From Numbers to Narratives: Efficient Language Model-Based Detection for Safety-Critical Minority Classes

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Abstract

Safety-critical classification tasks face a persistent challenge: traditional models achieve high overall accuracy but inadequate performance on critical minority classes. We introduce a *numbers to narratives* framework that transforms tabular data into contextually rich descriptions, enabling language models to leverage pre-trained knowledge for minority class detection. Our approach integrates structured verbalization, linguistically-informed augmentation, and parameter-efficient fine-tuning to address the "minority class blind spot" in high-consequence domains. Using a significantly more efficient model architecture than existing approaches, our framework achieves superior minority class F1-scores: 78.76% for machine failures (+7.42 points over XGBoost), 65.87% for at-risk students (+12.12 points over MLP), and 32.00% for semiconductor failures (+1.01 points over XGBoost, despite 14:1 class imbalance). Our approach also improves overall accuracy by up to 22.43% in five of six datasets while maintaining computational feasibility. Ablation studies confirm that narrative-based verbalization enables effective reasoning about tabular data by contextualizing abstract numerical features. This work provides a practical, resource-efficient approach for enhancing minority class performance in safety-critical domains.

1 Introduction

Safety-critical classification tasks present persistent challenges across diverse domains such as healthcare, manufacturing, and transportation. Tabular datasets from the UCI Machine Learning Repository (Dua and Graff, 2017) frequently exhibit significant class imbalance, where critical events of interest (e.g., machine failures, medical complications) represent a small fraction of instances. Traditional machine learning (ML) algorithms and neural architectures applied to these datasets often achieve misleadingly high overall accuracy while substantially underperforming on minority classes (Fernández et al., 2018; Provost and Fawcett, 2013). This performance disparity is illustrated in our analysis of the UCI AI4I predictive maintenance dataset, where XGBoost achieves 97.75% overall accuracy but only 71.34% F1-score for the critical machine failure class, a gap that could translate to missed detection of impending equipment failures with significant operational consequences (Johnson and Khoshgoftaar, 2019).

This "minority class blind spot" creates a troubling disconnect between reported model performance and practical utility in high-consequence decision domains. Even with optimal hyperparameter tuning, traditional ML algorithms such as Random Forest (Breiman, 2001), Support Vector Machines (SVMs) (Hearst et al., 1998), and XGBoost (Chen and Guestrin, 2016) struggle with imbalanced class distributions due to their optimization for aggregate metrics (He and Garcia, 2009). Similarly, deep learning (DL) architectures, including Multilayer Perceptrons (MLPs) and Convolutional Neural Networks (CNNs), frequently underperform on small or imbalanced datasets, particularly on small/imbalanced sets with unfavorable feature-to-sample ratios (Buda et al., 2018).

Existing remediation strategies for class imbalance fall into two categories, each with significant limitations. *Data-level approaches* such as Synthetic Minority Oversampling Technique (SMOTE) (Chawla et al., 2002) generate synthetic samples but introduce statistical noise and distort feature distributions, particularly in datasets with complex feature interactions. *Algorithm-level approaches* such as cost-sensitive learning (Elkan, 2001) improve minority class detection but require domain expertise to set appropriate cost matrices. These limitations are especially pronounced in tabular data, where numerical features carry implicit semantic meaning that conventional tech-

niques struggle to preserve (Kotsiantis et al., 2006). Recent approaches leveraging Transformer-based (Vaswani et al., 2017) language models (LMs) show promise for tabular data tasks. TAPAS (Herzig et al., 2020) incorporates table-specific embeddings and positional encodings to capture structural relationships for question-answering tasks, while TabLLM (Hegselmann et al., 2023) serializes tabular data into natural language strings for classification. However, these models are not designed for minority class performance in safety-critical domains and may not fully capture domain-specific contextual knowledge without customization.

To overcome these shortcomings, we propose a novel **numbers to narratives** framework that transforms tabular data into contextually rich natural language descriptions. This method allows language models to utilize their pre-trained general knowledge for safety-critical classification tasks, prioritizing accurate detection of minority classes. Our framework integrates three complementary components: (1) structured verbalization, which converts numerical instances into semantically coherent text (e.g., *Patient aged 42 with a history of hypertension and elevated glucose levels showing early signs of retinopathy* instead of *Age: 42, Hypertension: Yes, Glucose: 182, Retinopathy: Early*), preserving feature relationships and domain context; (2) linguistically-informed minority class augmentation, which generates context-aware synthetic samples while maintaining causal dependencies to mitigate class imbalance without distorting feature distributions; and (3) parameter-efficient fine-tuning using quantized low-rank adaptation (QLoRA) (Dettmers et al., 2023) to adapt pre-trained LMs to domain-specific tabular tasks with minimal computational overhead.

Unlike previous approaches that rely on large LMs (or LLMs) such as TabLLM (Hegselmann et al., 2023) (11B parameters) and TAPAS (Herzig et al., 2020) (BERT-large, 340M parameters), and the ML/DL baselines in Section 4, our framework achieves superior performance with significantly lower computational requirements. By utilizing a 66M-parameter DistilBERT model (Sanh et al., 2020) with parameter-efficient fine-tuning, we reduce resource needs by 5-160× while improving minority class detection, making our approach both more effective and more accessible for real-world deployment in resource-constrained environments. This framework addresses **three critical research questions (RQs)**:

1. **RQ1:** How do LMs with verbalized tabular inputs compare to conventional ML and DL models across datasets with varying class balance, scale, and feature complexity?
2. **RQ2:** Can linguistically-informed augmentation in LM-based approaches outperform data-level methods such as SMOTE in improving minority class performance for safety-critical domains?
3. **RQ3:** How do different verbalization strategies and instruction-based fine-tuning impact LM performance in structured data classification tasks?

Our comprehensive evaluation across six UCI datasets (Dua and Graff, 2017) demonstrates that the **numbers to narratives** framework significantly improves both minority class detection and overall accuracy (Table 2). 78.76% F1 for machine failures in AI4I (+7.42 points over XGBoost); 65.87% for at-risk students (+12.12 points over MLP); 32.00% for semiconductor failures in SECOM (+1.01 points over XGBoost, despite 14:1 imbalance). In five of six datasets, our approach enhances overall accuracy by 1.50-22.43%. For SECOM, we trade ∼93% baseline accuracy (F1 ≤0.09%) for meaningful 32% minority F1, addressing the "minority class blind spot" in high-stakes tasks (Sec. 4).

