A Context-Specific Operational Design Domain for Underground Mining (ODD-UM)

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Abstract. Autonomous and Semi-autonomous Machines (ASAM) can benefit mining operations. However, demonstrating acceptable levels of safety for ASAMs through exhaustive testing is not an easy task. A promising approach is scenario-based testing, which requires the Operational Design Domain (ODD) definition, i.e., environmental, time-off-day, and traffic characteristics. Currently, an ODD specification exists for Automated Driving Systems (ADS), but, as it is, such specification is not adequate enough for describing the mine nuances. This paper presents a context-specific ODD taxonomy called ODD-UM, which is suitable for underground mining operational conditions. For this, we consider the ODD taxonomy provided by the British Publicly Available Specification PAS 1883:2020. Then, we identify attributes included in the standard ISO 17757:2019 for ASAM safety and use them to adapt the original ODD to the needs of underground mining. Finally, the adapted taxonomy is presented as a checklist, and items are selected according to the data provided by the underground mining sector. Our proposed ODD-UM provides a baseline that facilitates considering the actual needs for autonomy in mines by leading to focused questions.

Keywords: Underground mining · Autonomous machines · Operational design domain · ISO 17757:2019 · PAS 1883:2020 · ODD-UM

1 Introduction

The use of autonomous and semi-autonomous machines (ASAMs) can provide economic benefits in earth-moving and mining operations. However, ASAMs can introduce hazardous situations that are generally not found on non-autonomous sites, due to, e.g., the complexity of the logistics and the interactions between ASAMs, people, and the environment [26]. In addition, determining acceptable levels of safety for autonomous machines through exhaustive testing is not an easy task. For example, to statistically demonstrate with 95% of confidence that

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autonomous cars are 20% better than human drivers, one would have to perform test driving of the autonomous cars for 11 billion miles [14], which in reality will need a large pool of such vehicles operating for many years. This aspect may delay ASAMs integration into the mine planning process. Thus, more appropriate mechanisms to demonstrate safety in autonomous mining should be envisioned.

A promising approach for testing ASAMs is scenario-based testing [21]. Scenarios serve as an interface between: 1) environment and self-perception modules and 2) mission-specific modules and tasks [27]. Scenarios can also serve to confine the scope of the hazard analysis and verification activities [10]. Thus, scenarios need to consider the specific conditions in which the machines are likely to operate to guarantee minimum levels of safety. Autonomy in mining, as prescribed by the standard ISO 17757:2019 [11] and recommended in the guideline for implementation of autonomous systems in mining [9], also considers the provision of operational conditions for safety assessment. However, specific descriptions are not provided. As a result, practitioners shall perform such identification by themselves, at the risk of missing essential aspects.

The ODD (Operational Design Domain), as considered by the standard SAE J3016:2021 [24], should describe the operational conditions for Automated Driving Systems (ADS), e.g., environmental, time-off-day, and traffic characteristics. However, such a definition is too general [1], opening room for diverse interpretations. To close this gap, the British Standards Institute has released the Publicly Available Specification PAS 1883:2020 [4] (input document for the standard ISO/UC 34503 [12]), which proposes an ODD taxonomy that covers the main operational characteristics that are likely to be faced by an ADS. However, the current ODD specification does not capture the mining nuances.

This paper presents a context-specific ODD, called ODD-UM, which is suitable for underground mining operational conditions. For this, we consider the ODD taxonomy provided by PAS 1883:2020, the description of the possible architecture for Automated Vehicles (AVs) to which an ODD will apply, which is provided by PAS 1880:2020 [3], and the standard ISO 17757:2019, which considers safety requirements for ASAMs. Then, we make a parallel between the ASAM architecture prescribed by ISO 17757:2019 and the AV architecture proposed by PAS 1880:2020 regarding a minimum set of requirements conceived for ADS architectures extracted from [18]. After that, we identify the specific operational conditions required for determining the safety risk for ASAMs by analyzing ISO 17757:2019. From such identification, we extract attributes that are used to adapt the original ODD to the needs of underground mining. Finally, an excerpt of the adapted taxonomy is presented as a checklist, and items are selected according to the data provided by the underground mining sector. Our proposed ODD-UM provides a baseline that facilitates considering the actual safety needs of the underground operational conditions, which are essential input for hazard analysis activities by leading to focused questions.

