SYSTEMATIZING THE UNUSUAL: A GUIDEWORD- AND ONTOLOGY-BASED METHOD FOR ROAD HAZARD IDENTIFICATION AND ANALYSIS IN DRIVING AUTOMATION SAFETY ASSURANCE (GOBI) AND A HAZARD CATALOG

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ABSTRACT

Automated driving systems must operate safely in open-world environments where rare, unusual, or hazardous conditions may arise. Identifying such conditions is challenging because they span a long tail of events that are infrequently observed in controlled testing or fleet-based data collection. This work introduces GOBI, a hybrid method for systematically eliciting, organizing, and analyzing road-traffic hazards. The method combines a top-down approach, which applies structured guidewords to elements of a road-environment ontology to hypothesize hazardous conditions, with a bottom-up approach that discovers additional hazards through the analysis of publicly available video and image recordings.

GOBI structures these discoveries into a catalog of hazardous conditions, supported by a refined ontology and a schema for detailed annotation. Videos and images from dashcams, infrastructure cameras, handheld devices, and other sources are analyzed to identify hazardous conditions, contributing factors, and environmental context. The catalog grows iteratively as new recordings reveal additional scene elements, hazard variants, and rare events. The approach benefits from the fact that publicly shared recordings often emphasize unusual or striking situations, providing access to a far broader range of edge cases than is feasible through dedicated data collection alone.

The method has been applied to build a catalog containing more than 300 hazardous conditions instantiated in over one thousand recordings. These span diverse categories, including infrastructure failures, environmental extremes, foreign-object hazards, unusual road-user behavior, and unexpected interactions across natural, built, and social environments. The resulting catalog offers a resource for designing safer automated driving systems and for supporting regulatory assessments of reasonably foreseeable hazards.

Future work includes developing artificial intelligence models capable of recognizing and reasoning about hazardous conditions in complex scenes, as well as automated tools to continuously discover and annotate new recordings. Such capabilities will allow the catalog to evolve in step with the emergence of new real-world hazards and support the advancement of robust, safety-oriented autonomous driving.

Keywords: Autonomous driving; driving automation; road hazards; edge cases; hazard identification; hazard analysis; operational design domain; road-environment ontology; guideword analysis; scenario-based safety; rare events; dashcam videos; video annotation; dataset development; safety assurance; open-world robustness; environmental hazards; foreign-object hazards; infrastructure failures; traffic anomalies; long-tail events; real-world recordings; safety-critical AI; computer vision for safety.

INTRODUCTION

Human drivers and driving automation systems alike must be able to recognize and respond appropriately to an open-ended set of road hazards. Driving automation here encompasses both advanced driver assistance systems (ADAS) and autonomous vehicles.

While proper behaviors in routine driving are well defined through traffic rules—such as obeying speed limits, maintaining safe following distances, and complying with traffic signals and other traffic control devices—real-world driving involves an infinitude of exceptional and rare situations that lie beyond these simple rules. Examples include unexpected obstacles, erratic or misbehaving road users, malfunctioning vehicles or infrastructure, crashes, and sudden hazardous environmental conditions.

Recent incidents involving partially automated vehicles and robotaxis further illustrate the challenge of handling rare hazards in practice. These systems have failed to anticipate, recognize, and properly respond to a collision among other road users [1], have collided with unusual road debris [2], and have continued driving over downed power lines

[3] or even a pressurized water hose deployed by emergency responders [4]. It also remains uncertain how current systems would respond to similarly uncommon but high-risk situations, such as a flooded roadway, a collapsed bridge, an overloaded vehicle ahead, a fishtailing trailer ahead, or a dump truck approaching an overpass with its bucket raised.

Human drivers rely on their general perceptual and reasoning capabilities to interpret such situations and determine a suitable response. Although their reactions may not always be optimal, the behavior of a licensed, alert, and unimpaired driver provides an important reference standard for assessing reasonable responses to road hazards—often referred to as the "reasonable person" standard in legal contexts [5].

The open-ended nature of possible road hazards presents a major challenge for the design and assurance of driving automation systems. It is impossible to anticipate all possible hazards in advance in order to design systems that can respond appropriately to each of them. A practical approach is therefore to identify broad categories of hazards and to build systems capable of handling representative cases within these categories. The aim is to systematically capture and categorize reasonably foreseeable hazards, assess their associated risks, and ensure that driving automation systems respond safely to them. While it may never be possible to enumerate all hazards in advance, the best achievable outcome is to establish a methodical process to elicit and organize them—both during system design and throughout operation.

This work introduces GOBI, a hybrid Guideword- and Ontology-Based method for road hazard Identification and analysis. The method applies a curated set of edge-case guidewords (e.g., unmarked, unusual, malfunctioning, confusing, illegal, oversize, extreme) to the entities of a detailed road-environment ontology—including road infrastructure, traffic participants, foreign objects, and environmental conditions—to systematically generate candidate hazardous conditions. The method operates in two complementary directions. Top-down, it analyzes guideword–entity combinations to hypothesize abstract hazard categories that capture deviations from normative conditions. Bottom-up, it searches for concrete instances of these hazards in real-world, crowd-sourced traffic recordings and uses these observations to validate, refine, and expand the hazard set. The interplay between these deductive (rule-based generation) and inductive (evidence-driven expansion) steps yields a structured, extensible, and evidence-grounded taxonomy of road hazards suitable for driving automation safety analysis and dataset construction.

This paper further complements the GOBI method by providing a hazardous-conditions catalog instantiated with real-world evidence. Each hazardous condition identified through the top-down guideword–ontology analysis is grounded in publicly available video or image recordings (e.g., dashcams, infrastructure-mounted cameras, handheld footage). These recordings serve as concrete exemplars of rare or unusual events, enabling verification of hazard definitions, refinement of taxonomy structure, and discovery of additional hazardous conditions and ontology elements not captured in initial top-down analysis. The resulting catalog thus not only enumerates hazardous conditions but anchors them in real incident data, illustrating how they manifest, how they interact with surrounding traffic, and why they are relevant for the design, testing, and assurance of driving automation systems.

By integrating a systematic hazard-elicitation methodology with an evidence-based library of real traffic recordings, GOBI provides a practical foundation for developing, evaluating, and benchmarking perception, prediction, and decision-making capabilities of automated driving systems—particularly in the long tail of rare but safety-critical scenarios that challenge current technologies.

Summary of Contributions. This paper makes the following contributions:

1. **GOBI: A Hybrid Guideword- and Ontology-Based Hazard Identification Method.** A systematic approach combining structured guidewords with a detailed road-environment ontology to generate and organize candidate hazardous conditions.

