Universität Stuttgart
Institut für Fahrzeugtechnik Stuttgart

Vertraulich

Wie schreibe ich eine Masterarbeit

How do I write a master's thesis

Masterarbeit

von

cand. emob abc def

Matr. Nr. 7654321

Institutsbetreuer:	Mathias Jaksch, M.Sc.
Externer Betreuer:	Dipl.-Ing. Hans Wurst, VW Group
Prüfer:	Prof. Dr.-Ing. H.-C. Reuss

Vorgelegt an der Universität Stuttgart
Institut für Fahrzeugtechnik Stuttgart
Lehrstuhl Kraftfahrzeugmechatronik

2021

Universität Stuttgart
Institut für Fahrzeugtechnik Stuttgart

Lehrstuhl
Kraftfahrzeugmechatronik
Prof. Dr.-Ing. H.-C. Reuss

Tel. (+49) 711 685 – 68501
Fax (+49) 711 685 – 68533

info@ifs.uni-stuttgart.de

31.10.2020 / HCR / JM

Masterarbeit

für

Herrn cand. emob abc def

Matr. Nr. 7654321

Thema: Wie schreibe ich eine Masterarbeit

How do I write a master's thesis

Textblock Zeile 01
Textblock Zeile 02
Textblock Zeile 03
Textblock Zeile 04
Textblock Zeile 05
Textblock Zeile 06
Textblock Zeile 07
Textblock Zeile 08
Textblock Zeile 09
Textblock Zeile 10
Textblock Zeile 11
Textblock Zeile 12
Textblock Zeile 13
Textblock Zeile 14
Textblock Zeile 15
Textblock Zeile 16
Textblock Zeile 17
Textblock Zeile 18
Textblock Zeile 19 – Anmerkung: Dies ist die letztmögliche Zeile auf dieser Seite!

Universität Stuttgart
Institut für Fahrzeugtechnik Stuttgart

Schutzvermerk:	Die Arbeit ist bis zum 30.04.2024 vertraulich zu behandeln
Institutsbetreuer:	Mathias Jaksch, M.Sc.
Externer Betreuer:	Dipl.-Ing. Hans Wurst, VW Group
Prüfer:	Prof. Dr.-Ing. H.-C. Reuss
Beginn:	31.10.2020
Abgabedatum:	30.04.2021 (Abgabe erfolgte fristgerecht)

Prof. Dr.-Ing. H.-C. Reuss

Universität Stuttgart
Institut für Fahrzeugtechnik Stuttgart

Erklärung

Hiermit versichere ich, abc def, dass ich die vorliegende Arbeit, bzw. die darin mit meinem Namen gekennzeichneten Anteile, selbständig verfasst und bei der Erstellung der Arbeit die einschlägigen Bestimmungen, insbesondere zum Urheberrechtsschutz fremder Beiträge, eingehalten und nur die angegebenen Quellen und Hilfsmittel benutzt habe.

Soweit meine Arbeit fremde Beiträge (z. B. Bilder, Zeichnungen, Textpassagen) enthält, erkläre ich, dass ich diese Beiträge als solche gekennzeichnet (z. B. Zitat, Quellenangabe) habe und dass ich eventuell erforderliche Zustimmungen der Urheber zur Nutzung dieser Beiträge in meiner Arbeit eingeholt habe.

Für den Fall der Verletzung Rechter Dritter durch meine Arbeit erkläre ich mich bereit, der Universität Stuttgart einen daraus entstehenden Schaden zu ersetzen bzw. die Universität Stuttgart von eventuellen Ansprüchen Dritter freizustellen.

Die Arbeit ist weder vollständig noch in wesentlichen Teilen Gegenstand eines anderen Prüfungsverfahrens gewesen. Ferner ist sie weder vollständig noch in Teilen bereits veröffentlicht worden. Das elektronische Exemplar stimmt mit den anderen Exemplaren überein.