This paper is organized as follows. Section 2 presents essential background information. Section 3 presents ODD-UM, our proposed ODD taxonomy for underground mining. Section 4 presents a case study, where we exemplified the use of ODD-UM. Section 5 presents the discussion of the findings. Section 6 presents related work. Finally, Sect. 7 presents the conclusion and future remarks.

2 Background

2.1 ISO 17757:2019

ISO 17757:2019 [11] provides safety requirements for autonomous and semi-autonomous machines (ASAMs) used in earth-moving and mining operations. The standard considers that work site operators should create an Autonomous Operating Zone (AOZ) at design-time where ASAMs are isolated or interactions with conventional manned machines are managed (see the standard, Annex C). An AOZ (See Fig. 1) is controlled by an access control system, by which monitored non-autonomous machines and persons are able to perform, in a controlled way, activities together with the ASAMs. ISO 17757:2019 also specifies safety criteria for the machines and their associated systems and infrastructure, as well as advice on their safe use in their defined functional environments.

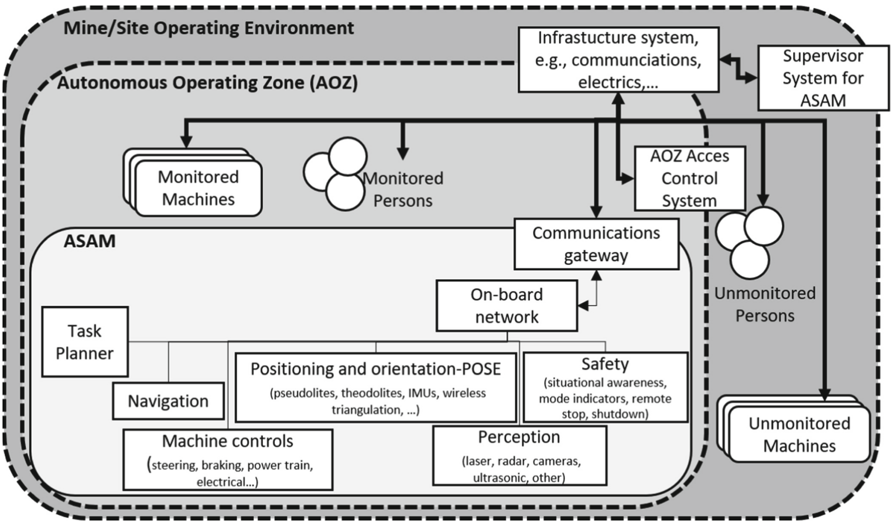

Fig. 1. Main elements in the ASAM system, as adapted by Tiusanen et al. [26]

Supporting infrastructure and operating area requirements should also be identified early in the project, as autonomous systems can have specific needs (e.g., fueling facilities, control rooms, communications network) [26]. Such identification is considered in specific parts of the document. For example, explicit mentions of the operational environment are made in:

- Clause 4.7, as a requisite for the change adaptation.
- Clause 8, as a requisite for navigation systems.
- Clause 9, as a requisite for the task planner.
- Annex B.3, as a prerequisite for risk and safety assessment.

More specific guidelines for building the operational environment can be extracted from specific clauses in the standard (see Table 1).

Table 1. ISO 17757:2019-selected clauses [11]

Clause	Description
Clause 4.3	The machine operating mode shall be indicated (flashing green for manual mode and flashing blue for autonomous mode)
Clause 4.8	Loss of electrical power is a potential source of hazards
Clause 6	Digital Terrain Maps (DTM) can suffer deterioration due to the road or site weathering and altered roads or other site work
Clause 7	The perception of an object can be occluded by dust, fog, snow, rain, or other obscurants. Perception results can also be unreliable due to poor lighting conditions, hidden obstacles, uneven ground, objects moving too fast to be detected, and negative objects (e.g., holes). Other essential characteristics to be considered for perception are the machine characteristics (e.g., speed, visibility, normal operation), the intended operating terrain (e.g., surface, underground, open area, tunnel), and the expected travel path
Clause 9	A task planner is associated with risk related to non-existent or hazardous paths (extracting areas, load areas, dumping areas) and the presence of other ASAM or humans interacting with the ASAM or some clearly defined combination of the two
Clause 10	Communications between the ASAM and the control area, the persons and other vehicles are also present in autonomous mines. Therefore, means shall be provided to deter unauthorized control and spoofing or sabotage of the ASAM systems networks
Clause 11	The ASAM supervisor system could fail if it has incorrect machine parameters
Annex D.1	Access control systems can encompass one or more technologies (e.g., light curtains, laser beams, mechanical guards, physical chains and signs, geofences, video imaging, or tag-based technologies)