2. **A Comprehensive Catalog of Hazardous Road Conditions.** Over 300 hazardous conditions derived from the ontology and guidewords, each refined through hazard analysis and augmented with real video exemplars instantiating them.

BACKGROUND AND RELATED WORK

Hazard Identification and Analysis Methods

A variety of hazard identification and analysis methods have been developed across safety-critical domains, each with different assumptions about the nature of hazards and the information available during system development. Preliminary Hazard Analysis (PHA)—also referred to as preliminary safety analysis—is widely used in the concept phase of systems in the chemical process industry, oil and gas, and aerospace [6], [7]. PHA typically focuses on identifying inherent, external, or domain-specific hazards, such as flammable materials, high-pressure systems, or geophysical events. The identification process is often keyword-driven, relying on standard lists of known hazards. While PHA is similar to GOBI in aiming to identify high-level or external hazards independent of system design details, it does not include a deductive step that systematically combines an environmental ontology with guidewords.

Hazard and Operability Study (HAZOP) [8] is another guideword-driven method and, like GOBI, includes a deductive component in which guidewords, such as less, more, late, early, and none, are applied to system elements to generate deviations. However, HAZOP is fundamentally a design-centric method: it applies guidewords to process parameters or system design representations, not to a structured ontology of the external environment. Moreover, GOBI employs a broader and more diverse set of guidewords tailored to environmental variability rather than process deviations.

System-Theoretic Process Analysis (STPA) [9] identifies unsafe control actions and emergent hazardous behaviors within a control structure. In the context of autonomous driving, STPA focuses on unsafe actions or inadequate feedback involving the driving automation system. GOBI is complementary: it can be applied prior to STPA to identify external environmental hazards and potential unsafe road-user behaviors that may later trigger unsafe control actions, which can then be analyzed more deeply using STPA.

Other widely used safety analysis methods such as Failure Modes and Effects Analysis (FMEA) [10] and Fault Tree Analysis (FTA) [11] focus primarily on internal failures of system components, software modules, or hardware subsystems, using design, implementation, and operational information. Their purpose is fundamentally different from GOBI's: they analyze internal failure mechanisms, whereas GOBI focuses on identifying external environmental hazards that arise from road conditions, infrastructure, and other road users.

Industry Standards on Hazard Identification and Analysis for Driving Automation

A number of industry standards address hazard identification and analysis for advanced driver assistance systems (ADAS) and automated driving systems (ADS), each with a different emphasis on internal malfunctions, performance limitations, and environmental factors. ISO 26262 Functional Safety (FuSA) [12] provides a structured framework for identifying and analyzing hazardous events and classifying their risk in terms of severity, exposure, and controllability. Its Hazard Analysis and Risk Assessment (HARA) process focuses primarily on hazards caused by malfunctions of electrical and electronic components, supported by methods such as FMEA and FTA. FuSA thus concentrates on internal, system-induced hazards rather than hazards originating from the external environment.

ISO 21448 Safety of the Intended Functionality (SOTIF) [13] addresses a complementary class of hazards: those arising when a system performs as designed but fails due to performance limitations, environmental complexity, or foreseeable misuse. SOTIF distinguishes between known and unknown unsafe scenarios and emphasizes the discovery of previously unknown risks. It explicitly considers external hazard factors, referred to as triggering conditions, that may degrade perception or decision-making. Although SOTIF provides a limited and non-exhaustive set of example hazards—including several environmental and behavioral triggers—the standard does not supply a systematic method for discovering or organizing the broader space of potential external hazards. STPA is commonly adopted as a method for performing SOTIF's Hazard Identification and Risk Evaluation (HIRE), but its focus remains on control actions and system behavior, rather than comprehensive elicitation of road-environment hazards.

UL 4600 (Standard for Safety for the Evaluation of Autonomous Products) [14] offers extensive lists of hazards relevant to autonomous vehicles and provides guidance for evaluating the completeness of safety cases. While it includes environmental and contextual considerations, its primary focus is on system-related hazards and on the assurance process itself, not on constructing a comprehensive taxonomy of road hazards or the full diversity of rare environmental and behavioral conditions encountered in real-world driving.

GOBI complements these standards by providing a systematic method for discovering and categorizing external hazards—particularly road-environment conditions, infrastructure anomalies, unusual road-user behaviors, and rare events. This makes GOBI especially relevant in the context of SOTIF, where it can support the identification of triggering conditions, hazardous situational factors, and vehicle-level hazardous behaviors that may later be analyzed with STPA or incorporated into SOTIF scenario evaluation and verification activities.

Road Environment Ontologies

GOBI relies on the availability of a road environment ontology, which provides a structured vocabulary for describing the elements, states, and behaviors of the road environment. Such vocabularies are typically organized into layers that stratify elements according to their temporal characteristics and dynamism, including road structure, traffic, foreign objects, and environmental conditions [15], [16], [17]. A road environment ontology also defines semantic relationships among entities—such as generalization hierarchies, part–whole (partonomy) relations, and attributes describing states or behaviors.

Several road-environment ontologies and ontology-like vocabularies have been proposed. These include WISE Drive [16] as well as the structured taxonomies appearing in standards for defining Operational Design Domains (ODDs), such as those from ASAM [18], BSI [19], and ISO [20]. These ontologies are typically represented in natural language, sometimes supplemented with a data schema that constrains how the terms may be instantiated in tools, scenario descriptions, or datasets.

Crowdsourced Camera Recordings of Road Hazards

Publicly available autonomous-vehicle (AV) datasets—such as NuScenes [21] or the Waymo Open Dataset [22]—contain many hours of on-road driving, but they overwhelmingly capture normal, uneventful driving. Crashes and other rare, safety-critical events are largely absent due to the limited duration of these datasets and the extremely low base rate of such events. Even extensive naturalistic driving datasets that span months or years, such as the 100-Car Study, contain only a small number of crashes or serious near-crashes, often on the order of dozens.

In contrast, crowdsourced dashcam recordings offer access to a much richer set of rare and safety-relevant situations. Dashcam usage is widespread—estimated at roughly 30% of vehicles in the United States [23] and 11% in Canada [24]—and drivers routinely share critical events online. Although this content is biased in terms of what is uploaded, the bias strongly favors rare, unusual, and safety-relevant events, including crashes, near-crashes, violations of traffic rules, reckless or illegal behavior by road users, infrastructure failures, roadway obstructions, and hazardous environmental conditions. Such content is often shared to warn others, document incidents, or generate engagement or revenue through viral videos [25]. Dashcam recordings are widely used in practice to reconstruct crashes [26], [27]. Footage from mobile phones and fixed infrastructure cameras available online provides additional coverage of rare events.

