these predicates.

| Domain        | State Variables                                      | Abbreviation |
|---------------|------------------------------------------------------|--------------|
| Driver        | Physical presence, consciousness, vigilance, ...     | $\text{drv}$ |
| Vehicle       | Speed, loc(ation), fault conditions, ...             | $\text{veh}$ |
| RoadEnv       | Daylight, weather, traffic, road, ...                | $\text{renv}$ |
Table 3: Model after two increments ($\mathfrak{R}_2$). $\|_i$ denotes true parallelism, ; concatenation.

| Description | Model Increment |
|-------------|-----------------|
| $\Sigma^*$ Introduce faults (e.g., from fault model) | veh.faults |
| $\mathcal{H}$ AP sensor $s_1$ fault | $A = p_0(\text{veh.faults})$ |
| $\mathcal{H}$ TDA LKA$^D$ software fault | $L = p_0(\text{veh.faults})$ |
| $\Sigma$ End. phases: Comb. of $A$ and $L$ | $AL \equiv A \land L, \overline{A}_1L \equiv \overline{A}_1 \land L$ |
| $\mathcal{E}$ Actions establishing $A$ and $L$ (e.g., from architecture analysis) | $f^A, f^L$, $\mathcal{E} = \{f^A, f^L\}$ |

Notation. In the following (Figures 5a, 5b, and 6), for each state, $H$ denotes that the hazard $H$ is active (phase $e^H$), $\overline{H}$ that $H$ contributed to a mishap (phase $e^H_m$, only in Table 3), and $\overline{H}_t$ that its $i$th mitigation phase is active (phase $m_i^H$). We do not indicate hazards which are in phase 0.

Incremental Forward Construction of the Risk Structure. Refining the regions $\text{haz}$ and $\text{saf}$ (Fig. 2b), we construct $\mathfrak{R}$ from three hazards $A$, $L$, and $R$ identified by hazld (Section 5). Table 3 sketches the construction of the first and second increments towards $\mathfrak{R}_2$, including the events $A = \text{"AP sensor } s_1 \text{ fault"}$ and $L = \text{"TDA LKA}^D\text{ software fault."}$

Fig. 5a shows $\Delta$ for $\mathfrak{R}_2$. According to Algorithm 1, we try to add the fault condition $L$ to $\sigma_0$ and other states in $\mathfrak{R}_1$ (i.e., black states in Fig. 5a). Based on the action $f^L$, this step yields the states $L$, $\overline{A}_1L$, and $AL$. Then, a mitigation step yields the states $\overline{A}_1$ and $AL_1$ and, finally, another step of endangerment analysis based on the action $f^A$ yields $AL_1$.

Risk Priority Estimation. From the state $AL$ with $sv(\overline{A}L) = f$, we can derive, e.g., $\text{rp}(\overline{A}_1)$ according to Eq. (1). We can as well derive $\text{rp}(\overline{A}_2) = \text{rp}(\overline{A}_3) = m$ because reaching $\overline{A}L$ by driving assistance control is no more possible.

Equivalences and Model Reduction. In Fig. 5a, for example,
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(a) After the 2\textsuperscript{nd} increment (cf. Table 3).

(b) Simplifying the state space ($\mathcal{H}_2$).

Fig. 5: Risk structure $\mathcal{H}_2$ and its simplification $\mathcal{H}_1$.

Table 4: Adding endangerments for the third increment ($\mathcal{H}_3$).

| Description | Model Increment |
|-------------|-----------------|
| $\mathcal{H}$ | Driver reaction time increases. |
| $\Sigma$ States | $R \equiv p_7(driver.vigilance)$ |
| $\mathcal{E}$ Action $e^R$, "driver looks sideward" | $e^R$, $E = \{f^A, f^L, e^R\}$ |
| $M$ | $m^L_2 \equiv warn \| normalStop$ |

- $\overline{A}_2 ≈_m \overline{A}_3$ because in both states $\overline{A}$ is mitigated and other hazards are inactive (0, cf. Definition 7),
- $\overline{A}_1 ≈_f \sigma_0$ because in $\overline{A}_1$ the degraded variants of LKA and ACC, i.e., $LKA^D$ and $ACC^D$, are in the loop,
- $\overline{A}_1 ≈_d \overline{A}_1 L$ because in both states $LKA^D$ and $ACC^D$ are in the loop,
- $\overline{A}_1 L ≈_f AL$ because in both states, LKA and ACC are in the loop, and
- $\overline{A}_1 L \not≈_h AL$ because ACC (part of AP) is faulty and $ACC^D$ (part of TDA) is fully operational.