2.2 Automated Vehicles and Operational Design Domain

The British Publicly Available Specification PAS 1880:2020 [3] provides an architecture for Automated Vehicles (AVs), which need to comply with defined ODDs as specified in PAS 1883:2020 [4]. Such architecture should encompass a minimum set of elements (see Fig. 2).

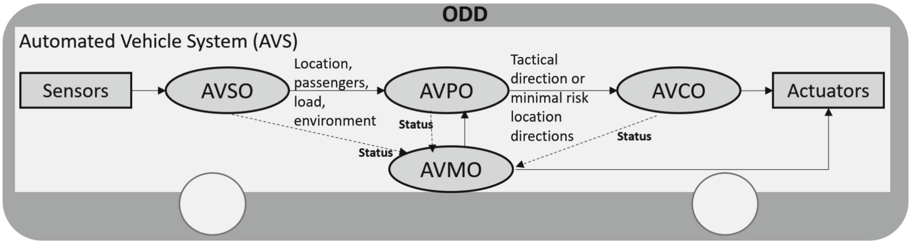

Fig. 2. Possible architecture for an AV control system [3]

In Fig. 2, the AVSO (AV Sensor Operations) should process the sensor data, send it to the AVPO (AV Planning Operations), and supply its status to the AVMO (AV Monitoring Operations). The AVPO should supply the next required vehicle movement (in the form of tactical or minimum risk location directions) to the AVCO (AV Control Operations), supply its status to the AVMO and comply with potential controlled stops requested by the AVMO. The AVCO should direct the next movement to the actuators and supply information about its status to the AVMO. Finally, the AVMO should monitor the AV compliance with the specified ODD and provide a controlled stop in case of a failure.

Entities are encouraged to define and document the Operational Design Domain (ODD) for each AV tested or deployed for use on public roadways [22]. An ODD should describe the operating conditions under which a given driving automation system is designed to function. The ODD taxonomy provided by PAS 1883:2020 provides, at the top level, three main attributes (see Fig. 3), i.e., scenery, environmental conditions, and dynamic elements. Such attributes contain sub-attributes, which are also comprised of sub-attributes.

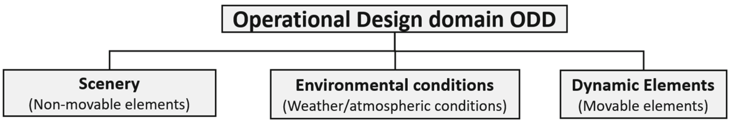

Fig. 3. ODD Taxonomy [4]

The scenery contains a) zone (e.g., geofenced areas, traffic management zones, school zones, region or states, interference zones); b) drivable area (e.g., type, geometry, lane specification, signs, edge, and surface); c) junctions (e.g., roundabouts and intersection); d) special structures (e.g., automatic access control, bridges, pedestrian crossings, rail crossings, tunnels, and toll plaza); e) fixed road structures (e.g., buildings, street lights, street furniture, and vegetation), and f) temporary road structures (e.g., construction site detours, refuse collection, road works, and road signage). The environmental conditions include a) weather (e.g., wind, rainfall, and snowfall); b) particulates (e.g., marine, non-precipitating water droplets or ice crystals, sand and dust, smoke and pollution, volcanic ash); c) illumination (e.g., day, night, cloudiness, artificial); and d) connectivity (e.g., communications vehicle to vehicle and vehicle to infrastructure). Finally, the dynamic elements include a) traffic (e.g., the density of agents, the volume of traffic, flow rate, agent type, and presence of special vehicles); b) subject vehicle (e.g., ability to change lanes, volume of traffic and flow rate).