Importantly, the bias toward capturing long-tail, safety-critical phenomena aligns with the objective of this work: to systematically explore and categorize rare and potentially hazardous road events that are underrepresented in conventional AV datasets.

Prior research has leveraged crowdsourced videos to support safety assurance of automated driving systems, including extracting test scenarios from crash dashcams [28] and evaluating the abilities of vision-language models to interpret crash videos [29]. In contrast, this work does not focus on isolated collections of crash videos; rather, it aims for the systematic identification and analysis of road hazards, and their grounding in real-world recordings, across a much broader and more diverse set of hazardous conditions than crashes alone.

THE GOBI METHOD

The proposed method consists of five steps (Figure 1). It begins with *road-traffic system ontology development*, which defines the environmental elements that will later be combined with edge-case guidewords during the *hazard identification* step. Applying these guidewords to ontology elements yields candidate hazardous conditions, which are then examined in the *hazard analysis* step to determine their potential risks, causes, and effects. The subsequent step, *recording search and selection*, aims to identify publicly available video and image recordings that instantiate the hazardous conditions discovered. Finally, the selected recordings undergo detailed *analysis and annotation*. Insights gained through recording search, analysis, and annotation feed back into the ontology and hazard-identification steps, enabling the discovery of additional environmental elements and hazardous conditions in a bottom-up manner, as illustrated by the dashed arrows in Figure 1. The following subsections describe each step in more detail.

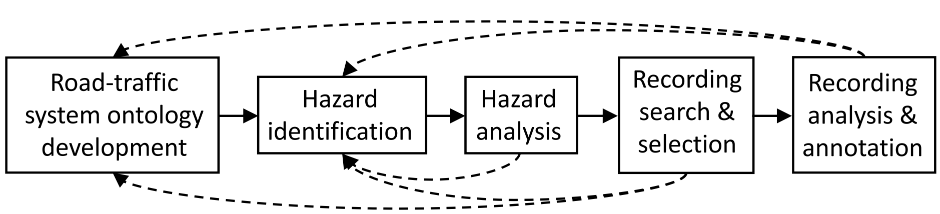


Figure 1: Overview of GOBI.

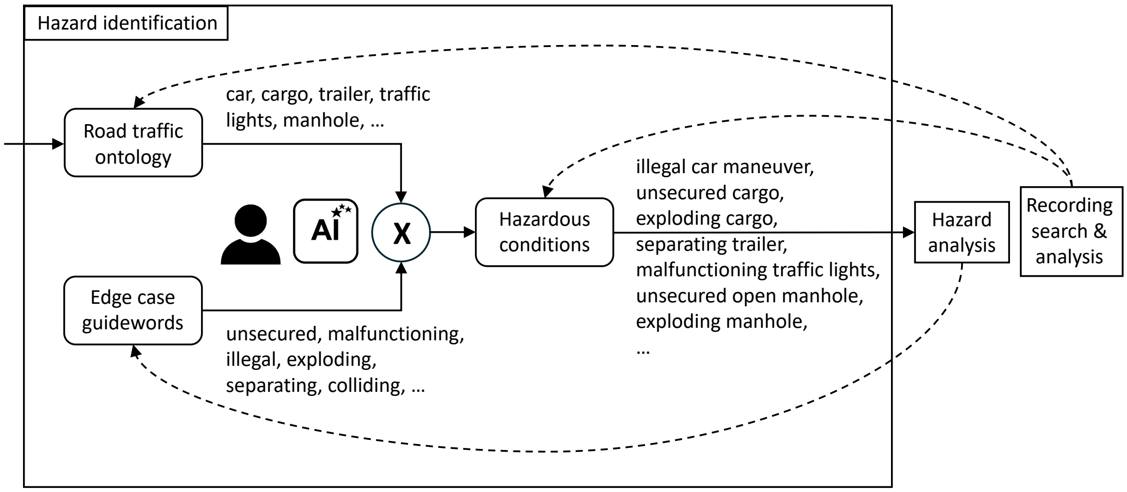


Figure 2: Hazard identification.

Road-Traffic System Ontology Development

The first step in GOBI is the development of an ontology that identifies the elements present in the operating environment of a vehicle equipped with driving automation. An ontology consists of terms, referred to as *entities*, together with their properties, relationships, and definitions of their semantics. Common relationships include generalization and partonomy. Ontologies may vary in their degree of formality; for practical purposes, definitions are typically stated in natural language, while the structural aspects can be captured using a schema definition language such as XML or JSON Schema to facilitate structured annotation of video and image recordings. Practical recommendations for ontology development and representation are available elsewhere [30].

GOBI focuses on hazards external to the vehicle equipped with driving automation. These hazards can originate in its environment, which includes the road-traffic system and its surrounding systems: the natural, built, and social environment, as well as non-road traffic (e.g., rail and air traffic) that may interact with road traffic. The road-traffic system includes the road infrastructure (roadways, sidewalks, roadside, traffic devices, tunnels, and bridges), road users (road and off-road vehicles, pedestrians, and animals), foreign objects (any objects not normally expected on roadways), and related IT systems. The natural environment includes lighting and weather conditions, bodies of water, wild fires, and geophysical events. The built environment includes buildings and utility poles and lines. The social environment includes social events—such as festivals, protests, unrest, or conditions that increase the likelihood of impaired road users.

Existing ODD standards provide a useful starting point for ontology development (e.g. [18], [19], [20]), but the ontology required for GOBI is typically far more refined and comprehensive than what these standards specify. The method assumes that the ontology is iteratively refined as additional knowledge sources (e.g., road-design and traffic-device manuals) are consulted and as traffic recordings are analyzed. Large language models (LLMs) trained on Internet-scale data are also helpful for identifying additional elements and variants and for extending the ontology.

Hazard Identification

The core of GOBI is *hazard identification* through the application of *edge-case guidewords* to elements of the road-environment ontology (Figure 2). Edge-case guidewords denote deviations from normative conditions (e.g., *malfunctioning*, *illegal*), inherent hazards (e.g., *exploding*, *collapsing*), extreme values (e.g., *extreme*, *speeding*), and rare or unusual conditions (e.g., *unusual*, *rare*). The method assumes a curated list of edge-case guidewords—typically comprising many dozens—that can be extended over time as driving automation systems are developed and operated in the presence of diverse hazardous conditions. Applying these guidewords to elements of the road-environment ontology helps identify hazardous conditions. *A hazardous condition is defined as a driving-scenario condition that creates or increases the risk of a crash or other safety risk (e.g., blocking emergency response), and thus requires recognition and an appropriate response during vehicle operation.*

For example, applying the guideword “exploding” to the ontology element “manhole” yields the hazardous condition

(a) Bouncing manhole cover

(b) Manhole with damaged cover

(c) Vehicle dislodging manhole cover

(d) Unsecured open manhole

(e) Collision with open manhole

(f) Collision with open manhole

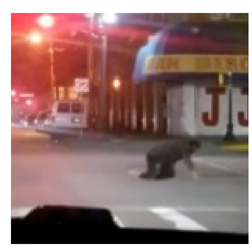
(g) Water surge through manhole

(h) Manhole fire

(i) Manhole fire

(j) Manhole explosion

(k) Multi-manhole explosion



(l) Pedestrian emerging from manhole

Figure 3: Various manhole-related hazards observed in urban environments.

