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Knowledge-Based Derivation of Relevant Scenario Objects for Testing Automated On-Sight Train Operations

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Abstract

The testing of automated rail vehicles presents substantial challenges. This is particularly evident in the context of automated on-sight train operation, where the reliability of perception systems must be assessed through rigorous and systematic testing. Scenario-based testing, which is frequently applied for this purpose, requires fundamental information regarding relevant scenario parameters and potential events. In the railway domain, the availability of extensive real-world operational data is limited, which makes the structured use of knowledge essential. This work uses the example of an automated hump locomotive, representing an automated on-sight driving railway vehicle, to demonstrate how relevant knowledge entities and derived scenario objects can be extracted from a corpus of knowledge sources while considering the system-specific operational design domain. Suitable sources are defined, relevant knowledge entities are identified, and a dataset of scenario objects is established. The evaluation of the object list is carried out using an analytical approach based on object occurrence frequency. The resulting dataset of scenario objects can be integrated into knowledge-based scenario generation and supports the targeted derivation of scenarios tailored to the specific operational design domain.

Keywords: scenario-based testing, automatic train operation, automatic on-sight train operation, knowledge generation, scenario objects, operational design domain, text mining, term frequency.

1 Introduction

Digitalization and automation represent two of the primary key elements shaping the future development of the railway sector. Due to staff shortages, capacity constraints, and politically driven objectives, a shift of operational workflows and processes away from purely human interaction toward digitalized and automated procedures has become necessary. [1]

This includes, among other aspects, the implementation of automatic train operation (ATO) systems. Their development differs particularly with respect to the use of various train control and protection systems. For instance, the automated driving mode within the European Train Control System (ETCS) is already applied in mainline operations [2]. Beyond mainline driving, many areas of railway operations still rely on on-sight driving without active train protection. This includes, for example, shunting processes as well as provisioning and stabling movements. In such cases, when operating in a non-automated mode, the driver remains fully responsible for train control, environmental monitoring, and safe operation [3]. Automation toward automatic on-sight train operation (OS-ATO) can, analogous to road traffic, be achieved through the integration of appropriate perception systems. In addition to the development of such systems, rigorous testing of their reliability and fault-free functionality is indispensable. Scenario-based testing is increasingly being adopted for this purpose. Building on experiences and developments from the automotive sector [4], a knowledge-based method for deriving test scenarios for OS-ATO was introduced in [5]. The focus is deliberately placed on knowledge-based scenario generation, as a purely data-driven approach is not feasible due to the limited availability of extensive real-world measurement data in the railway domain [5], [6]. As an application example, the VAL project [7] investigates the testing of an automated hump locomotive at the Munich North shunting yard. In [8] a methodology for combining scenarios based on scenario objects and classes is presented.

Building on the simplified knowledge-generation approach and the reduced object dataset used therein, this paper establishes a systematic methodology for creating a convergent object dataset and adapts the resulting object data accordingly. The objective is to comprehensively represent the operational environment and potential situations or objects based on domain knowledge, and to prioritize them through appropriate weighting. For purely digital testing that aims to fully replicate the operational environment, the shunting yard is too extensive. It consists of several parallel track sections connected by a combination of multiple switches. Each parallel track is fundamentally identical in terms of functionality, but its local position results in different influences from the surrounding environment and the actors present. Therefore, the focus must be placed on globally relevant track areas and potential objects that are critical for testing. Furthermore, environmental changes are always possible and should not be treated as immutable test parameters. Therefore, for a reliable ATO system, it is essential not only that functional requirements from specifications and the subsequent operational design domain (ODD) are met, but also that the system does not incorrectly or inadvertently react to irrelevant objects, thereby avoiding false or unintended responses.