Stuttgart, den 30.04.2021

_____

abc def

Preamble

Contents

Acronyms **VII**

Symbols **IX**

List of Figures **XI**

List of Tables **XIII**

Kurzfassung **XV**

Abstract **XVII**

1 Introduction **1**
1.1 Background and Context 1
1.2 Problem Statement 2
1.3 Research Objectives 3
1.4 Significance of the Study 4
1.5 Thesis Structure 5
1.6 Project Plan 6
1.6.1 Exposé Phase (November - January) 6
1.6.2 Implementation Phase (December - March) 7
1.6.3 Finalization Phase (April) 7

2 Theoretical Background **9**
2.1 Database Management Systems 9
2.1.1 Relational Database Management Systems 9
2.1.2 Non-Relational Database Systems 11
2.1.3 Database Normalization 12
2.2 Database Design Methodologies 13
2.2.1 Entity-Relationship Modeling 13
2.2.2 Object-Relational Mapping 14
2.3 Software Development Methodologies for Automotive Systems 15
2.3.1 Use Case Driven Development 15
2.4 Access Control and Security Models 16
2.4.1 Role-Based Access Control 16
2.4.2 Attribute-Based Access Control 18
2.5 Version Control and Temporal Database Concepts 18
2.5.1 Traditional Version Control Systems 19
2.5.2 Temporal Database Concepts 19

2.5.3 Database Versioning Approaches 20

3 State of the Art **23**
3.1 Parameter Management in Automotive Software Development 23
3.1.1 Evolution of Automotive Parameter Management 23
3.1.2 Challenges in Automotive Parameter Management 24
3.1.3 Current Approaches and Their Limitations 25
3.2 Database Version Control Systems 26
3.2.1 Traditional Database Versioning Approaches 26
3.2.2 Versioning Strategies for Structured Data 27
3.2.3 Temporal Database Approaches 28
3.2.4 Version Control for Parameter Management 29
3.3 Role-Based Access Control in Enterprise Systems 30
3.3.1 RBAC Model and Extensions 30
3.3.2 RBAC in Database Systems 30
3.3.3 Access Control for Automotive Parameter Management 31
3.4 Database Integration with Enterprise Systems 32
3.4.1 Enterprise Integration Patterns 32
3.4.2 Database Synchronization Approaches 33
3.5 Research Directions 34

4 Methodology and Concept Development **35**
4.1 Requirements Analysis 35
4.1.1 Functional Requirements 35
4.1.2 User Role Requirements 36
4.1.3 Data Management Requirements 37
4.1.4 Integration Requirements 37
4.2 System Architecture Design 38
4.2.1 Entity-Relationship Model 38
4.2.2 Temporal Database Consideration 39
4.2.3 Release/Phase Separation Rationale 39
4.2.4 Database Schema Design 40
4.2.5 Version Control Mechanism 41
4.2.6 Parameter Definition Database Synchronization 41
4.3 Validation Mechanisms 43
4.3.1 Data Integrity Constraints 43
4.3.2 Business Rule Validation 43
4.3.3 Conflict Resolution Strategies 44
4.3.4 Audit and Traceability Mechanisms 44

5 Implementation **47**
5.1 Database Structure Implementation 47
5.1.1 Core Data Entities 47
5.1.2 User Management and Access Control 50
5.1.3 Release Management Implementation 53
5.1.4 Variant and Segment Management 55
5.1.5 Change Tracking Mechanisms 58
5.2 Version Control Implementation 59
5.2.1 Release Phase Management 59
5.2.2 Parameter History Tracking 60
5.2.3 Freeze Mechanism Implementation 62
5.3 Query Optimization Strategies 63
5.3.1 Indexing Strategy 63
5.3.2 Partitioning Implementation 65
5.4 Integration Implementation 66
5.4.1 Parameter Definition Database Synchronization 66
5.4.2 Vehicle Configuration Database Exchange 68
5.4.3 Parameter File Generation Support 69
5.4.4 Integration Architecture Overview 70
5.5 Security Implementation 71
5.5.1 Role-Based Access Control 71
5.5.2 Data Security Measures 73
5.5.3 Audit Trail Implementation 73