More levels of attributes exist for some of the sub-attributes. For example, in the drivable area geometry, one sub-attribute (of three) is called horizontal plane, which also has two sub-attributes called straight lines and curves. In addition, the ODD specification is conceived to be used as a checklist, where selected attributes can be expressed in natural language. For example, the fact that the attribute school is selected in the zone attribute is written as *"For zones, we allow school."* The interested reader can find more elaborated examples of the checklist, their textual translation, and details of all the sub-attributes conceived for automated driving operational environments in PAS 1883:2020 [4].

3 ODD-UM: ODD Extension for Underground Mining

3.1 Our Approach

We followed three steps (see Fig. 4) for defining a context-specific ODD addressing underground mining. Initially, we performed a standards comparison. Such comparison is based on the architecture described by ISO 17757:2019 and PAS 1880:2020 (see Sect. 3.2). Such comparison led to the understanding that normative documents are conceptually aligned in their conception of autonomy. As such, the work done in PAS 1883:2020 has significance and can be adopted as a baseline for formulating a context-specific ODD. Then, we determined the original ODD suitability (see Sect. 3.3). From this step, we understood the general differences between both contexts. Finally, we identified the context-specific attributes extracted explicitly from ISO 17757:2019, that are more suitable for the mining context (see Sect. 3.4).

3.2 Standards Comparison

Generalized methods for analyzing safety risks in any system are commonly linked with the architecture of such systems and the context in which they will operate. In particular, for an ADS, the minimum set of components for such an architecture, apart from the interfaces with sensors and actuators, should consider [18]: 1) mapping and localization for handling the localization of vehicle within physical spaces; 2) object recognition for handling the detection and prediction of objects, both static and dynamic, that surround the vehicle; and 3) trajectory planning and control for handling the overall vehicle motion and path planning within the pathways. In this section, we make a parallel between the

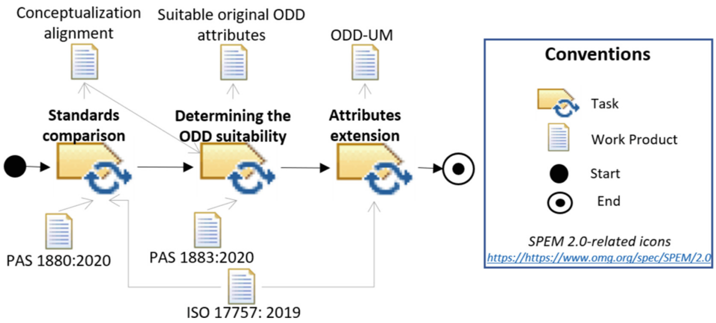

Fig. 4. Approach for the ODD extension for underground mining

architectures proposed by PAS 1880:2020 (presented in Fig. 2) and the architecture for ASAM described in ISO 17757:2019 (presented in Fig. 1 as the innermost square) to expose the similarity of interpretations considered in the two normative documents regarding the minimum set of requirements for an ADS architecture. Such a parallel is presented in Table 2.

As we can see in Figs. 1 and 2, the ASAM and AV should function in a defined operation environment, called AOZ for the former and ODD for the latter. Thus, both documents consider operational conditions that are named differently but fulfil a similar function. However, there are fundamental differences between these two types of environments. For example, the AV is required to do tasks for safe operations in on-road conditions, which have specific conditions that constrain their operation, e.g., weather situations. Moreover, transporting people

Table 2. Comparison between AV and ASAM

Requirements	PAS 1880:2020	ISO 17757:2019
Localization and Perception	AVSO	Elements used to identify the POSE and the perception mechanism
	AVCO	Machine controls and actuators that implement planned actions.
Planning	AVPO	The navigation system and the task planner of the ASAM that are in charge of navigating a predetermined or dynamically determined path and defining the next step of the ASAM.
Control	AVMO	Mechanisms in the ASAM system that are in charge of the management of safety and communications.