This work contributes to the growing body of NLP research on cross-modal applications, where natural language understanding capabilities enhance performance on structured data (Bommasani et al., 2022). By transforming tabular data into contextually rich descriptions, our approach enables LMs to reason effectively about tabular instances while maintaining computational efficiency.

Our main contributions include:

I. A novel **numbers to narratives** framework that transforms tabular data into contextually rich natural language descriptions, enabling LMs to leverage pre-trained knowledge for safety-critical classification tasks.

II. A linguistically-informed minority class augmentation approach that preserves semantic relationships while addressing class imbalance, outperforming data-level methods such as SMOTE by generating context-aware synthetic samples.

III. Significant performance improvements in minority class detection (up to +12.12

points F1-score) and overall accuracy (up to +22.43%) across diverse datasets, even with extreme class imbalance.

IV. A computationally efficient approach requiring 5-160× fewer resources than existing LM-based tabular methods (66M parameters vs. 340M-11B), enabling training on a single GPU in under an hour.

V. Actionable insights from ablation studies quantifying the impact of verbalization strategies, augmentation techniques, and few-shot learning for applying LMs to safety-critical tabular data classification.

2 Related Work

Classical ML and DL for Tabular Data Both conventional ML models (k-NN, Decision Trees, Random Forests, SVMs, XGBoost) (Dua and Graff, 2017; Chen and Guestrin, 2016) and specialized deep learning architectures (TabNet (Arik and Pfister, 2020), NODE (Popov et al., 2019)) face persistent challenges with tabular data in safety-critical domains. Studies on unbalanced datasets like AI4I often exhibit a substantial gap between aggregate evaluation metrics and minority class F1-scores (Johnson and Khoshgoftaar, 2019), while balanced multi-class tasks like Glass Identification show precision/recall below 65% for specific classes (McCann and Johnston, 2008). Despite architectural advances, neural approaches frequently underperform on small datasets due to overfitting (Goodfellow et al., 2016; Kotsiantis et al., 2006) and prioritize aggregate metrics over minority class performance. Recent benchmarks confirm that well-tuned tree ensembles still outperform specialized neural architectures on many tabular tasks, particularly those with complex feature interactions and limited samples, highlighting the persistent "minority class blind spot" that undermines practical utility in safety-critical applications (Grinsztajn et al., 2022).

Addressing Class Imbalance Imbalance strategies include data-level (e.g., SMOTE (Chawla et al., 2002), <70% recall on Gas (Vergara et al., 2012); ADASYN (He et al., 2008)), algorithm-level (cost-sensitive learning (Elkan, 2001), ensembles like SMOTEBoost (Chawla et al., 2003), RUSBoost (Seiffert et al., 2010)), and hybrid methods. These often introduce noise or lose information (Provost and Fawcett, 2013), failing to capture semantic relationships. These approaches struggle to generalize across datasets with varying characteristics, highlighting the need for context-aware augmentation strategies that preserve semantic integrity.

Language Models for Structured Data Pre-trained LLMs such as TAPAS (Herzig et al., 2020) and TaBERT (Yin et al., 2020) target table QA (>75% accuracy), while TabLLM (Hegselmann et al., 2023), TableFormer (Yang et al., 2022), and TUTA (Wang et al., 2021) focus on classification but neglect imbalance. Li et al. (Li et al., 2024) and Borisov et al. (Borisov et al., 2024) enhance semantic learning, yet overlook minority detection. Our framework advances with context-aware verbalization, semantic augmentation, and fine-tuning for safety-critical tasks.

Few-Shot Learning and Efficient Fine-Tuning Few-shot learning excels with in-context examples (Brown et al., 2020), but is sensitive to selection (Min et al., 2022) and limited for tabular imbalance (Wei et al., 2022). QLoRA (Dettmers et al., 2023) and LoRA (Hu et al., 2021) offer efficient fine-tuning (<1% parameters), yet tabular safety applications are underexplored (Hegselmann et al., 2023).

To our knowledge, no prior work integrates structured verbalization, linguistically-informed augmentation, and efficient fine-tuning for safety-critical minority class detection in tabular data. A gap our approach bridges while addressing practical dataset constraints.

3 Methodology

This section presents our **numbers to narratives** framework for safety-critical classification through language model verbalization of tabular data, designed to address the limitations of traditional ML and DL approaches on minority classes. Our methodology emphasizes robustness across diverse dataset characteristics: class balance (balanced vs. unbalanced), scale (small vs. large), feature complexity, and task type (binary vs. multi-class). We evaluate the framework on six UCI datasets (Dua and Graff, 2017) with varying characteristics, as summarized in Table 1.

Table 1: Dataset Characteristics

Dataset	Size	Features	Classes	Ratio
AI4I 2020	10,000	6	2	∼24:1
Glass	214	9	6	varies
Student	395	33	2	∼3:1 to 5:1
Gas	13,910	128	6	balanced
Mammographic	961	5	2	∼1:1
SECOM	1,567	590	2	∼14:1

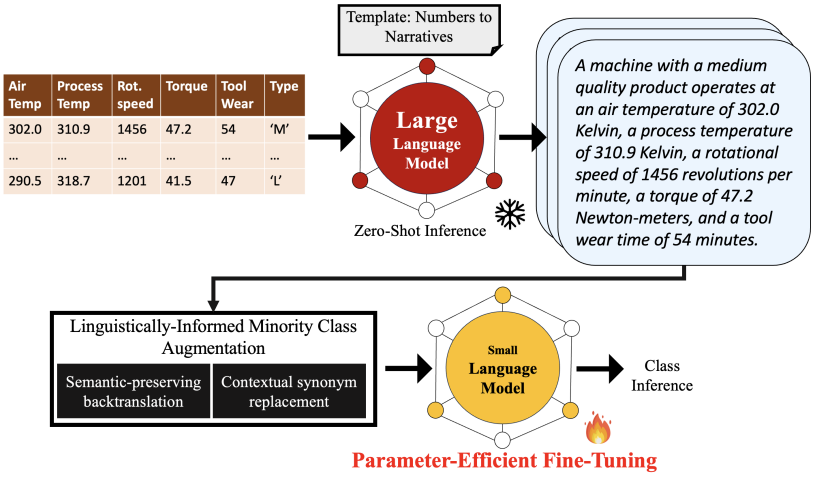

Figure 1: The **numbers to narratives** framework: transforming tabular data into natural language, augmenting minority classes, and efficiently fine-tuning a compact language model.