2 Methodological Knowledge Generation for Railway-specific Scenario-based Test Cases

The derivation of relevant objects based on domain knowledge integrates into the process presented in [5] and [8], as illustrated in Figure 1. The focus lies on the process steps 'Railway-specific Dataset' and the construction of the 'Scenario Object Database' (SOD), utilizing the 7-Layer Model introduced in [9]. As input parameters, the driving system is defined according to the VAL project. The OS-ATO system is intended to autonomously execute shunting tasks within the arrival tracks of the Munich North shunting yard, couple to wagon groups, and reliably stop in front of obstacles located within the driving path. Using the framework introduced in [10] the ODD of the system is defined. The ODD fundamentally determines the thematic scope within which knowledge sources must be analysed and relevant knowledge must be derived.

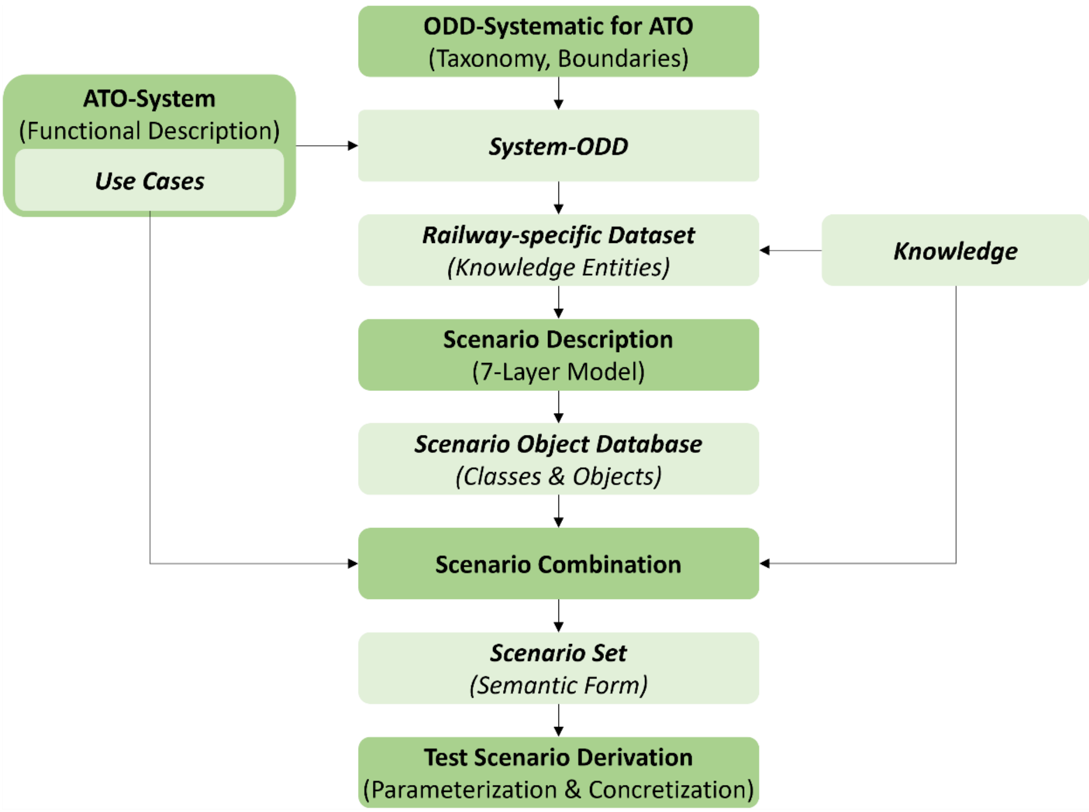

Figure 1: Knowledge-based Scenario Generation [5].