6 Evaluation and Validation **77**
6.1 Validation Methodology 77
6.1.1 Test Scenario Development 77
6.1.2 Performance Measurement Framework 78
6.2 Functional Testing Results 78
6.2.1 User Management Validation 78
6.2.2 Release Management Validation 82
6.2.3 Variant Management Validation 85
6.3 Performance Analysis 89
6.3.1 Query Performance Assessment 89
6.3.2 Storage Requirements Analysis 91
6.4 Integration Testing 93
6.4.1 Parameter Definition Database Synchronization 93
6.4.2 Vehicle Configuration Integration 93
6.5 Comparison with Excel-Based Approach 94
6.5.1 Feature Comparison 94

6.5.2 Performance Comparison 95
6.5.3 Data Integrity Comparison 96

Bibliography **97**

A User Management Test Cases **101**
A.1 Role-Based Permission Test Cases 101
A.2 Module-Based Access Control Test Cases 103
A.3 Direct Permission Assignment Test Cases 104
A.4 Phase-Specific Permission Test Cases 105
A.5 Boundary Case Test Cases 105
A.6 Test Implementation Details 106
A.7 Role Permission Matrix 108

B Variant Management Test Cases **109**
B.1 Variant Creation Test Cases 109
B.2 Segment Modification Test Cases 110
B.3 Performance Test Cases 113
B.4 Test Implementation Details 114
B.5 Test Environment Configuration 119

Acronyms

Symbols

Symbol	Unit	Description
F_{N}	N	Force
τ	Nm	Torque

List of Figures

1.1 Gantt Chart of the planned work schedule. 8

2.1 Example of a Relational Schema [40] 10
2.2 Major Types of NoSQL Databases [16] 12
2.3 Entity-Relationship Diagram for Core VMAP Entities [25] 14
2.4 Use Case Diagram of switching system [20] 15
2.5 Role-Based Access Control Model [33] 17
2.6 Temporal Database Example [24] 20

4.1 Hybrid Role-Permission Model 36
4.2 Entity-Relationship Diagram for VMAP Database 38
4.3 Comparison of Version-based vs. Phase-based Parameter Synchronization Approaches 42
4.4 Audit Trail for Phase Freeze Operation 45

6.1 Variant Modification Audit Trail 87
6.2 Storage allocation across different entity types for the full dataset. . . . 91
6.3 Performance Comparison with Excel-Based Approach 95

List of Tables

6.1 Sample Module Developer Role Permission Test Cases 79
6.2 User Management Test Results 81
6.3 Phase Transition Test Results 82
6.4 Phase Freeze Protection Test Cases 84
6.5 Variant Operation Performance Metrics 86
6.6 Segment Modification Test Cases 88
6.7 Segment Operation Performance 88
6.8 Query Performance Comparison 89
6.9 Storage Requirements Analysis 92
6.10 Feature Comparison with Excel-Based Approach 95

A.1 Administrator Role Permission Test Cases 101
A.2 Module Developer Role Permission Test Cases 101
A.3 Documentation Team Role Permission Test Cases 102
A.4 Read-Only User Role Permission Test Cases 103
A.5 Module-Based Access Control Test Cases 103
A.6 Direct Permission Assignment Test Cases 104
A.7 Phase-Specific Permission Test Cases 105
A.8 Boundary Case Test Cases 106
A.9 Role Permission Matrix 108

B.1 Variant Creation Test Cases 109
B.2 Segment Creation Test Cases 111
B.3 Segment Update Test Cases 112
B.4 Segment Deletion Test Cases 112
B.5 Variant and Segment Performance Test Cases 113