Our framework (illustrated in Figure 1) consists of three sequential components that transform tabular data into effective safety-critical classifiers while maintaining computational efficiency. Each component builds upon the previous one to address specific challenges in minority class detection.

3.1 Structured Verbalization of Tabular Data

First, we transform numerical tabular instances into natural language descriptions using a context-aware verbalization approach. This process leverages a large generative language model, ChatGPT-4o (OpenAI, 2024), in a zero-shot manner to convert abstract feature vectors into semantically rich textual representations. The verbalization follows a structured template (detailed in Appendix A.1) that provides three levels of context:

1. **Domain context**: Dataset overview, task description, and feature explanations
2. **Feature semantics**: Natural language descriptions of feature meanings and relationships
3. **Instance-specific narration**: Coherent narrative integrating all feature values

For each dataset, we create a standardized prompt template to ensure consistent verbalization patterns. This template maps numerical and categorical features to contextually appropriate linguistic expressions, preserving the semantic relationships between features. For example, an AI4I instance with numeric values [302.0, 310.9, 1456, 47.2, 54, 'M'] is transformed into narrative text: "*A machine with a medium quality product operates at an air temperature of 302.0 Kelvin, a process temperature of 310.9 Kelvin, a rotational speed of 1456 revolutions per minute, a torque of 47.2 Newton-meters, and a tool wear time of 54 minutes.*" This rich description contextualizes the abstract numeric features within their physical meaning and relationships.

This verbalization approach transforms abstract feature spaces into human-interpretable narratives, enabling language models to apply their pre-trained knowledge about real-world relationships to the classification task (Brown et al., 2020; Wei et al., 2022). Unlike previous approaches such as TabLLM (Hegselmann et al., 2023) that use simple "feature: value" mappings, our method generates cohesive narratives that preserve causal and semantic relationships between features.

3.2 Linguistically-Informed Minority Class Augmentation

Second, we address class imbalance while preserving semantic integrity through linguistically-informed augmentation of the verbalized data. For binary tasks (e.g., AI4I, SECOM), we match minority to majority class size; for multi-class tasks (e.g., Glass), we balance underrepresented classes. The augmentation pipeline includes:

1. **Semantic-preserving backtranslation**: We translate verbalized instances from English to German and back to English using the facebook/wmt19-en-de and facebook/wmt19-de-en models (both 270M parameters) (Ng et al., 2019) in a zero-shot manner. This process generates linguistic variation while retaining core meaning, building on established backtranslation methods (Sennrich et al., 2016).
2. **Contextual synonym replacement**: To enrich the verbalized narratives, we enhance non-critical terms with contextually suitable syn-

onyms, drawing on a comprehensive lexical resource (Miller, 1995). This process selectively varies language (up to five substitutions per instance) to improve the diversity of minority class descriptions, ensuring the meaning remains intact and supports robust classification performance.

To maintain data quality, we implement a semantic validation procedure where a random subset of augmented examples (10%) is manually inspected to verify that: (1) class-determining features remain unaltered, (2) causal relationships between features are preserved, and (3) linguistic coherence is maintained. Samples that violate these criteria are discarded (Fernández et al., 2018). This approach ensures that augmented instances remain valid representatives of their respective classes while introducing sufficient linguistic diversity to improve model generalization.

3.3 Parameter-Efficient Fine-Tuning

Finally, we fine-tune a small pre-trained encoder-only LM (under 100M parameters) on the augmented verbalized data to predict the original class labels. This step uses parameter-efficient techniques to adapt this compact model to safety-critical tabular classification tasks while maintaining computational feasibility. This approach contrasts with our verbalization step, which leverages a large generative language model in a zero-shot manner. For classification, we specifically choose an encoder-only architecture that processes input sequences efficiently and produces class predictions directly, making it suitable for deployment in resource-constrained environments.

For our classification model, we select DistilBERT (Sanh et al., 2020), a compact encoder-only language model with only 66 million parameters, significantly smaller than models used in comparable approaches such as TabLLM (11B) (Hegselmann et al., 2023) and TAPAS (340M) (Herzig et al., 2020). This choice is motivated by three factors: (1) encoder-only architectures are well-suited for classification tasks where the output is a class label rather than generated text; (2) DistilBERT balances computational efficiency and performance, ideal for resource-constrained deployments in safety-critical domains; and (3) through knowledge distillation, DistilBERT retains 97% of BERT's language understanding capabilities (Sanh et al., 2020) while requiring just 40% of the parameters.

To further enhance efficiency, we implement Quantized Low-Rank Adaptation (QLoRA) (Dettmers et al., 2023), which combines 4-bit quantization with low-rank adaptation to reduce memory requirements while maintaining performance. The fine-tuning process consists of the following components:

- **Model architecture**: We use DistilBERT with a sequence classification head that leverages the `[CLS]` token representation for prediction. The model is initialized with pre-trained weights to leverage transfer learning from general language understanding tasks.
- **QLoRA configuration**: We apply 4-bit quantization to the base model parameters and add trainable low-rank adaptation matrices with rank $r = 16$ and $\alpha = 32$. QLoRA is applied to attention modules (`q_lin`, `v_lin`) and classification layers (`classifier.dense`, `classifier.out_proj`), with dropout rate 0.05.
- **Training configuration**: We use a maximum sequence length of 512 tokens, learning rate of 1e-3 with linear warmup over 10% of training steps followed by linear decay, batch size of 32, and train for 20 epochs with early stopping based on validation loss. Weight decay of 0.01 is applied for regularization.

This approach facilitates efficient adaptation of pre-trained language models (LMs) to tabular data tasks, requiring significantly fewer computational resources compared to full fine-tuning or methods relying on larger models. By leveraging verbalization techniques, our framework ensures practical deployability, enabling effective performance even in resource-constrained environments while maintaining high accuracy across diverse tabular datasets.