"exploding manhole" (see Figure 2 for additional examples). Not all guideword–ontology combinations are meaningful or relevant within a particular ODD; implausible combinations can be discarded during the combination step and later during hazard analysis. The combination process may be supported by a LLM to assist domain experts, as indicated in Figure 2. Additional hazardous conditions may also be discovered during video and image search and analysis, which can in turn lead to the identification of new edge-case guidewords when analyzing these newly observed conditions (see Figure 3 for manhole explosion and other examples of real-world manhole hazards occurring in urban environments). Existing crash-event typologies (e.g., Model Minimum Uniform Crash Criteria [31]) provide another source of hazardous conditions, including both crash types and their associated pre-crash events or conditions.

Hazard Analysis

The identified hazardous conditions are analyzed to determine their associated risks, causes, effects, appropriate responses, and occurrence likelihood, the latter often being location-specific. For example, manhole explosions create several immediate risks for a vehicle driving over or near the affected area: the vehicle may be overturned, or the manhole cover may be propelled upward and puncture the vehicle floor. A secondary hazard arises when a heavy cover is launched tens of meters into the air and subsequently falls onto traffic. In addition, nearby vehicles may brake or swerve abruptly, creating potential for secondary collisions, and vehicles may collide with an open manhole (see Figures 3e,3f). Manhole explosions are typically caused by flammable gases and particles accumulating within the manhole well, such from smoldering cable insulation [32] or methane from sewers or leaking gas lines. Such explosions are sometimes preceded by visible smoke emanating from the cover vents, potentially for minutes (see Figure 3h). Driving automation should be capable of recognizing these precursor cues, as well as detecting an explosion itself, and should maintain a safe distance from the affected manhole and surrounding traffic. It should also recognize and respond appropriately to falling manhole cover and open manhole hazards, which follow a manhole explosion. The likelihood of manhole explosions may be higher in certain areas, such as urban roads containing aging utility infrastructure. For example, the New York City Fire Department had nearly 4,000 dispatches for manhole explosions between 2009 and 2018 [33]. Appendix C includes a sample hazard analysis page for "manhole explosion".

Traffic Recording Search and Selection

An analyzed hazardous condition triggers a search for publicly available recordings that exemplify it. Such recordings may include images or videos captured by a variety of camera types, including dashboard cameras (dashcams), infrastructure-mounted cameras, doorbell cameras, drone cameras, rider-mounted cameras, and handheld cameras. The search may rely on general Internet search engines or on dedicated social media platforms that host dashcam content (e.g., ViralHog or Reddit's dedicated dashcam communities). Crafting effective text-based search queries often requires iterative refinement to surface relevant content, especially when using general-purpose search engines. Approximate reverse-image search can be highly effective for finding visually similar content once an initial exemplar is available; the initial image may also be generated using generative AI from textual descriptions to bootstrap the search process.

The identified recordings must be verified as authentic (i.e., not deepfakes), for example by cross-checking with independent sources such as news media reports. The search process frequently uncovers related recordings that may instantiate other hazardous conditions, including both previously identified conditions and entirely new ones.

Traffic Recording Analysis and Annotation

The selected videos must be analyzed to determine their origin, the general traffic conditions present, all applicable hazardous conditions, and any additional events or contextual factors relevant to those hazards. This information is captured using a structured annotation schema derived from the road-traffic ontology. An excerpt of such an annotation for the video in Figure 4 is shown in Figure 5, which serves as a running example throughout this subsection.

The annotation schema organizes information into several sections. The first section, *metadata*, captures contextual information such as location, date, and time of the recording. As illustrated in Figure 5, the metadata identifies the recording as a dashcam video from Burlington, Ontario, taken on May 26, 2020, on the eastbound QEW approaching Fairview Street. Establishing the precise location and time often requires consulting news media, matching landmarks visible in the video, or comparing the scene to online mapping platforms. The metadata also records the camera type ("dashcam") and other camera characteristics—information critical for understanding the viewpoint and potential visibility limitations.

The second section, *recording-wide conditions*, describes environmental and contextual properties of the scene,

Figure 4: Keyframes of dashcam video showing tire blowout, vehicle losing control, and veering into opposite traffic.

```yaml
is_a: road traffic video
annotation_level: basic
metadata:
  country: Canada
  state_or_province: Ontario
  city: Burlington
  street_address: eastbound QEW approaching Fairview St (towards Toronto)
  geocoordinates: 43.319369, -79.813935
  year: 2020
  month: "05"
  day: "26"
  time: daytime
  source:
    source_url: https://www.youtube.com/watch?v=KmZWxvu-WcY
  note: "In May 2020, the Ontario Provincial Police (OPP) investigated ..."
  camera_info:
    framing_type: wide-angle
    camera_location:
      - type: dashcam
        view: front view
applicable_hazardous_conditions:
  - ["tire_blowout", ["11.01s", "13.67s"]]
  - ["damaged_vehicle_in_traffic", ["11.01s", "14.58s"]]
  - ["dust_obscuration", ["11.01s", "14.58s"]]
  - ["foreign_object_hazard", ["11.11s", "14.41s"]]
  - ["vehicle_part_separation", ["11.44s", "13.67s"]]
  - ["vehicle_losing_control", ["11.21s", "14.58s"]]
  - ["uncontrolled_moving_vehicle", ["11.21s", "14.58s"]]
  - ["vehicle_veering_into_oncoming_traffic", ["11.21s", "14.58s"]]
  - ["emergency_evasive_maneuver", ["12.01s", "14.58s"]]
  - ["vehicle_collision_with_fixed_object", ["13.41s", "14.36s"]]
  - ["vehicle_crossing_median_or_centerline_unintentionally", ["13.41s", "14.58s"]]
recording_wide_conditions:
  lighting: daylight
  atmospheric:
    - few clouds
    - no obscuration
  driving_side: right
  road_function: freeway
  zone: suburban
  horizontal_alignment: tangent
  vertical_alignment: level
  abbreviated_cross_section: divided multi-lane
  relation_to_junction: non-junction
  road_surface_type: asphalt
  road_surface_condition: dry
  pavement_marking_visibility: high
  vehicular_traffic_density: moderate
  pedestrian_traffic_density: no traffic
```


Figure 5: Example YAML annotation of video from Figure 4 (excerpt).

such as lighting, weather, road function, surface condition, pavement marking visibility, and traffic density. In Figure 5, the recording-wide conditions specify daylight, few clouds, a dry asphalt surface, a divided multi-lane freeway, and moderate traffic. These descriptors parallel environmental attributes used in national crash databases (e.g., NHTSA [31]), enabling consistency with established reporting practices.