For the derivation of relevant scenario objects based solely on domain knowledge, a well-founded knowledge base is essential. To this end, an extensive literature review is conducted to identify suitable sources. In addition to project-specific documents, the focus is placed on publicly accessible sources from the German-speaking railway domain. The sources are categorized into the following eight groups. While all categories are fundamentally important, the classification provides a coarse indication of their relative relevance. To investigate current operational procedures and workflows at the marshalling yard, several 'Operational Analyses' (OA) are examined. These analyses provide comprehensive insights into the interdependencies and execution of shunting operations. As a second major source category, 'Formalities & Guidelines' (FG) encompass legal requirements, regulations, and specific operational rules. To incorporate real-world conditions, situations, and incidents, accident databases and reports are reviewed within the category 'Statistics on Accidents' (SA), while real-world measurement data are analysed within the category 'Public & Self-Collected Measurement Data' (MD). Although such sources are only partially available in the railway sector, their strong grounding in real operational conditions makes them indispensable. The category 'Literature and Research Reports' (LR) covers the state of the art and current research, focusing on comparable research projects as well as foundational knowledge from academic and technical literature. Sources in this category are widely available and can easily complement the overall knowledge base. As a more specialized category, 'Existing Datasets' (ED) include available datasets related to specific object groups. 'Expert Knowledge' (EK) comprises information obtained from domain specialists and other expert contributors. Any remaining sources that cannot be assigned to one of the aforementioned categories are grouped under 'Others' (O).

Each source is additionally assigned a primary data type. The dataset consists of text-based (tb), image-based (ib), data-based (db), and other (o) types, such as expert interviews and site visits. Moreover, to improve the evaluability of the sources and the objects derived from them, each source is assessed according to three criteria. The first criterion evaluates the degree to which the source covers shunting-related topics. The second criterion, no object and class specificity, indicates whether the source provides general information or highly specific details on individual objects or classes. The third criterion, reality, assesses whether the source is based on abstract descriptions or real-world data. Each criterion is rated using the three-level scale low (l), medium (m), and high (h). Table 1 presents the corpus of sources used, including their category assignment, project relevance, evaluation criteria, and, where available, the corresponding literature reference. First, the project-specific sources are listed, followed by the remaining sources in a cyclical sequence across the categories. This procedure ensures a balanced analysis across all categories.

Number	Source	Category	Project context	Datatype	Shunting-related	No object and class specificity	Reality	References
1	Shunting yard inspection	OA	yes	o	h	h	h	-
2	Specification sheet VAL project	FG	yes	tb	h	h	h	[11]
3	VAL measurement data	MD	yes	db	h	h	h	-
4	VAL2020 project report	LR	yes	tb	h	h	h	[12]
5	VAL project glossary	ED	yes	tb	h	h	m	internal
6	Questionnaire for train drivers	EK	yes	tb	h	h	h	internal
7	Sequence diagram shunting	OA	yes	tb	h	m	m	internal
8	Control panel and operational zone diagrams shunting yard	ED	yes	ib	h	m	h	internal
9	VAL2020 project experience	EK	yes	o	h	h	h	-
10	Ride-on shunting run	OA	yes	o	h	h	h	-
11	Guideline 408 shunting	FG	no	tb	l	h	m	[13]
12	Federal Railway Accident Investigation Board Germany	SA	no	tb	m	h	h	[14]
13	OSDaR23 dataset	MD	no	db	m	h	h	[15]
14	ATO sensors project report	LR	no	tb	m	h	m	[16]
15	DB Cargo freight wagon catalogue	ED	no	ib	h	l	m	[17]
16	Personal experience and knowledge	EK	no	o	h	h	h	-
17	Online videos, social media, etc.	O	no	ib	m	h	m	[18]
18	Railway Operating Regulations Germany	FG	no	tb	l	h	m	[19]
19	Federal Office for Railway Accident Investigation Germany	SA	no	tb	m	h	h	[20]
20	RailSem19 dataset	MD	no	db	m	m	h	[21]
21	ATO risk project report	LR	no	tb	m	h	m	[22]
22	Weather data Munich	ED	no	db	m	l	h	[23]
23	VAL2000 project experience	EK	no	o	h	h	h	-
24	Transportation service regulations 438	FG	no	tb	m	h	m	[24]