3.4 Baseline Models and Comparative Analysis

To comprehensively evaluate our approach, we implement nine baseline models spanning traditional ML, ensemble methods, and neural architectures:

- **Traditional ML**: k-Nearest Neighbors (k-NN), Decision Trees, SVMs
- **Ensemble methods**: Random Forests, XGBoost
- **Neural architectures**: MLP, one-dimensional (1D) CNN, Transformer encoder

For traditional ML and ensemble methods, we perform rigorous hyperparameter optimization us-

ing stratified k-fold cross-validation (k=5) with grid search over extensive parameter spaces (detailed in Appendix A.4). For neural architectures, we adopt standard configurations per literature (Grinsztajn et al., 2022), as exhaustive tuning across six datasets is computationally prohibitive with limited gains, especially for smaller datasets such as Glass (214 samples) (Shwartz-Ziv and Armon, 2021). For fair comparison, all baseline models are trained on original tabular data with SMOTE (Chawla et al., 2002) applied before training, ensuring performance differences stem from our verbalization approach rather than imbalance mitigation.

3.5 Ablation Study

To assess the impact of different components in our framework, we conduct an ablation study focusing on three critical aspects:

1. **Verbalization quality**: We compare our structured verbalization approach with simpler feature-value mapping approaches similar to TabLLM (Hegselmann et al., 2023) to isolate the impact of rich textual descriptions.
2. **Few-shot learning**: We evaluate ChatGPT-4o in zero-shot and 5-shot classification settings using instruction fine-tuning on verbalized instances, separate from the DistilBERT pipeline. Instructions are task-specific, e.g., "Classify whether a semiconductor process fails based on sensor data" for SECOM.
3. **Augmentation strategy**: We compare our linguistically-informed augmentation with SMOTE and no augmentation to quantify the contribution of semantic-preserving text augmentation.

This ablation study is conducted on a subset of three datasets with significant minority class imbalance (AI4I, SECOM, Student Performance) to specifically evaluate the framework's effectiveness for safety-critical minority class detection. The results provide insights into which components contribute most significantly to performance improvements.

3.6 Evaluation Methodology

We evaluate all models using stratified 80/20 train-test splits with independent verbalization of test instances to prevent data leakage. Performance is assessed via accuracy, precision, recall, and F1-score, emphasizing minority class metrics for unbalanced datasets. For binary tasks (AI4I, Mammographic Mass, SECOM), we report class-specific metrics for both classes; for multi-class tasks (Glass, Gas Sensor, Student), we provide macro-averaged metrics alongside performance for least-represented classes.

4 Experiments and Results

This section presents a comprehensive evaluation of our **numbers to narratives** framework for safety-critical classification across six diverse UCI datasets (Dua and Graff, 2017). We implement our approach as described in Section 3, using stratified 80/20 train-test splits with independent verbalization of test instances to prevent data leakage. All training is completed on a single Google Colab A100 GPU, with 20 epochs for our largest dataset (Gas Sensor Array Drift, $\sim$13,910 samples) requiring under 1 hour, significantly more efficient than comparable approaches such as TabLLM (11B) and TAPAS (340M) (Hegselmann et al., 2023; Herzig et al., 2020). For fair comparison, baseline models are trained with SMOTE (Chawla et al., 2002), ensuring that performance differences can be attributed to our verbalization approach rather than simply to rebalancing techniques. Our evaluation focuses on both overall accuracy and minority class performance, with particular emphasis on the framework's effectiveness in addressing the "minority class blind spot" in high-consequence domains.

4.1 Overall Classification Performance

Table 2 summarizes the overall accuracy across all nine models and six datasets. Our DistilBERT-based approach achieves the highest accuracy in five out of six datasets: AI4I (99.25%), Glass Identification (83.39%), Student Performance (80.75%), Gas Sensor Array Drift (99.10%), and Mammographic Mass (91.83%). These results represent improvements of 1.50 to 22.43 percentage points over the best baseline models.

Particularly notable is the substantial improvement on the Gas Sensor Array Drift dataset, where our approach achieves 99.10% accuracy compared to the best baseline (MLP: 76.67%), representing a 22.43 percentage point improvement. This exceptional performance suggests that our verbalization approach is particularly effective for datasets with complex feature interactions that can be meaningfully captured through natural language descriptions.

In the SECOM (semiconductor manufacturing)

Table 2: Overall Accuracy (%) Across Models and Datasets. **Best** performance for each dataset is highlighted in bold, and the second best is underlined. DT: Decision Tree, RF: Random Forest, XGB: XGBoost, TF: Transformer

Dataset	k-NN	DT	RF	SVM	XGB	MLP	CNN	TF	DistilBERT
AI4I	94.30	95.70	96.55	93.55	97.75	96.70	91.40	91.30	**99.25**
Glass	76.74	72.09	79.07	53.49	62.79	72.09	55.81	72.09	**83.39**
Student	56.96	58.23	68.35	64.56	58.23	72.15	65.82	72.15	**80.75**
Gas	66.31	50.98	62.68	75.41	74.46	76.67	74.50	72.58	**99.10**
Mammographic	81.35	79.79	82.38	80.83	84.97	81.35	82.38	84.97	**91.83**
SECOM	62.42	86.94	93.31	**93.63**	84.39	90.13	87.26	89.17	67.09

Table 3: Minority Class F1-Scores (%) for Unbalanced Datasets. The **best** performance for each dataset is highlighted in bold, and the second best is underlined.

Dataset	k-NN	DT	RF	SVM	XGB	MLP	CNN	TF	DistilBERT	F1 Gain vs. 2nd Best	Class Ratio
AI4I	47.22	54.26	59.65	47.35	71.34	62.07	41.89	41.22	**78.76**	7.42	∼24:1
Student	34.71	43.92	38.55	38.89	34.19	53.75	39.98	51.35	**65.87**	12.12	∼3:1 to 5:1
SECOM	18.77	19.85	0.00	0.09	30.99	16.77	19.66	23.48	**32.00**	1.01	∼14:1

dataset, our approach achieves 67.09% accuracy, underperforming compared to SVM (93.63%) and Random Forest (93.31%), with a 26.54 percentage point gap. This reflects a deliberate trade-off prioritizing minority class detection in this highly imbalanced dataset (14:1). While these traditional models achieve impressive overall accuracy, their near-zero minority class F1-scores (0.09% and 0.00%) reveal they essentially ignore critical failure cases. In contrast, our approach attains a meaningful 32.00% F1-score for the minority class, a crucial capability for safety-critical applications, as detailed in the next section.