A third section, *applicable hazardous conditions*, lists the hazardous conditions instantiated in the recording, together with their corresponding time intervals in the video. For example, the annotation in Figure 5 includes hazards such as `tire_blowout`, `vehicle_losing_control`, and `vehicle_veering_into_oncoming_traffic`, each associated with specific timestamps indicating when the condition becomes visible or relevant to vehicle behavior. These intervals allow downstream analyses to relate hazardous events across frames and to study temporal and causal relationships.

A fourth section lists *related elements and events* connected to each hazardous condition, capturing contributing factors and immediate consequences (not shown in Figure 5). In the running example, these include events such as the dust cloud generated by the tire blowout and the truck's subsequent uncontrolled movement across lanes, including its lane position throughout the recording. This section provides detailed attributes for road structure, involved road users, and events.

Although vision–language models (VLMs) can assist in the annotation process—for example, by highlighting candidate events or proposing hazardous-condition labels—skilled human annotators remain essential. Current VLMs frequently misidentify objects, miss important cues, or segment events incorrectly, especially in fast-moving, visually cluttered, or unusual scenarios. Human review ensures the precision and reliability required for safety-critical analysis.

Finally, the annotation and analysis process is inherently iterative. As more videos are examined, new ontology elements or hazardous conditions may be discovered. This necessitates updates to the ontology as well as revisions to previously completed annotations—a process we refer to as *evolutionary annotation*. For instance, encountering a truck tire blowout in Figure 5 may prompt the addition of new subclasses of vehicle-part failures or refinements to the taxonomy of loss-of-control events, which may then require re-examining earlier annotated recordings for consistency.

RESULTS

GOBI was executed to construct a catalog of hazardous conditions together with recordings that instantiate them. The effort began with the WISE Drive ontology [16], which served as the initial structure for representing elements of the road-traffic environment.

At the current stage, over 347 hazardous conditions have been identified (see Appendix B for the full list). The catalog is supported by a growing multimedia dataset that includes 893 videos and 344 images, mostly from the US and Canada, illustrating specific hazardous conditions. Approximately one hundred hazardous conditions were identified during the initial top-down pass, in which edge-case guidewords were systematically applied to ontology elements. This process was supported by GPT-4 and GPT-5, which assisted in generating candidate hazardous conditions and producing initial drafts of hazard analyses (such as in Appendix C). The remaining hazardous conditions emerged through bottom-up discovery as relevant or related recordings were found and analyzed, leading to the iterative expansion of the catalog. Appendix A provides the full lists of edge-case guidewords that were curated throughout the process.

The road-traffic system ontology and the hazardous condition catalog are defined using Markdown documents with YAML front matter to specify semantic relationships such as `is_a` (cf. Appendix C). This representation enables convenient browsing and querying within Obsidian, a note taking tool, including automatic generation of lists of videos that instantiate a given hazardous condition. A JSON Schema derived from the ontology defines the annotation format for recordings, ensuring structured and consistent representation. All recordings and their annotation files are stored in a Git repository, enabling version control, collaborative editing, and traceability as the ontology and hazardous-condition catalog evolve.

DISCUSSION

The likelihood of encountering any given hazardous condition is highly location-dependent. For example, people riding on top of a car or van may be relatively common in parts of South-East Asia and Africa, yet such behavior constitutes an edge case in North America and Europe. This geographic variability highlights the importance of contextualizing hazardous conditions with respect to the operational design domain (ODD) in which driving automation is deployed.

The widespread availability of dashcam videos on public platforms introduces a beneficial bias for edge-case discovery. Because unusual, hazardous, or surprising events are more likely to be shared and to attract attention, online dashcam collections disproportionately contain rare situations that are highly valuable for constructing an edge-case catalog. The sheer number of human drivers and privately operated dashcams far exceeds that of any individual automated driving fleet, allowing exposure to a vastly broader range of real-world phenomena than could be captured through controlled testing or fleet-based data collection alone.

There exist many possible ways to decompose or name hazardous conditions, just as ontologies themselves may be organized in multiple valid ways. The specific form of the taxonomy is therefore less important than its coverage—namely, that it accounts for all reasonably foreseeable road hazards relevant to the intended ODD. A recurring tension arises between introducing increasingly specialized hazardous-condition categories and maintaining more general categories augmented with attributes. For example, the current ontology contains many subclasses of foreign-object hazards, reflecting the diversity of conditions observed in real recordings.

Ideally, development of the hazardous-condition catalog should be an ongoing process. Future tooling could support automated ingestion and classification of large media collections, including dashcam videos, and could propose new annotations or ontology extensions as novel hazardous conditions are identified. Such tooling might also search the Internet proactively to discover emerging road hazards, enabling continuous expansion of the catalog.

A key challenge is determining which hazardous conditions should be handled by automated driving systems. The "reasonable person" standard offers guidance [5]: if a condition is reasonably foreseeable and can be handled by a skillful, alert, unimpaired human driver, then an automated vehicle should be expected to handle it at least as safely. Recent incidents involving current-generation robotaxis—such as difficulties with recognizing pressurized water hoses, downed power lines, or flooded roads—demonstrate the limitations of existing systems when confronted with unexpected or rare conditions. Many of the more than 300 hazards identified to date would likely pose significant challenges to current deployed systems. The resulting catalog is therefore valuable not only for future development of more capable AI systems but also for regulatory bodies, which may require manufacturers and operators to assure proper behavior under the conditions represented in the catalog.

A further challenge concerns the assessment of risk for prioritizing which hazardous conditions should be addressed during driving automation development. Risk combines likelihood and severity, and both components are difficult to estimate for open-world hazards. The likelihood of a hazardous condition—its exposure—varies substantially by geographic region, and for many rare pre-crash conditions, population-level statistics are unavailable. In practice, estimating exposure may require expert judgment and coarse classification into likelihood categories, similar to the approach taken in ISO 26262 HARA. Assessing the conditional likelihood of outcomes given a hazardous condition is equally challenging: the actual risk depends on the specific scenario context, necessitating the decomposition of each hazardous condition into more concrete variants. Similar issues arise when estimating severity. While the severity of specific recorded crash scenarios can often be approximated—directly or via proxies such as delta V [34]—assigning severity to abstract hazardous conditions is difficult without further assumptions to instantiate the scenario. Addressing these methodological challenges in systematic risk quantification is an important direction for future work.