is the most common usage of an AV. Conversely, an ASAM is mainly created for transporting heavy materials such as rocks, ore, or waste. Furthermore, the operational environment of an ASAM is naturally constrained by the mine/site conditions, which provides a layer of controllability that is missing for road vehicles. Besides the mine entrance, weather conditions such as rain, are not well suited to describe the operational condition inside the mine, but they can be the source of weather-induced roadway conditions, such as standing water or flooded terrains. These particular characteristics may also restrict the tactical and operational manoeuvres that the ASAM must perform. For example, in an underground mine, the presence of rocks surrounding the roads is a natural constraint that could facilitate the navigation and the route planning of the ASAM since navigation possibilities are limited and easier to perceive. Similarly, it may constrain the provision of safety zones for unprotected persons or special kinds of vehicles that need to enter the zones during emergencies.

3.3 Determining the Suitability of the Original ODD

According to the standard ISO 17757:2019 (recalled in Sect. 2.1), several risks can be caused by the conditions in which the ASAMs operate. In particular, the operational environment is a prerequisite for the design of the navigation system, the task planner, and the change and risk management activities. Thus, there is a need to explain the operational conditions, but there is no concrete specification of how to do it. An analysis performed on different clauses of the standard ISO 17757:2019 shows a correlation regarding the top-level attributes proposed in the ODD taxonomy, i.e., scenery, environmental conditions, and dynamic elements (see Fig. 3). In particular, Clause 6 (see Table 1) refers to the drivable area in which ASAMs would operate when it refers to the deterioration of Digital Terrain Maps (scenery). In addition, Clause 7 mentions the possible causes of risks for perception mechanism, including attributes related to environmental conditions, and as in Clause 6, the drivable area. The same clause also considers machine characteristics (dynamic elements). It also refers to the intended operating terrain and the expected travel path, covering aspects related to zones and other structures (special, fixed, and temporary road conditions). Finally, Clause 10 considers the communications (environmental conditions) as an essential condition for autonomy work. Thus, the original ODD taxonomy has some degree of fitness for describing the operational design domain that ASAMs would encounter in underground mines.

3.4 Attributes Extension

A detailed analysis of the standard ISO 17757:2019 shows domain-specific concepts that can be used to extend the scenery of the original ODD (see elements in grey in Fig. 5). For example, the standard proposes an AOZ, which is the zone that encapsulates the ASAM operations. In particular, an AOZ is *"a designated area in which machines are authorized to operate in autonomous mode."* Thus, AOZs are by-design restricted zones that use specific infrastructure. The standard ISO 17757:2019 proposed two kinds of infrastructure for controlling the access in an AOZ (see Annex D.1 in Table 1): the physical (e.g., mechanical guards, physical chains, and signs) and digital (e.g., light curtains, laser beams, geo-fences, video imaging, and tag-based technologies). This distinction will permit considering their implications, e.g., the use of digital infrastructure requires communication links. Thus, we add a sub-attribute called *infrastructure* in the attribute zone, which includes *physical* and *digital* as its sub-attributes.

In addition, ASAM is a broad definition of automated or semi-automated machines that required *traffic control techniques*, which can be *centralized* or *distributed*. The *allowed traffic* (i.e., monitored and/or unmonitored people and vehicles) is also an essential part of the AOZ. As for the original ODD, the AOZ may also contain interference zones. Therefore, we extend them with specific consideration regarding *communication* and *visual interference*. The drivable area also has some modifications. In particular, the lane specification can be extended with possible travel directions, e.g., *up to down* and *down to up* directions. In the attribute *fixed road structures* we include the kind of working areas that exist in underground mining as described in Clause 9, i.e., *extracting, load, charging, moving, and dumping areas*. As it is common that mines only have one lane to go in both directions, it is important to consider *meeting* zones as well. In addition, we decided to add the sub-attributes *workers crossing* and *emergency exit* to special structures, and *construction work* to temporary road structures.