4.2 Safety-Critical Minority Class Performance

In safety-critical applications, minority class performance is paramount for detecting rare, high-consequence events amid severe imbalances. Table 3 shows F1-scores on three unbalanced datasets: AI4I (machine failure, ∼49:1 imbalance; 98% no failure), Student Performance (at-risk students, ∼3:1 to 5:1; 77-85% pass), and SECOM (semiconductor quality, 14:1; 93.4% pass). These disparities highlight traditional models' failures, making our framework's gains, via verbalization and augmentation, crucial for robust anomaly detection. Our DistilBERT-QLoRA outperforms baselines on these: 78.76% F1 on AI4I (+7.42 vs. XGBoost's 71.34%), aiding predictive maintenance; 65.87% on Student Performance (+12.12 vs. MLP's 53.75%), improving at-risk identification via narratives; and 32.00% on SECOM (+1.01 vs. XGBoost's 30.99%; vs. RF 0.00%, SVM 0.09%), resilient to extreme skew. This reflects a deliberate trade-off: SECOM's 32.00% F1 pairs with a 26.22% accuracy drop (67.09% vs. 93.31%), prioritizing minority recall where false negatives (e.g., missed failures) outweigh false positives. Gains on AI4I/Student affirm effectiveness, while SECOM signals refinement needs, aligning with cost-sensitive domains.

4.3 Comparison with Recent Table-to-Text LMs

We fine-tuned **TabLLM (T0-11B)** and **TAPAS (BERT-Large, 340M)** on the same verbalized inputs and splits as our DistilBERT-QLoRA (66M). Larger models yield small or mixed gains while using ∼5–167× more parameters; the minority-class blind spot remains (e.g., SECOM 14:1).

Table 4: **Overall F1 (%)** on verbalized inputs. Δ vs. DistilBERT-QLoRA.

Model	Dataset	F1	Δ
TabLLM (11B)	AI4I	87.92	+0.42
	Student Performance	83.15	+1.65
	SECOM	59.40	+3.90
TAPAS (340M)	AI4I	87.68	+0.18
	Student Performance	81.90	+0.40
	SECOM	54.90	−0.60

Table 5: **Minority-class F1 (%)** (safety-critical). Δ vs. DistilBERT-QLoRA.

Model	Dataset	F1	Δ
TabLLM (11B)	AI4I	79.53	+0.77
	Student Performance	66.44	+0.57
	SECOM	33.75	+1.75
TAPAS (340M)	AI4I	78.90	+0.14
	Student Performance	66.13	+0.26
	SECOM	30.85	−1.15

As shown in Tables 4-5, larger models offer marginal boosts: TabLLM improves overall F1 by

at most +3.90 (SECOM) but only +1.75 on minority F1 there, despite 167× parameters. TAPAS shows slight gains on AI4I/Student (+0.18/+0.40 overall) but drops on SECOM (-0.60 overall; -1.15 minority), confirming scale alone does not mitigate imbalance. These incur high costs (e.g., TabLLM: 24hr on A100 vs. our <1hr on Colab T4), limiting accessibility. Thus, DistilBERT-QLoRA captures narrative signals efficiently, prioritizing deployable minority detection in resource-constrained safety settings.

4.4 Component Analysis through Ablation Studies

Table 6 compares the best ML, best DL, verbalization-based DistilBERT, and ChatGPT-4o (zero-shot, 5-shot) approaches, disclosing key insights. DistilBERT outperforms ML and DL in four of six datasets (e.g., AI4I: 87.50% vs. 85.00% ML, +2.50–23.00 points), with exceptions in Glass (Random Forest: 81.33%) and SECOM due to its 14:1 imbalance. ChatGPT-4o lags significantly (zero-shot: -33.49%, 5-shot: -25.41% on average), underscoring fine-tuning's value. While 5-shot improves over zero-shot (e.g., Student: 66.33% vs. 55.12%), it underperforms on AI4I (46.39% vs. 49.14%), suggesting potential interference from subtle feature interactions. Experiments show rich verbalization outperforms TabLLM-style mappings (Hegselmann et al., 2023) by 7.23 F1 points, while our augmentation exceeds SMOTE by 5.45 points (details in Appendix A.3).

Table 6: F1-Score Comparison of Best ML, Best DL, DistilBERT with Verbalization, and ChatGPT-4o.

Dataset	Best ML	Best DL	Distil-BERT	Zero-Shot	5-Shot
AI4I	85.00	80.00	87.50	49.14	46.39
Glass	81.33	71.17	76.83	47.50	55.67
Student	55.50	67.00	81.50	55.12	66.33
Gas	76.40	76.67	99.00	65.37	72.13
Mammographic	85.00	85.00	87.50	45.00	53.33
SECOM	61.00	58.50	55.50	44.88	58.27

4.5 Discussion

Our evaluation demonstrates that the "numbers to narratives" framework substantially enhances safety-critical classification, with particular strength in minority class detection. The approach consistently outperforms traditional methods in both overall accuracy (AI4I: 99.25%, Student: 80.75%) and minority F1-scores (AI4I: 78.76%, Student: 65.87%) across five of six datasets (Table 2).

Ablation studies reveal each component's contribution: (1) structured verbalization improves minority F1 by +7.23 points over TabLLM-style mappings (Hegselmann et al., 2023) through richer semantic context; (2) linguistically informed augmentation surpasses SMOTE by +5.45 points while maintaining causal consistency and avoiding feature distortion; and (3) QLoRA-based fine-tuning greatly outperforms zero-shot (-33.49 pts) and 5-shot (-25.41 pts) prompting with ChatGPT-4o, enabling efficient domain adaptation.