LIMITATIONS

The list of edge cases produced by GOBI is inherently open-ended. Although higher-level categories are more likely to encompass specific instances—and a systematic taxonomy derived from road-environment elements increases this coverage—the catalog remains incomplete. Its usefulness depends on continued curation and extension over time as new conditions are discovered.

Most hazardous conditions identified to date are instantiated from scenarios involving human drivers. While hazardous conditions specific to driving automation certainly exist, the primary failure mode targeted by this work concerns scenarios that were not accounted for during the development of automated driving systems, causing these systems to be unable to recognize or otherwise properly handle them. Data collected by any single fleet is unlikely to span the long tail of rare events captured across the much larger population of human drivers equipped with dashcams.

Another inherent limitation arises from the use of single-camera recordings (e.g., dashcams, doorbell cameras, handheld recordings). Such cameras provide only a partial view of the scene, and access to a full 360-degree perspective could alter the interpretation of certain events or reveal contributing factors not visible in the available footage.

Finally, the frequency of hazardous conditions in the collected media does not necessarily reflect their prevalence in the real world. While the dataset contains meaningful signals, some types of events are disproportionately easy to find—such as car surfing or skitching—whereas others are rarely captured, such as experiencing an earthquake while crossing a bridge. As a result, the dataset should not be interpreted as a statistical representation of hazard frequencies but rather as a repository of qualitatively diverse and illustrative edge cases that are grounded in reality.

CONCLUSIONS

GOBI was introduced as a hybrid method for identifying and analyzing hazardous conditions in the road-traffic environment. The method combines a deductive, guideword-driven approach anchored in a structured ontology with a bottom-up process grounded in real-world recordings. This dual strategy enables the systematic discovery of hazardous conditions and the construction of a catalog that is both comprehensive and empirically rooted.

By leveraging publicly available dashcam and other online video sources, GOBI facilitates the identification of hazardous conditions that are too rare to be reliably captured in any single field data collection campaign. The resulting work includes not only the GOBI framework but also a catalog of more than 300 hazardous conditions, accompanied by real-world video exemplars, providing a unique and practical resource for research, development, and assurance of driving automation systems.

Future work includes the development and benchmarking of AI models capable of interpreting these recordings—specifically, detecting hazardous and related conditions, reasoning about them, and proposing appropriate responses. Additional research is also needed to automate aspects of dataset curation, including tools to ingest large media collections and systems that can continuously search the Internet to discover novel hazardous conditions. Such advances would support the ongoing evolution of the catalog and contribute to improving the robustness and safety of driving automation systems.

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APPENDIX A: EDGE-CASE GUIDEWORDS

- abandoned
- abnormal
- aggressive
- blinding
- blocked
- burning
- collapsing
- complex
- conflicting
- confusing
- contaminated
- crash involved
- damaged
- dangerous
- disabled
- disastrous
- disloged
- detaching
- disoriented
- disregarding
- distracted
- dragging
- drifting
- drowning
- ejected
- emergency related
- erratic
- exotic
- exploding
- extreme
- failing
- falling
- fatigued
- fishtailing
- flooded
- foreign
- heavy
- highly complex
- highly dynamic
- highly vulnerable
- illegal
- impaired
- improper
- inherently hazardous
- leaking
- malicious
- massive
- misleading
- misplaced
- missing
- near crash involved
- negligent
- obscured
- obstructed
- out of context
- oversize
- overturning
- panicked
- poorly visible
- pranking
- protruding
- racing
- raised
- runaway
- rare
- separating
- sharp
- smoking
- sparking
- speeding
- spraying
- striking

- stunt performing
- sudden
- surprising
- swaying
- threatening
- throwing
- too close
- trapped
- unaware
- unclear
- uncontrolled
- unfamiliar
- unique
- unmarked
- unpredictable
- unprotected
- unsafe
- unsecured
- unstable
- unsupervised
- unusual
- urgent
- vandalized
- veering
- violent
- vision restricted

APPENDIX B: LIST OF HAZARDOUS CONDITIONS

Environment

Atmospheric conditions
- dust obscuration
- severe aerosol cloud
- heavy rain
- severe fog
- severe hail storm
- severe rain storm
- freezing rain
- severe smoke
- snow storm
- strong wind
- tornado
- vehicle tire spray
- whiteout
- drifting snow
- blowing snow

Built environment condition
- building collapsing
- partially collapsed building
- crane collapsing
- debris falling from structure
- gas explosion
- sewer break
- utility pole falling on road
- overhead sign or signal support falling on road
- water main break

Geophysical conditions
- earth tremors
- flood
- landslide
- rockslide
- mud spray
- lava flow
- lightning strike
- sinkhole
- vehicle falling into sinkhole
- snow avalanche
- volcanic eruption
- wild fire

Lighting conditions
- sun glare
- headlight glare
- malfunctioning streetlights

Social environment condition
- demonstration
- mass event
- violent mob
- SWAT action

Foreign Objects

Foreign object hazard
- foreign object hazard
- foreign material hazard
- vehicle to foreign object collision
- driving over foreign object debris
- tree falling on road moving foreign object hazard
- debris falling on traffic
- lost cargo
- cargo spill
- contaminated road surface
- dangerous good spill
- tire puncture spike strip on roadway
- downed power lines
- pressurized water hose on roadway
- vehicle entanglement
- detached vehicle parts
- rolling detached vehicle wheel

Road

Bridge conditions
- road bridge collapsing
- bridge collapsing on road
- bridge movement in high winds
- collapsed road bridge
- collision with bridge overhead structure
- collision with bridge pier or support

- collision with bridge rail
- debris falling from bridge
- ice bombs from bridge structure
- spray over bridge in high winds
- vehicle cargo falling from bridge
- vehicle fall from bridge
- wind overturning vehicle on bridge
- wind swaying vehicle on bridge
- road users trapped on rising drawbridge
- mechanical failure of bridge locks

Cycling facility conditions
- obstructed or blocked bike lane
- inadequate separation from motor vehicles

Junction conditions
- interchange with exit left
- interchange with exits left and right
- interchange weaving area
- intersection with complex lane guidance
- complex roundabout
- entrapment between railroad level crossing gates
- vehicle stuck over raised railroad level crossing