25	Investigation reports from the Austrian Federal Bureau of Safety Investigation	SA	no	tb	m	h	h	[25]
26	GERALD dataset	MD	no	db	m	m	h	[26]
27	Kompas project report	LR	no	tb	m	h	m	[27]
28	Survey internet forum	EK	no	o	m	h	l	-
29	Guideline 301	FG	no	tb	m	l	m	[28]
30	Swiss Transportation Safety Board	SA	no	tb	m	h	h	[29]
31	Railway infrastructure manual	LR	no	tb	m	m	m	[30]
32	Guideline 408 trains run	FG	no	tb	h	h	m	[13]
33	Rail vehicle technology	LR	no	tb	m	m	m	[31]
34	Railway signalling regulations	FG	no	tb	m	l	m	[32]
35	Railway construction and infrastructure	LR	no	tb	m	m	m	[33]
36	Railway systems engineering	LR	no	tb	m	m	m	[34]
37	European train control system	LR	no	tb	l	m	m	[2]
38	Railway construction	LR	no	tb	m	m	m	[35]
39	Communication-based train control	LR	no	tb	l	m	m	[36]

Table 1: Corpus of sources. (Category: OA = Operational Analyses, FG = Formalities & Guidelines, SA = Statics on Accidents, MD = Public & Self-Collected Measurement Data, LR = Literature and Research Reports, ED = Existing Datasets, EK = Expert Knowledge, O = Other / Datatype: tb = text-based, ib = image-based, db = data-based, o = other / Criteria: h = high, m = medium, l = low)

Based on the identified knowledge sources, relevant knowledge is extracted in a successive process and transformed into scenario objects. Following the methodology described in [8] each object is assigned to a corresponding class. The sources are analysed in the order presented in Table 1. Every ODD-relevant entity identified during the review is stored in a database and may be assigned to one or multiple objects or classes. Similar or seemingly equivalent entities are consolidated under identical objects to reduce the overall size of the resulting SOD. Newly identified objects are subsequently cross-checked against all previously analysed sources using a search algorithm. Through the structured assignment of classes to the 7-Layer Model, an organized database of scenario objects is established. The classes and objects cited within the layers below serve as indicative examples. Layer 1 'Railway System and Signals' includes, for instance, the class *signals*, containing objects such as basic main and protection signals as well as relevant shunting signals. Layer 2 'Stationary Objects' comprises, among others, the class s*tructures*, with objects such as buildings of various sizes, and the classes t*ree*, *bush*, and *grass*, representing different types of vegetation. Layer 3 'Temporary Changes of Layers 1, 2, (&4)' describes *temporary objects*, such as fallen objects originating from Layer 2 (e.g., a fallen tree or mast), or objects within the class l*ost cargo*, representing items that appear unexpectedly in the track area after falling from a wagon. Layer 4 'Dynamic Objects' includes movable objects such as locomotives, freight wagons, road vehicles, cyclists, and cars, represented in the classes *traction vehicles*, *wagons*, and *road vehicles*. All environmental conditions are captured in Layer 5 ‘Environmental Conditions’, including classes such as *precipitation*, l*ight conditions* and *surface conditions*, with objects describing precipitation type and intensity, light incidence and brightness, or the surface condition of the rail and surrounding ground. Layer 6 ‘Digital Information’ contains, for example, the class l*ocalization*, with object information related to positioning signals. Layer 7 ‘Shunting Order’ represents the external information layer, describing data transmitted to the system from external sources, such as permissible speed limits stored in the class m*aximum permitted speed* for specific track sections. Following a comprehensive analysis of the available sources, a total of 443 relevant objects and 49 object classes have been delineated.