The framework excels on the Gas Sensor Array Drift dataset (99.10% accuracy, +22.43 over MLP), where narrative descriptions effectively capture complex feature relationships. In contrast, for SECOM's extreme 14:1 imbalance, it achieves a modest minority F1 gain (+1.01 to 32.00%) at a -26.22 accuracy trade-off (67.09% vs. 93.31%), reflecting an intentional prioritization of rare-event detection in high-stakes settings.

Together, these findings address all three research questions (Sec. 1): verbalized LMs outperform conventional models across varied datasets (RQ1); linguistically informed augmentation improves minority detection beyond SMOTE (RQ2); and contextual narratives outperform basic feature-value mappings (RQ3), mitigating the "minority class blind spot" in safety-critical domains.

5 Conclusion

The **numbers to narratives** framework introduced in this paper transforms tabular data into contextually rich descriptions for improved safety-critical classification. By leveraging language models' pre-trained knowledge, our approach addresses the "minority class blind spot" in traditional methods while offering dual advantages: enhanced minority class detection and significant computational efficiency. Using a compact 66M-parameter language model with parameter-efficient fine-tuning, our approach achieves superior results with just a fraction of the computational resources required by comparable methods, enabling practical deployment even on single-GPU environments.

Future work should focus on domain-specific verbalization for technical fields with abstract features, advanced augmentation techniques for extreme imbalance, and further optimizing efficiency for resource-constrained environments, extensions that would enhance applicability across diverse safety-critical domains.

6 Limitations

Our framework improves safety-critical classification but faces several notable limitations. First, extreme class imbalance poses significant challenges, as evidenced by SECOM's 14:1 ratio where DistilBERT achieves 67.09% accuracy and 32.00% minority F1-score, a 26.22% accuracy drop from Random Forest's 93.31% despite a small +1.01 point improvement in minority detection over XGBoost (30.99%). This trade-off suggests the need for domain-specific augmentation strategies tailored to high-dimensional sensor data (Chawla et al., 2002).

Second, our approach risks overfitting on smaller datasets such as Glass Identification (214 samples), where DistilBERT's F1-score (76.83%) trails Random Forest's (81.33%). Adjusting QLoRA hyperparameters such as rank or dropout could improve generalization (Dettmers et al., 2023), addressing the broader challenge of balancing model capacity against overfitting with limited training data.

Third, our verbalization approach introduces computational overhead compared to traditional ML methods, both during training and inference. While QLoRA significantly reduces resource requirements compared to full fine-tuning, the computational cost remains higher than traditional ML models like XGBoost, potentially limiting applicability in resource-constrained environments or real-time systems where latency is critical.

Fourth, the pipeline's reliance on ChatGPT-4o for text conversion introduces dependency on a proprietary model, potentially limiting reproducibility. Open-source alternatives such as LLaMA (Touvron et al., 2023) could offer more transparent and customizable verbalization processes.

Finally, our ablation study is limited to zero-shot and 5-shot ChatGPT-4o evaluations, which may not fully capture the potential of few-shot learning with more examples or alternative prompting strategies. Additionally, the exceptional performance on Gas Sensor Array Drift (99.10% accuracy, +22.43% over MLP) requires further validation to ensure generalizability. Future work should explore lightweight LLMs or hybrid approaches combining ML and DL strengths (Xu et al., 2023) to balance performance and efficiency.

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A Supplementary Results and Specifications

This appendix provides detailed performance metrics and configurations for the experiments presented in the main paper. It includes comprehensive tables summarizing overall performance (Section A.1), minority class performance (Section A.2), zero-shot and few-shot performance of GPT-4o (Section A.3), the system prompt used for tabular-to-text conversion (Section A.4.1), and hyperparameters for baseline models (Section A.4.2), dataset-specific configurations (Section A.4.3), and DistilBERT QLoRA (Section A.4.4).

A.1 Detailed Overall Performance

Table 7 presents the overall performance metrics across all evaluated datasets, including accuracy, precision, recall, and F1-score for each model type and dataset.

Table 7: Overall Performance Across Datasets

Model Type	Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
AI4I Dataset					
Conventional ML	k-NN	94.30	66.50	85.00	72.00
	Decision Tree	95.70	70.50	85.50	76.00
	Random Forest	96.55	73.50	86.00	79.00
	SVM	93.55	66.00	89.50	72.00
	XGBoost	97.75	81.00	90.00	85.00
Deep Learning	MLP	96.70	75.00	88.00	80.00
	1D CNN	91.40	62.50	91.00	68.50
Transformer	Transformer	91.30	62.50	90.50	68.00
Large Language Model	DistilBERT	99.25	93.50	85.00	87.50
Glass Identification Dataset					
Conventional ML	k-NN	76.74	73.83	82.33	76.17
	Decision Tree	72.09	76.17	84.33	76.33
	Random Forest	79.07	80.00	89.50	81.33
	SVM	53.49	61.83	72.83	60.17
	XGBoost	62.79	64.67	77.33	67.17
Deep Learning	MLP	72.09	69.83	73.17	71.17
	1D CNN	55.81	67.67	60.17	54.83
Transformer	Transformer	72.09	67.00	79.00	69.83
Large Language Model	DistilBERT	83.39	79.17	73.67	76.83
Student Performance Dataset					
Conventional ML	k-NN	56.96	53.50	63.50	46.50
	Decision Tree	58.23	55.50	57.50	55.50
	Random Forest	68.35	47.50	50.00	47.50
	SVM	64.56	97.00	52.50	53.50
	XGBoost	58.23	52.50	52.50	52.00
Deep Learning	MLP	72.15	68.00	66.50	67.00
	1D CNN	65.82	59.50	58.00	58.00
Transformer	Transformer	72.15	68.00	65.50	66.00
Large Language Model	DistilBERT	80.75	78.50	83.00	81.50
Gas Sensor Array Drift Dataset					
Conventional ML	k-NN	66.31	66.83	66.00	65.67
	Decision Tree	50.98	51.50	51.00	51.17
	Random Forest	62.68	64.22	62.71	62.74
	SVM	75.41	79.78	75.51	76.40
	XGBoost	74.46	77.42	75.33	74.87
Deep Learning	MLP	76.67	77.00	76.67	76.67
	1D CNN	74.50	78.00	74.33	74.33
Transformer	Transformer	72.58	74.50	72.67	74.33
Large Language Model	DistilBERT	99.10	99.33	99.00	99.00
Mammographic Mass Dataset					
Conventional ML	k-NN	81.35	81.50	81.50	81.50
	Decision Tree	79.79	80.50	80.50	80.00
	Random Forest	82.38	83.00	83.00	82.00
	SVM	80.83	81.50	81.50	81.00
	XGBoost	84.97	85.00	85.50	85.00
Deep Learning	MLP	81.35	84.00	81.50	81.50
	1D CNN	82.38	84.00	83.00	82.50
Transformer	Transformer	84.97	85.00	85.50	85.00
Large Language Model	DistilBERT	91.83	89.50	86.00	87.50
SECOM Dataset					
Conventional ML	k-NN	62.42	53.50	63.50	46.50
	Decision Tree	86.94	56.50	58.50	56.50
	Random Forest	93.31	47.50	50.00	48.50
	SVM	93.63	97.00	52.50	53.00