Manhole conditions
- bouncing manhole cover
- manhole with damaged cover
- manhole with partially dislodged cover
- collision with open manhole
- manhole cover blow off
- manhole explosion
- manhole fire
- pedestrian emerging from manhole
- unsecured open manhole
- vehicle dislodging manhole cover
- water surge through manhole

Pavement markings
- faded lane marking
- confusing or conflicting lane marking
- slippery marking when wet
- overlapping or excessive marking

Road surface conditions
- pavement art hazard
- surface irregularity interaction
- road surface damage
- road surface under construction

Roadside conditions
- static occlusion
- blocking sidewalk
- vehicle collision with fixed object
- motorcyclist collision with fixed object
- pedalcyclist collision with fixed object
- vehicle falling off roadside

Temporary road structure conditions
- roadblock
- unmarked construction site
- yellow caution tape spanned over roadway
- loose or misaligned steel plates
- confusing or misleading temporary pavement markings
- improper or misplaced temporary signage
- poorly marked or unlit temporary detour
- wet or slippery temporary surfaces
- weight restricted temporary structure
- vehicle collision with temporary traffic control device

Traffic sign or signal conditions
- obstructed stop or yield sign
- missing or damaged warning sign
- confusing or conflicting signs
- malfunctioning traffic signal
- faded or poorly illuminated sign
- vandalized sign
- excessive signage
- improperly placed or misleading sign

Tunnel conditions
- inadequate tunnel lighting or sudden transition
- poor tunnel air quality
- tunnel congestion blocking emergency access
- flooding inside tunnel
- smoke inside tunnel
- fire or explosion in tunnel

Weather-related road surface conditions
- aquaplaning
- extreme leaf accumulation
- extreme snow accumulation
- icy road surface
- road surface water pooling

Traffic

Air traffic conditions
- airplane emergency landing on road
- airplane crashing on road
- airplane colliding with road users
- airplane blocking traffic
- airplane fire or explosion
- airplane collision with fixed object
- balloon landing on road
- balloon crashing on road
- drone crashing on road
- paraglider landing on road
- rocket falling on road
- skydiver landing on road

Animal conditions
- large animal on road
- large animal entering vehicle path
- vehicle animal collision
- exotic animal on road
- dead animal on roadway
- bird strike
- animal attacking vehicle

Animal drawn vehicle conditions

- vehicle spooking animal drawing vehicle
- animal drawn vehicle moving with no driver
- vehicle to animal drawn vehicle collision

Animal rider conditions
- vehicle passing animal rider too closely
- vehicle spooking ridden animal
- animal throwing off rider
- vehicle to animal rider collision

Cycle and personal mobility device conditions
- pedalcyclist with unusual cargo
- vulnerable road user clothlined
- vulnerable road user losing balance
- potentially unstable pedalcyclist
- pedalcyclist losing balance
- motorcyclist losing balance
- object falling on pedalcyclist
- object falling on motorcyclist
- skitching
- vehicle to pedalcyclist collision
- pedalcyclist to pedalcyclist collision
- motorcyclist to motorcyclist collision
- vehicle to motorcyclist collision
- collision with parked motorcycle
- vehicle to personal mobility device rider collision

Emergency vehicle conditions
- emergency vehicle speeding with active signal
- emergency vehicle with active signal blocked by traffic
- vehicle failing to yield to emergency vehicle with active signal
- vehicle following emergency vehicle with active signal
- police vehicle chasing another vehicle
- emergency vehicle stopped in active lane
- vehicle improperly overtaking emergency vehicle
- emergency vehicle passing intersection with conflicting traffic
- vehicle panic braking due to siren

Pedestrian conditions
- child dashing onto roadway
- child playing on roadway
- costumed pedestrian on roadway
- disabled pedestrian on roadway
- elderly pedestrian on roadway
- pedestrian using pogo stick on road
- pedestrian using stilts on road
- impaired pedestrian on roadway
- pedestrian darting into vehicle path
- pedestrian crossing on do not walk signal
- pedestrian emergency
- pedestrian in unusual location on road
- pedestrian in unusual pose on roadway
- pedestrian involved in vehicle crash
- pedestrian pranking autonomous vehicle
- pedestrian throwing object on traffic
- pedestrian transporting unusual object on roadway
- pedestrian violence
- small child on roadway
- unusual grouping of pedestrians
- vehicle pedestrian collision
- pedestrian underride entrapment and dragging
- failure to notice traffic person
- unclear signalling by traffic person
- disregard for traffic person

Railed vehicle conditions
- vehicle blocking streetcar tracks
- streetcar to vehicle collision
- train to vehicle collision

Towed vehicle conditions
- towed vehicle fishtailing
- towed vehicle separation
- runaway separated towed vehicle

Trailer conditions
- trailer separation
- separated trailer
- trailer fishtailing
- vehicle trailer collision

Truck conditions
- tanker leaking cargo
- cement mixer drum separation
- snowplow spray on traffic
- dump truck with raised bucket
- mobile crane with raised arm
- snowplow blade collided with obstacle
- snowplow blade snapped down

Vehicle conditions
- airborne vehicle following crash
- vehicle spinout
- vehicle losing control
- uncontrolled moving vehicle
- dump truck driving with raised bucket
- mobile crane driving with raised arm
- damaged vehicle in traffic
- disabled vehicle in active lane
- disabled vehicle on freeway shoulder
- distracted driving
- driver abandoning moving vehicle
- driver abandoning vehicle in traffic
- dynamic occlusion
- emergency evasive maneuver
- emergency braking maneuver
- emergency reversing maneuver
- cut-out reveal hazard
- erratic driving
- vehicle driver incapacitated
- vehicle fall on road
- vehicle fall on traffic
- vehicle fire or explosion
- vehicle immersion
- vehicle overturn or rollover
- overturned vehicle sliding
- vehicle part separation
- vehicle skidding
- vehicle with windshield obstructed by contamination
- vehicle with ice or snow accumulation

- vehicle with ice or snow separating
- slow moving vehicle
- tire blowout
- vehicle generating friction sparks
- unusually looking vehicle
- vehicle collision with overhead structure
- high clearance vehicle approaching low clearance structure
- vehicle crossing median or centerline unintentionally
- vehicle veering into oncoming traffic
- hood of moving vehicle opening
- vehicle cruising with open hood
- brake failure
- vehicle downhill runaway
- runaway vehicle using escape ramp
- highly vulnerable rider
- pedestrian attempting to enter moving vehicle
- person jumping from vehicle
- jackknife
- object falling on vehicle
- occupant ejection
- oversize vehicle
- oversize vehicle encroaching into oncoming lane
- rider ejection
- animal ejection
- vehicle drifting out of lane
- road departure
- vehicle tipping sideways
- vehicle leaking fuel
- vehicle driving with open fuel tank
- vehicle driving with fuel hose in tank opening
- post crash vehicle movement