To assess the suitability of the final SOD for the given ODD, the number of identified objects is analysed with respect to the number of sources. Figure 2 illustrates the distribution of newly identified objects contributed by each source. The project-specific sources that were added first are shown in blue. Due to the similarity of their content, a converging behaviour is already observable at this stage. The subsequently added sources, which were incorporated cyclically, are shown in red. While the underlying set of sources is insufficient to claim a fully comprehensive dataset, a clear convergence of the SOD is observable. Notably, a significant increase occurs at source 12 ‘Federal Railway Accident Investigation Board Germany’ [14], which is primarily attributable to the substantially greater length and detail of this source. Additionally, the distribution of objects across the number of sources in which they appear is examined. Approximately 22% of the objects occur in only one source. Around 52% appear in at least two and up to ten sources, while roughly 26% are represented in more than ten sources. This demonstrates that the relevance of objects varies considerably across the full set of sources. For this reason, the identified objects are evaluated in greater detail regarding their relevance in the following chapter.

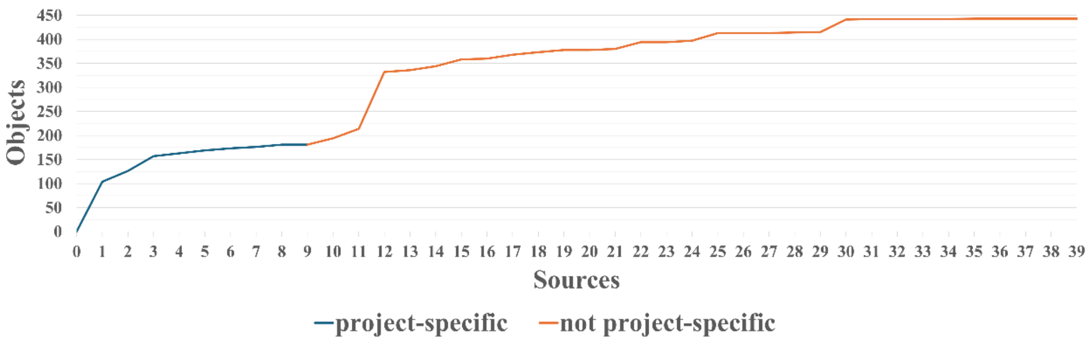

Figure 2: Converging Scenario Object Database Based on the Source Corpus (blue: project-specific, red: not project-specific).

3 Evaluation of the Derived Scenario Objects

In principle, all objects generated through the knowledge-based derivation process are relevant for testing the OS-ATO system. Nevertheless, to optimize system validation and to ensure a targeted alignment of scenario-based test cases, it is beneficial to systematically assess and cluster the objects. This can be achieved through different methodological approaches. One approach focuses on evaluating the likelihood of an object occurring within a scenario. The objective is to determine how probable it is that any of the identified objects will appear during the operation of the OS-ATO system. To quantify this, the objects must be weighted both within each individual source and globally across all sources. Inspired by the commonly used statistical term frequency-inverse document frequency *TF-IDF* shown in Equation (1), which determines the relevance of a term t within a collection of documents d [37], an adapted formulation (2) is developed for the present application. In the *TF-IDF* measure, the *TF* component represents the relative frequency of an object within a source, while the *IDF* factor indicates how rare a term is across the corpus of all sources *N*. Thereby, rare terms are considered more relevant for the overall search space.

$$TF - IDF(t,d) = TF(t,d) \cdot IDF(t) \tag{1}$$

where:

$$TF(t,d) = \frac{Number\ of\ occurences\ of\ t\ in\ d}{Total\ number\ of\ terms\ in\ d}$$

$$IDF(t) = \log\left(\frac{N}{Number\ of\ sources\ containing\ t}\right)$$

The *TF-IDF* measure cannot be directly applied to the present use case, as the frequency of occurrence across multiple sources must be weighted positively rather than negatively. The *IDF* component is therefore omitted and replaced by a dispersion weighting *DW*, which serves as an occurrence factor. In addition, the *TF* component is modified. To reduce the influence of strongly varying source lengths, the relative frequency of an object is determined for each source, analogous to *TF*, but, deviating from Equation (1), this frequency is normalized by the total number of object occurrences within that source and subsequently aggregated across all sources in the corpus (TF_P).