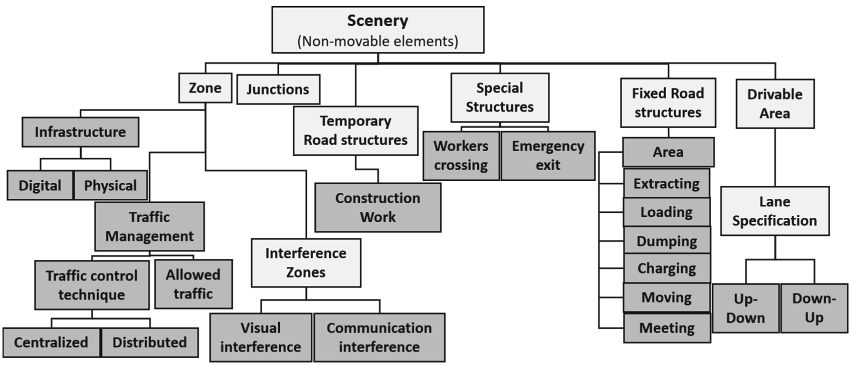

Fig. 5. Additional attributes for the scenery

Regarding the environmental conditions, some extensions are also required (see Fig. 6). In particular, electrical power is not considered in the original ODD taxonomy, but it is considered in Clause 4.8 as an essential condition for the safety of autonomous machines. Thus, we add *electrical supply* as an attribute of the environmental conditions with the two sub-attributes: *charging areas* (for machines that move with the help of battery) and *electrical contact systems* (for trolley trucks). In addition, mechanisms for communication between the supervisor systems and other elements are considered in Clause 10. Such mechanisms are essential to maintain control of the ASAMs and the monitored/unmonitored machines and persons. For this reason, we added a *supervisor system and ASAM* as sub-attributes of connectivity. Finally, there are artificially induced conditions in a mine such as *ventilation* and *tunnel lights* for illumination.

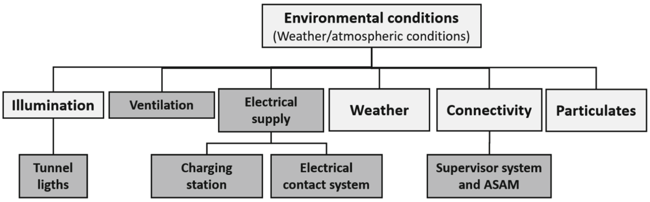

Fig. 6. Additional attributes for the environmental conditions

The supervisor system should also include information regarding the ASAM and other vehicles that are allowed to move inside the AOZ (see Clause 11). For this reason, the attribute "Dynamic Elements" are also extended (see Fig. 7). In particular, in the attribute "Presence of special vehicles", we could consider the most common options such as *road maintenance, road header, concrete truck, and shut down systems (which are a kind of emergency vehicles).* In addition, allowed *maximum speed* and *maximum dimension* for the machines are required for the subject vehicles. The *maximum dimension for the load* is also included since such dimensions could surpass the selling of the mine in the entrance part of the mine or touch the electricity cables installed in the selling of the mine. Clause 4.3. also considers that machines need to indicate their operation mode. Thus, the attribute *Mode-Warning* is extended. Such an attribute could consider the options *flashing green* and *flashing blue*, which are currently indicated by the standard. More specific information related to the machines does not regard the operational design domain and should be created in different documents, which could be referenced in the hazard analysis activity.

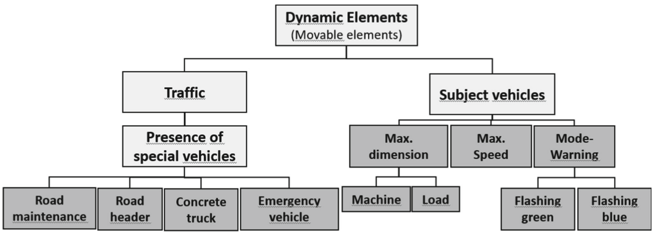

Fig. 7. Extended attributes for the dynamic elements

4 Case Study

The mine site under consideration corresponds to a tunnel aimed at communicating an ore extraction site with gravel storage. The purpose is to maximize the efficiency of material transportation by using autonomous haulers with ensuring safety in the tunnel. Suppliers can provide safety mechanisms at different levels, for example, machine control, machine management, and traffic operation. However, suppliers lack knowledge of the specific aspects of the mine environment. Therefore, an initial step is to provide the baseline characteristics for the envisioned tunnel. Accordingly, a checklist (as also provided in PAS 1883:2020) is designed with the attributes consolidated in Sect. 3. We illustrate the use of the context-specific ODD-UM checklist by considering some of the attributes permitted by our case study (see Table 3).