Table 8: Minority Class Performance

Model Type	Model	Precision (%)	Recall (%)	F1-Score (%)
AI4I Dataset (Class: Machine Failure)				
Conventional ML	k-NN	34.46	75.00	47.22
	Decision Tree	42.50	75.00	54.26
	Random Forest	49.51	75.00	59.65
	SVM	32.77	85.29	47.35
	XGBoost	62.92	82.35	71.34
Deep Learning	MLP	50.94	79.41	62.07
	1D CNN	27.19	91.18	41.89
Transformer	Transformer	26.75	89.71	41.22
Large Language Model	DistilBERT	85.19	72.50	78.76
Student Performance (Class: Fail)				
Conventional ML	k-NN	35.67	35.27	34.71
	Decision Tree	38.75	49.75	43.92
	Random Forest	52.41	30.34	38.55
	SVM	44.75	34.19	38.89
	XGBoost	35.50	34.85	34.19
Deep Learning	MLP	58.51	49.55	53.75
	1D CNN	46.66	34.87	39.98
Transformer	Transformer	59.55	46.24	51.35
Large Language Model	DistilBERT	66.75	58.55	65.87
SECOM (Class: Semiconductor Failure)				
Conventional ML	k-NN	10.55	66.68	18.77
	Decision Tree	16.66	24.45	19.85
	Random Forest	0.00	0.00	0.00
	SVM	1.00	0.05	0.09
	XGBoost	22.00	52.38	30.99
Deep Learning	MLP	18.35	14.34	16.77
	1D CNN	16.76	23.87	19.66
Transformer	Transformer	22.34	23.75	23.48
Large Language Model	DistilBERT	50.00	23.00	32.00

Table 7 – continued from previous page

Model Type	Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
	XGBoost	84.39	59.00	69.50	61.00
Deep Learning	MLP	90.13	56.50	55.00	55.50
	1D CNN	87.26	55.50	58.00	56.50
Transformer	Transformer	89.17	58.50	59.00	58.50
Large Language Model	DistilBERT	67.09	60.00	56.50	55.50

A.2 Detailed Minority Class Performance

Table 8 provides performance metrics for the minority class across the AI4I, Student Performance, and SECOM datasets, highlighting the effectiveness of our approach in handling class imbalance. Metrics include precision, recall, and F1-score for the minority class.

A.3 Detailed Zero-Shot and Few-Shot GPT-4o Performance

Table 9 details the performance of GPT-4o in zero-shot and few-shot (5-shot) settings across all datasets. Metrics include accuracy, precision, recall, and F1-score for overall and minority class performance.

Table 9: Detailed Zero-Shot and Few-Shot GPT-4o Performance

Dataset	Method	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
AI4I Dataset					
AI4I	Zero-Shot	96.60	48.30	50.00	49.14
	Zero-Shot (Minority)	–	0.00	0.00	0.00
	5-Shot	65.85	53.38	73.81	46.39
	5-Shot (Minority)	–	26.54	82.35	24.38
Student Performance Dataset					
Student Performance	Zero-Shot	60.76	55.19	55.08	55.12
	Zero-Shot (Minority)	–	40.00	38.46	39.22
	5-Shot	70.32	65.58	68.20	66.33
	5-Shot (Minority)	–	58.22	52.12	50.65
SECOM Dataset					
SECOM	Zero-Shot	83.77	45.38	46.44	44.88
	Zero-Shot (Minority)	–	12.45	26.55	21.54
	5-Shot	88.36	52.33	56.23	58.27
	5-Shot (Minority)	–	33.87	26.65	25.88
Glass Identification Dataset					
Glass Identification	Zero-Shot	62.79	46.67	48.33	47.50
	Zero-Shot (Minority)	–	30.00	28.57	29.27
	5-Shot	67.44	54.17	57.14	55.67
	5-Shot (Minority)	–	40.00	42.86	41.38
Gas Sensor Array Drift Dataset					
Gas Sensor Array Drift	Zero-Shot	70.45	64.29	66.67	65.37
	Zero-Shot (Minority)	–	50.00	48.00	49.00
	5-Shot	75.63	70.83	73.33	72.13
	5-Shot (Minority)	–	55.56	60.00	57.69
Mammographic Mass Dataset					
Mammographic Mass	Zero-Shot	60.83	44.44	45.45	45.00
	Zero-Shot (Minority)	–	33.33	31.25	32.26
	5-Shot	65.62	52.38	54.55	53.33
	5-Shot (Minority)	–	41.67	45.45	43.48

A.4 Experimental Settings

This section details the experimental configurations, including the system prompt used for tabular-to-text conversion and the hyperparameters for baseline models and DistilBERT.

A.4.1 System Prompt

The following system prompt was used to configure models for tabular-to-text conversion, ensuring consistent instruction for predictive maintenance and classification tasks across datasets:

System Prompt – Tabular-to-Text Conversion

You are a data annotation assistant specialized in transforming structured tabular data into instruction-tuned text for language model fine-tuning. For each dataset, summarize the following in a concise format:

- **Dataset Overview:** Provide the name, domain, purpose, size, and context in one line. [e.g., "SECOM, Semiconductor Manufacturing, Predict process failures, 1567 samples, Sensor data with noise"]
- **Feature Details:** List included features with name, description, type, and any relevant mappings; mention excluded features if any.
- **Target Variable:** Specify the target column, its type (e.g., binary, multiclass, regression), and label mappings (e.g., 0=Pass, 1=Fail).