Furthermore, each source is assigned a weighting factor WF_d based on the averaged evaluation criteria defined in Table 1. Sources with a higher relevance to shunting operations ($WF_{shunting}$), a lower level of object and class specificity ($WF_{specific}$), and a higher degree of real-world grounding ($WF_{reality}$) receive a stronger weight. The individual factors are distributed within the range 0.9–1.1, corresponding to the categories low, medium, and high.

This results in the dispersion-weighted pooled term frequency $TF_P\text{-}DW$, as shown in Equation (2).

$$TF_P - DW(t,d) = TF_P(t,d) \cdot DW(t) \tag{2}$$

where:

$$TF_P(t,d) = \sum_{d=1}^{N} WF_d \cdot \frac{Number\ of\ occurences\ of\ t\ in\ d}{Total\ number\ of\ occurences\ in\ d}$$

$$WF_d = \frac{(WF_{shunting} + WF_{reality} + WF_{specific})}{3}$$

$$DW(t) = \frac{Number\ of\ sources\ conataining\ t}{N}$$

The described calculation methodology implies that objects occurring with moderate to high relative frequency across a larger number of sources receive the highest weighting. Objects that appear frequently across sources but with lower relative frequency remain relevant, whereas objects that occur in only a few sources, even if they show high relative frequency within those sources, are assigned lower relevance in the overall assessment.

To determine the relative frequency, the direct occurrence count of each object is identified per source using a search algorithm. For text-based documents, all associated entities are detected while accounting for grammatical variations, abbreviations, and linguistic forms, and the resulting matches are aggregated. In addition, indirect mentions through class-level occurrences are proportionally added to the object-level counts. For data-based sources, the number of occurrences is taken directly from the corresponding database. For image-based and miscellaneous sources, each object is assigned a normalized absolute frequency of 1 for simplification.

The objects are then grouped into seven categories according to their computed $TF_P\text{-}DW$ value, with the distribution shown in Table 2. The category *extremely common* includes objects such as straight track sections, curved track sections, and persons equipped with personal protective equipment (PPE). This result aligns with expectations, as trackways are indispensable for railway operation and various PPE-equipped staff are present at the shunting yard. These objects also exhibit the highest occurrence factors. The *very common* category includes, among others, shunting locomotives, freight trains, and persons without PPE. This corresponds well to the investigated use case of an automated shunting system and further emphasizes that the presence of persons, regardless of PPE, is highly relevant for system testing. The *common* category contains various signals, freight wagons, switches, and crossings, as well as some notable objects such as derailed wagons or outbreaking fires. The *moderate* category includes more specific freight wagon types and the largest share of environmental conditions. These four categories represent the core objects in the basic functional testing of the OS-ATO system. These include the objects necessary for executing a shunting order, as well as those that can have the greatest impact on the system. The *rare* category comprises additional dynamic objects such as road vehicles and animals, as well as various static infrastructure or vegetation elements. The *very rare* category includes, among others, specialized auxiliary vehicles and lost cargo. The final category, *extremely rare*, contains all remaining objects with exceptionally low occurrence probability. These objects are primarily relevant for testing choosen special cases. All other categories can contribute as weighting factors to scenario generation during the combination process. The higher the occurrence probability, the smaller the parameterization step size for concrete scenarios. This results in broader coverage of potential scenarios involving highly weighted objects and optimizes system testing by focusing on the most relevant situations.

Group	TF_P-*DW* Separation	Number of Objects
extremely common	>1	3
very common	> 0.5 & ≤ 1	5
common	> 0.1 & ≤ 0.5	63
moderate	> 0.05 & ≤ 0.1	56
rare	> 0.01 & ≤ 0.05	87
very rare	> 0.005 & ≤ 0.01	56
isolated case	≤ 0.005	173

Table 2: Grouping of objects according to the TF_P-*DW* measure.