Table 3. ODD-UM checklist

Attribute	Sub-Attributes		Selection
Zone			
Infrastructure	Digital	Geofence	✓
		Light curtains	
		Laser beams	
		Video imaging	
		Tag-based technologies	✓
	Physical	Mechanical guards	
		Physical chains	
		Signs	
Traffic Management	Traffic control technique	Centralized	✓
		Distributed	
	Allowed traffic	Monitored vehicles	✓
		Monitored Persons	✓
		Escorted unmonitored Person/vehicle	✓
Interference Zone	Communication interference		
	Visual interference		✓
Fixed Road Structures			
Area	Extracting		
	Loading		
	Dumping		
	Charging		
	Moving		✓
	Meeting		✓
Drivable Area			
Lane Specification	Number of lanes		1
	Direction of travel	Up to Down	✓
		Down to up	✓

From Table 3, we extract initial information regarding the conditions that mine operators would consider to be the baseline for the ASAMs operations. In particular, only digital infrastructure, i.e., geofences and tag-based technology, are allowed. In addition, the mine operators consider centralized traffic control and traffic operations beyond the ASAMs, i.e., monitored persons, vehicles and escorting unmonitored persons and vehicles. They also know that only visual interferences (due to rocks) are allowed in the mine. Moreover, the mine operators consider two areas, i.e., moving and meeting areas, in the fixed road structure attribute. Finally, only one lane is allowed for the drivable area. This lane should serve both directions (up to down and down to up).

Our industrial partners fill the checklist with the elements that consider suitable for the tunnel. In their words, instantiating the checklist force them to think in the actual needs of the site and to revise the case. It also leads to focused questions. For example, what is the distance between the areas? How many machines can coexist in the meeting zone? How would ASAMs detect geofences? How do we safely manage the existence of unmonitored people/vehicles? As a result, the filled checklist could serve as a tool for understanding the real conditions of the environment and for brainstorming during risk analysis.

5 Discussion

5.1 Potential Benefits of a Context-specific ODD

From the application of the ODD-UM (see Sect. 4), despite the simplicity of our example, we have identified some points that are worth discussing. Our first observation is the uncomplicated way attributes are presented for selection in a checklist. Checklists are easy to complete and permit a focused selection of characteristics. If necessary, a checklist can also be complemented with additional attributes as required. Second, a properly defined ODD could lead to the definition of operational tactics and manoeuvres. For example, lane switching strategies are unnecessary if the mine only has one lane (as presented in our instantiated ODD-UM). Third, the resulting scenarios extracted from the checklist facilitate considering the actual needs of the specific underground operational conditions that are in focus. For example, utilizing digital infrastructures (such as geofences and tag-based technologies) requires a communication link to centralized control. Failures can occur to such a link causing undesirable consequences. In addition, problems with the surface in a particular terrain could lead to crashes. Thus, the description of the ODD's scenarios can be considered a baseline for performing hazard analysis.

A context-specific ODD helps the systems integrator derive all relevant parts of a scenario, i.e., all relevant dynamic and static elements and such conditions of the environment that may have implications on how the ASAM should behave. Details of the scenarios can be augmented with additional features. For example, what happens if we add laser curtains in the geofenced zone? Moreover, a well-defined ODD provides the interface between the environment and the perception mechanisms included in an ASAM. In that light, extracted scenarios may be part of the requirements included in the contractual specifications between site operators and ASAM's providers. An ASAM working outside such scenarios cannot be considered safe. Finally, an extended ODD taxonomy for underground mining can be considered a tool for optimization since the scenarios extracted become parameters that can be restrictive in one situation and relaxed one by one in other situations as per need. For example, what happens if we select physical infrastructures during design instead of digital infrastructures to control the AOZ? Can we use the same design in a new area? Thus, the impact of using an extended ODD covering specific attributes included in autonomous underground mines is worth further research.