Simplifications can be derived from Fig. 5a, where we might (i) merge two states $(\sigma_1, \sigma_2) \in \approx_d$ if $rp(\sigma_1) = rp(\sigma_2)$, or (ii) merge two consecutive states on a "safe" mitigation path, e.g. from any $\sigma \in haz$ to $\sigma_0$ if actions such as $limp-home$, $shutdown$, and $repair$ are feasible from $\sigma$.

Fig. 5b shows a simplification $\mathcal{H}_1^L$ of $\mathcal{H}_2$. We omit irrelevant transitions ($f^L$) and collapse the mitigation-equivalent ($\approx_m$) states $\overline{A}_2$ and $\overline{A}_3$. Consequently, with the states $\overline{A}_{2,3}$ and $\overline{A}_L$ we get a refinement of $saf$. According to Eq. (2), $\overline{A}_2$ is a safest possible state reachable from $A$.

Next, Table 4 and Fig. 6 describe a cut-out of $\mathcal{H}_3$ after the third increment where we added the event $R \equiv \"Driver reaction time increases.\"$
7 Discussion of Limitations, Applicability, and Strengths

The abstraction $\Sigma^e$ (Section 3) is subject to standard signal processing steps, i.e., sampling of continuous signals at discrete time points, quantization of dense domains to form finite domains, and clamping of domains. We assume all signals to be sampled faster than their respective NYQUIST period, sufficiently small quantums, and sufficiently large ranges of data types. Furthermore, we expect a mitigation planner to be fast enough (sufficiently low latency) to provide outputs for effective and optimal control. Note that the risk structure abstracts from the low-level parameters necessary for actual control of mitigations which takes place at the level of $\Sigma^e$.

The treatment of these issues will determine how accurate mitigations can take place at the right time and duration. In addition, we might consider higher-order mitigations to handle adverse impacts of first-order mitigations. However, such impacts have to be identified as hazards to get recognized in $\mathfrak{R}$.

Elaborating on risk regions (Section 4), $\text{mis}$ represents mitigation-less harmful states, however, $\text{haz}$ includes all states where mitigations are feasible. Consequently, we allow “bad things to happen” as long as we have partial mitigations, e.g. an airbag would prevent from reaching $\text{mis}$ at a certain probability.

8 Conclusion and Future Work

We presented risk structures as a model to design high-level controllers capable of runtime hazard mitigation, i.e., of maintaining or reaching the safest states in a given operational situation. We sketched an incremental approach to develop mitigation strategies. Safety measures are a combination of reducing or eliminating endangerments with constructing or strengthening mitigations. Risk structures can help to derive safety requirements for a control system architecture. Moreover, they can lay a basis for the evaluation, choice, and combination of mitigation strategies. Our example highlights challenges to tackle in hazard mitigation of fail-operational automated driving. Finally, we indicate how several formalisms—temporal specification, predicate abstraction, and transition systems—can coherently aid in hazard mitigation planning.
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Future Work. Based on risk structures, we aim to evaluate criteria such as (i) time, energy, and cost of mitigations, (ii) the role of human intervention, (iii) resilience to change of operational situations, (iv) control system simplicity.

In the next steps, we want to efficiently automate the derivation of acceptable mitigation strategies, and synthesize feasible and affordable mitigation strategies. Based on weights, we can define desirable properties of mitigation strategies implemented in \( \mathbb{N} \), e.g., monotonicity.

Definition 8 (Mitigation Monotonicity). Let \( S \subseteq \Delta^{\mathbb{N}} \) be a strategy (Definition 5) and \( n \in \mathbb{N} \setminus \{0\} \). We call \( S \) mitigation monotonous iff for each path \( \sigma_0 \xrightarrow{a_0} \ldots \xrightarrow{a_{n-1}} \sigma_n \in S \) : \( \forall i \in \{0, \ldots, n-1\} : rp(\sigma_i) \geq rp(\sigma_{i+1}) \).

Intuitively, during planning we seek mitigation paths containing only endangerments, if any, which do not increase risk priority. This might, however, be a definition to be relaxed for practical use by, e.g., allowing \( rp \)-distances.

Given that we use our algorithm off-line, it is important to make the poss and estimate steps in Algorithm 1 interactive for the safety engineer. Moreover, instead of elaborating os-specific risk structures off-line, we aim at using our algorithm to generate such structures on-line given a specific operational situation, and combine this with a transition system switching between operational situations. Given that we use our algorithm on-line, it is important to develop simplification rules to be applied to \( \Sigma \) based on the equivalences in Section 4.

We plan to evaluate our results in the automotive industry whose aims include checking whether fail-operational extensions of given in-vehicle network architectures for automated driving can be made acceptably safe.

Finally, for a regulatory agency to apply our approach to AV, we have to show (i) our approach using a large example involving several operational situations, (ii) how our abstraction can be verified, and (iii) that the limits of controllers do not constrain our approach to achieve safe stable control loops.

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