Another possible way to structure the SOD is to consider the influence and relevance of each object for the sensor system used. For a lidar sensor, object size and material reflectivity are decisive criteria. Each object is therefore assigned metadata describing its three-dimensional dimensions and the reflectivity of its material. This enables the large number of objects to be grouped according to size and reflectivity, and it allows the creation of generic test bodies that represent entire object groups. For camera-based sensing, the colour characteristics of an object are of primary importance, which is why an additional logical colour variation is introduced for the test bodies. This approach is particularly useful in early stages of testing and development, when the system is not yet in its final state. A related method is presented in [38].

A third way to evaluate the SOD is to consider the potential position of each object. For the OS-ATO system, the most relevant objects are those that may appear directly within the driving path or within the clearance gauge. These include various railway vehicles that the system must interact with, such as wagons that need to be coupled, as well as potential hazards and obstacles that require timely stopping. Objects located further away from the track, such as fixed infrastructure, are expected to have a lower impact on system reliability. However, interference between these objects and the perception system cannot be excluded and may lead to critical misinterpretations in specific cases. This distinction also allows differentiation between early and late stages of system testing, which influences the depth and scope of the test cases. The integration and applicability of this approach will be examined further in the scenario generation process as the project progresses.

4 Conclusions and Contributions

The approach described in this work for the systematic derivation of scenario objects based on a corpus of knowledge sources results in a comprehensive SOD. A wide range of relevant objects is identified and qualitatively assessed according to their influence on scenario generation. The total number of objects can be considered convergent in terms of quantity. Although the SOD cannot be regarded as globally complete due to the limited number of available sources, it provides an appropriate basis for the targeted alignment of scenario-based testing within the defined ODD. In the future, the SOD can be further expanded and consolidated for the ODD by enlarging the corpus of sources and performing additional validation cycles to examine the convergence of the object list. The comprehensive integration of the results presented here into the overall methodology introduced in [5] is still the subject of ongoing research. Further investigations will examine the validity of the object evaluation and the convergence of the SOD. In addition, the combination of the different evaluation approaches presented in this work will be explored. Linking the object grouping based on the $TF_P\text{-}DW$ measure with the introduction of generic test bodies and the focus on specific object positions may provide a suitable compromise between object diversity and the practical feasibility of the resulting scenario set. This will be incorporated into the continued research activities.

Further development steps must examine how the method can be improved through additional refinements. At present, the contribution of class-level occurrences to the relative frequency of an object is weighted equally for all objects within the same class. It must be evaluated whether this affects the results, since objects within a class may differ significantly in relevance. One possible solution is a two-stage calculation approach. In the first stage, all direct object occurrences are determined. Based on their $TF_P\text{-}DW$ values, a distribution of objects within the class can be defined. In the second stage, the influence of class-level occurrences can be incorporated accordingly. Furthermore, an extension of the source analysis to include sources in other languages is intended to be examined. This would allow for cross-translation of the identified entities and thereby qualitatively expand the search space. Moreover, further investigations can also examine the transferability of the presented method to other areas of automated railway systems. In principle, such an adaptation should be methodologically feasible, although it has not yet been verified. The necessary steps for transferring the method include updating the existing ODD, adapting the relevant corpus of sources, adjusting the current object list to the new ODD, and analysing both existing and newly added sources for additional objects to extend the SOD.

In conclusion, the method developed for the OS-ATO use case, demonstrated through the example of an automated shunting locomotive, produces coherent and practically meaningful results. The integration of the identified objects into the generation of concrete scenarios provides a structured basis for deriving a representative distribution of relevant test cases. The derived objects must subsequently be implemented as virtual assets for the scenario-based testing of the OS-ATO system. This enables their integration into the virtual scenario [39] and supports the execution of system tests within the simulation environment.

Acknowledgements

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