5.2 Relation with the SPI Manifesto

The Software Process Improvement (SPI) Manifesto [23] is a document that collects principles and values gathered from experiences to emphasize key success factors regarding improvement work. As we highlighted in our previous work [6], the use of context-specific standards is a way to learn from the experience of others and is valuable to define and improve context-specific projects. Therefore, the work we present in this paper is aligned with the SPI manifesto since we formulate an extension of the ODD that aims at fulfilling three aspects. First, it uses a publicly available specification that contains state-of-the-art ODD. Second, it consolidates the context-specific attributes that could occur in a mine. And third, it aligns with an applicable standard that address safety.

In particular, with our work in this paper, two values present in the SPI manifesto are highlighted. First, the ODD taxonomy created for road vehicles is extended to the underground mining context. Such extension could facilitate the ODD definition in mining projects. This aspect can be related to the principle that SPI initiatives should *"know the culture and focus on needs"*. Second, the ODD-UM also provides means for modeling the environmental conditions that the mining practitioners understand. This aspect can be related to the principle *"Use dynamic and adaptable models as needed"*.

6 Related Work

6.1 ODD Specification

The specification of ODDs is fundamental for the safety of Autonomous Driving Systems (ADS) as it helps understand the requirements of operating within a particular environment and deriving different driving scenarios. However, ODD specifications varies from one operating environment to another and has implications for the design of the ADS. In addition, the complexity and dynamicity of the environment make it challenging to effectively describe the ODD [19]. As a consequence, the lack of common definitions and a standard process for deriving the ODD slow the development of the ADS.

Attempts have been done to standardize the definition of the ODD specification. In [27], the authors place special attention on the conceptualization of scene, situation, and scenario for automated driving, while in [8] and in [16], the authors proposes a taxonomy of basic terms and a list of ODD factors, respectively. More detailed ODD taxonomies are surveyed in [21,25] and [13]. The previous works (i.e., [8,16,21,25,27] and [13]) have in focus road conditions, but mining conditions are not included.

In the context of heavy-duty mobile machinery, there are some initial references to operational conditions. For example, in [2], the authors consider some elements for the site description (e.g., geographical areas and zones, conditions and assumptions regarding humans behavior in the AOZ, relevant infrastructures, other machines and exposed humans) as a necessary input for the hazard analysis, but specific attributes are not provided. Context-specific taxonomies are also created. For example, in [20], the authors propose a taxonomy for determining the levels of automation for machinery, extending the six levels proposed by SAE J3016:2021. However, to our knowledge, there is no ODD taxonomy that provides the specific attributes required in autonomous mining. The problem with a general ODD is that it leaves the choice to the developers, who may not have enough expertise to interpret it [17]. For this reason, a context-specific ODD could be a starting point for determining, in a systematic way, such conditions and support the general process required to include ASAMs in mines.

6.2 Application Domains

The application domain impacts the ODD specification and the design of the ADS. For example, in a restricted access area, such as a construction site, the minimum requirement for safe operation is to use a LiDAR sensor, however, this requirement is not valid in another application domain, such as a public road, where the minimum requirement for the safe operation of the ADS is a camera, LIDAR, and radar sensors to detect other road users all around the vehicle [7]. Moreover, Bussemaker [5] has determined the requirements for the LiDAR sensor in highway and rural environments. Kini [15] has also studied the LiDAR placement and sensor redundancy for different types of AVs. Most of these studies considered urban, rural or highway working environment and specific type of AVs, which is not directly applicable to the mining industry and need to be extended, based on context-specific attributes.

7 Conclusions and Future Work

This paper presents a context-specific ODD taxonomy, called ODD-UM, suitable for underground mining operational conditions. ODD-UM takes, as inputs, the ODD taxonomy provided by PAS 1883:2020, the descriptions of the AV architecture provided by the PAS 1880:2020, and the context-specific attributes provided by the standard ISO 17757:2019, which prescribes safety requirements for ASAMs. As a result, our proposed ODD-UM uses state-of-the-art ODD definitions, consolidates the context-specific attributes likely to occur in a mine, and aligns with applicable standards that address safety.

There are several aspects to consider for future work. First, we need to validate the extended taxonomy by considering more case studies and experts' opinions. Second, we consider using the scenarios derived from the extended taxonomy to provide general systems requirements and consider them further for the hazard analysis. Finally, tool support for taxonomy utilization could also be provided.

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