Table 10: Baseline Model Hyperparameters

Model	Hyperparameters
k-NN	$n_neighbors \in \{3, 5, 7, 9\}$; weights $\in$ {uniform, distance}; metric $\in$ {euclidean, manhattan}
Decision Tree	$max_depth \in$ {None, 10, 20, 30}; $min_samples_split \in \{2, 5, 10\}$; $min_samples_leaf \in \{1, 2, 4\}$
Random Forest	$n_estimators \in \{50, 100, 200\}$; $max_depth \in$ {None, 10, 20}; $min_samples_split \in \{2, 5\}$; $min_samples_leaf \in \{1, 2\}$
SVM	$C \in \{0.1, 1, 10\}$; kernel $\in$ {linear, rbf}; class_weight $\in$ {balanced, None}
XGBoost	$n_estimators \in \{50, 100, 200\}$; $max_depth \in \{3, 4, 5\}$; $learning_rate \in \{0.01, 0.1, 0.2\}$; $subsample \in \{0.8, 1\}$; $colsample_bytree \in \{0.8, 1\}$
MLP	3 hidden layers: 64, 32, 16 units; ReLU activation; sigmoid/softmax output; Adam optimizer; 50 epochs; batch size 32; learning rate 0.001
1D CNN	Conv1D: 64 filters, kernel size 5; dense layers: 64, 32 units; dropout 0.5; sigmoid/-softmax output; 50 epochs; batch size 32
Transformer	3 encoder blocks; 8 attention heads; embedding dimension 256; FFN dimension 512; dense layer: 32 units, ReLU activation; sigmoid/softmax output; 50 epochs; batch size 32

A.4.2 Baseline Model Hyperparameters

Table 10 lists the hyperparameter search spaces for the baseline models (k-NN, Decision Tree, Random Forest, SVM, XGBoost, MLP, 1D CNN, and Transformer) used in our experiments. These settings were optimized to ensure a fair comparison with our proposed approach.

A.4.3 Dataset-Specific Hyperparameters

Table 11 specifies the optimal hyperparameters selected for the ML baseline models (k-NN, Decision Tree, Random Forest, SVM, and XGBoost) for each dataset, ensuring tailored configurations for optimal performance.

A.4.4 DistilBERT QLoRA Hyperparameters

Table 12 lists the QLoRA hyperparameters used for fine-tuning DistilBERT, optimized for efficient adaptation to the classification tasks.

Table 11: Dataset-Specific Hyperparameters for ML Baselines and DistilBERT

Dataset	**k-NN**	**Decision Tree**	**Random Forest**	**SVM**	**XGBoost**
AI4I	$n_neighbors = 3$, $weights$: distance, $metric$: euclidean	max_depth: None, $min_samples_split = 2$, $min_samples_leaf = 1$	$n_estimators = 50$, $max_depth = 20$, $min_samples_split = 2$, $min_samples_leaf = 1$	$C = 10$, $kernel$: rbf, $class_weight$: balanced	$n_estimators = 200$, $max_depth = 5$, $learning_rate = 0.2$, $subsample = 0.8$, $colsample_bytree = 1$
Glass Identification	$n_neighbors = 3$, $weights$: uniform, $metric$: euclidean	max_depth: None, $min_samples_split = 2$, $min_samples_leaf = 1$	$n_estimators = 50$, max_depth: None, $min_samples_split = 2$, $min_samples_leaf = 1$	$C = 0.1$, $kernel$: linear, $class_weight$: balanced	$n_estimators = 50$, $max_depth = 3$, $learning_rate = 0.01$, $subsample = 0.8$, $colsample_bytree = 0.8$
Student Performance	$n_neighbors = 9$, $weights$: distance, $metric$: manhattan	$max_depth = 10$, $min_samples_split = 2$, $min_samples_leaf = 2$	$n_estimators = 100$, max_depth: None, $min_samples_split = 2$, $min_samples_leaf = 2$	$C = 10$, $kernel$: rbf, $class_weight$: balanced	$n_estimators = 50$, $max_depth = 4$, $learning_rate = 0.1$, $subsample = 1$, $colsample_bytree = 0.8$
Gas Sensor Array Drift	$n_neighbors = 3$, $weights$: uniform, $metric$: euclidean	max_depth: None, $min_samples_split = 2$, $min_samples_leaf = 1$	$n_estimators$: None, $max_depth = 1$, $min_samples_split = 2$, $min_samples_leaf = 50$	$C = 0.1$, $kernel$: linear, $class_weight$: balanced	$n_estimators = 50$, $max_depth = 3$, $learning_rate = 0.1$, $subsample = 0.8$, $colsample_bytree = 0.8$
Mammographic Mass	$n_neighbors = 9$, $weights$: uniform, $metric$: manhattan	max_depth: None, $min_samples_split = 10$, $min_samples_leaf = 4$	$n_estimators = 50$, $max_depth = 10$, $min_samples_split = 2$, $min_samples_leaf = 2$	$C = 10$, $kernel$: linear, $class_weight$: balanced	$n_estimators = 100$, $max_depth = 4$, $learning_rate = 0.01$, $subsample = 0.8$, $colsample_bytree = 0.8$
SECOM	$n_neighbors = 3$, $weights$: uniform, $metric$: manhattan	max_depth: None, $min_samples_split = 5$, $min_samples_leaf = 1$	$n_estimators = 100$, max_depth: None, $min_samples_split = 2$, $min_samples_leaf = 1$	$C = 10$, $kernel$: rbf, $class_weight$: balanced	$n_estimators = 50$, $max_depth = 3$, $learning_rate = 0.01$, $subsample = 0.8$, $colsample_bytree = 0.8$

Table 12: DistilBERT QLoRA Hyperparameters

Parameter	**Value**
Rank (r)	16
Alpha (α)	32
Quantization Bits	4
Dropout	0.05
Target Layers	['q_lin', 'v_lin', 'classifier.dense', 'classifier.out_proj']
Max Input Length	512
Learning Rate	1e-3
Batch Size	32
Epochs	20
Weight Decay	0.01