Illegal vehicle maneuvers
- running red light
- illegal u turn
- passing with insufficient clearance
- passing in no passing zone
- passing on shoulder
- overtaking on shoulder
- cutting in
- brake checking
- failure to yield at stop sign
- failure to yield during left turn
- failure to yield during right turn
- failure to yield to vehicle in intersection
- failure to stop at stop sign
- failure to brake for traffic ahead
- blocking intersection
- vehicle blocking on-ramp
- speeding
- motor vehicle lane splitting
- cutting across multiple lanes
- cutting across multiple lanes causing collision
- lane change causing collision
- lane changing across exit neutral area
- lane changing across entry neutral area
- driving in reverse on freeway
- driving in reverse on arterial
- driving on freeway shoulder
- vehicle driving in parking lane
- overtaking with insufficient gap
- failure to merge onto freeway
- failure to yield to pedestrian in crosswalk
- road rage
- stunt driving
- tailgating
- vehicle straddling centerline
- wrong way driving
- turn into wrong lane
- straight from left turn lane
- straight from right turn lane
- right turn from left turn lane
- left turn from right turn lane
- illegal parking
- blocking crosswalk
- improper backing
- improper lane usage
- failure to signal
- failure to stop for school bus
- racing on public road
- driving on median
- vehicle driving on roadside
- driving on sidewalk
- motor vehicle using bike lane
- uncontrolled vehicle entry into roadway
- entering freeway from roadside

Vehicle collision
- vehicle to vehicle collision
- multi vehicle collision
- multi vehicle pileup
- vehicle underride entrapment and dragging

Vehicle with unsafe cargo
- vehicle improperly transporting animals
- vehicle with dangerous goods
- vehicle with oversized or improperly secured cargo
- vehicle cargo separation
- vehicle cargo shifting
- vehicle with unsafe cargo followed too closely
- cargo obstructing driver vision
- vehicle with unusual cargo

APPENDIX C: HAZARD ANALYSIS: MANHOLE EXPLOSION

Summary

is_a: hazardous manhole condition

Definition: a hazardous condition involving an explosion within a manhole, causing debris, flames, or gases to eject forcefully and posing significant risks to road users.

Synonyms: manhole blast, underground utility explosion

A *manhole explosion* refers to a sudden and violent release of energy within a manhole, often due to gas buildup, electrical faults, or chemical reactions. Such explosions can eject manhole covers and other debris, release flames or hazardous gases, and disrupt traffic flow, creating multiple safety hazards for road users.

Reasons for Increased Risk

- **Flying debris:** Exploded manhole covers and other materials can become high-speed projectiles, striking vehicles, pedestrians, or infrastructure.
- **Flames and heat:** Explosions may release fire, posing burn risks and damaging nearby vehicles and structures.
- **Hazardous gases:** Toxic or flammable gases may be released, endangering road users and emergency responders.
- **Roadway damage:** Explosions can create craters or severely damage the road surface, leaving hazards for vehicles.

Proper Response

<u>*Driver response.*</u> Slow down, anticipate the risk when detecting smoke from a manhole, avoid the affected area, track any blown-off cover, and follow detours or instructions from emergency personnel.

<u>*Automated vehicle response.*</u> Detect smoke from a manhole, anticipate a potential explosion, detect the explosion and its aftermath, track blown-off covers and other debris, reroute to avoid the affected area, and communicate potential hazards to a centralized traffic management system.

Hazards

- **Vehicle damage:** Impact from debris or flames can damage windshields, body panels, tires, and other vehicle components.
- **Overturning hazard:** A blown-off cover may strike the undercarriage and overturn a vehicle.
- **Occupant injury:** Occupants may be struck by debris or injured by heat and gases.
- **Open or damaged manholes:** Vehicles may collide with open manholes with blown-off or damaged covers.
- **Collision:** Sudden avoidance maneuvers may lead to secondary collisions with other road users.
- **Traffic blockage:** The explosion and resulting debris can completely block travel lanes.

Hazard Mechanisms

- **Gas accumulation:** Flammable gases and particulate matter build up and ignite due to sparks or heat from electrical faults or other sources (e.g., methane from sewer systems or damaged gas lines).
- **Electrical faults:** Malfunctioning underground electrical systems generate sparks or arcs, igniting flammable gases.
- **Pressure build-up:** Chemical reactions or surges in underground systems cause rapid pressure increases leading to explosions.

Causes

- **Utility malfunctions:** Faults in electrical, gas, or sewer systems can lead to dangerous conditions underground.
- **Improper ventilation:** Lack of adequate venting allows gas buildup to reach explosive levels.
- **Poor maintenance:** Aging or poorly maintained infrastructure increases the likelihood of incidents. Salt from winter maintenance accelerates corrosion of electrical wires in utility shafts.
- **Extreme weather:** Lightning strikes or heavy rain infiltrating underground systems can contribute to explosions.

Effects

- **Debris hazards:** High-speed projectiles endanger vehicles, pedestrians, and nearby structures.
- **Open roadway hazards:** Explosions may leave exposed open or damaged manholes and utility cavities.
- **Secondary explosions:** Nearby manholes or connected infrastructure may also explode.
- **Traffic disruption:** Significant delays and rerouting may be required due to road blockages.

Risk Amplifiers

- High pedestrian or vehicle density near the explosion site.
- Presence of flammable materials or chemicals in nearby vehicles or structures.
- Nighttime or poor visibility, reducing the ability to identify and avoid hazards.
- Multiple connected manholes, increasing the risk of chain-reaction explosions.

Sample Specialized Conditions

- A smoking manhole emits visible plumes shortly before exploding, causing nearby vehicles to brake or swerve to avoid it.
- A manhole explosion during rush hour in an urban area, ejecting covers and debris that strike multiple vehicles and injure pedestrians.
- A manhole explosion triggered by an underground electrical fault, igniting nearby sewer gas and causing flames to shoot into the air.
- A cyclist is severely injured when an exploding manhole ejects debris into their path, causing a crash.
- A series of manholes connected by underground gas lines explode in sequence, creating widespread hazards and road closures.
- A delivery truck driving over a manhole at the moment of explosion sustains significant undercarriage damage.
- A bus driving over a manhole at the moment of explosion is struck by the blown-off cover, which punctures the floor and enters the passenger cabin.
- A car driving over a manhole at the moment of explosion overturns.
- A blown-off manhole cover falls down and strikes the windshield of a car.