Kurzfassung

Abstract

1 Introduction

Modern commercial vehicles represent a quintessential example of cyber-physical systems, where sophisticated software enables precise control over complex mechanical components. The software controlling these vehicles has grown exponentially in complexity over recent decades, evolving from simple engine management to comprehensive control of virtually all vehicle functions. At the core of this evolution is the Electronic Control Unit (ECU)—a specialized computer that executes software to manage specific vehicle functions [7]. Contemporary commercial vehicles contain dozens of interconnected ECUs working in concert to ensure optimal performance, efficiency, and safety across diverse operating conditions.

1.1 Background and Context

The automotive industry has undergone a profound transformation over the past decades, evolving from predominantly mechanical systems to highly sophisticated mechatronic platforms [29]. This evolution has been particularly pronounced in the commercial vehicle sector, where modern trucks rely on complex networks of Electronic Control Units to manage everything from engine performance to safety systems [7]. These systems must adapt to a wide range of operational conditions, regulatory requirements, and market-specific configurations, creating a significant challenge in managing software variability.

At the heart of this variability management lies the Common Powertrain Controller (CPC)—a central ECU managing critical functions related to engine and transmission control. The CPC's operation is governed by thousands of configurable parameters that determine how the powertrain behaves under specific conditions [39]. These parameters influence everything from basic engine timing to sophisticated emission control strategies, making their precise configuration essential for vehicle performance, efficiency, and regulatory compliance.

The parameter management challenge is further complicated by the global nature of modern vehicle development. Commercial vehicles must conform to different emissions regulations, operate in diverse environmental conditions, and meet varying customer expectations across global markets. Consequently, a single vehicle model may require numerous parameter configurations, each tailored to specific combinations of market requirements, hardware configurations, and customer specifications [41].

1.2 Problem Statement

The current approach to parameter management in commercial vehicle development relies predominantly on distributed Excel spreadsheets, a methodology that emerged during a period when parameter counts were manageable and development teams were smaller [41]. However, as software complexity has increased exponentially, this fragmented approach has introduced significant limitations and risks to the development process.

Development teams distributed across different locations must coordinate changes to thousands of parameters, track their versions, and ensure consistency across multiple vehicle platforms. The absence of a centralized version control system makes it exceptionally difficult to track changes effectively and manage releases. This situation becomes particularly critical when dealing with safety-critical parameters that directly influence vehicle performance and regulatory compliance.

The manual nature of current processes, combined with the lack of automated validation mechanisms, introduces substantial risks of data inconsistency, version conflicts, and delayed implementation of critical parameter updates. Parameter changes are not consistently verified against established rules and constraints, potentially leading to incompatible configurations or non-compliant behavior [39].

Integration with critical enterprise systems presents another significant challenge. The current process of synchronizing data with internal database systems involves several manual steps, consuming valuable development resources and introducing potential points of failure in the configuration management workflow. The absence of automated data validation and synchronization mechanisms creates additional risks for data integrity and consistency across these interconnected systems.

Furthermore, the increasing emphasis on rapid development cycles and continuous integration in the automotive industry demands a more sophisticated approach to parameter management [7]. The existing system's limitations become particularly apparent when considering the need for simultaneous development of multiple vehicle variants, each requiring specific parameter configurations for different markets and regulatory environments.

These challenges collectively underscore the urgent need for a modern, database-driven solution that can address the complexities of contemporary automotive software development while providing a scalable foundation for future growth and adaptation.

1.3 Research Objectives

This thesis aims to address the fundamental challenges in automotive parameter management through the development of database architecture for VMAP (Variant Management and Parametrization), a web-based application for powertrain parameter configuration. The research objectives encompass both theoretical foundations and practical implementation considerations, focusing on creating a robust solution that meets the complex demands of modern vehicle development processes.

The primary research objective centers on developing a centralized database architecture that can effectively manage the complexity of powertrain parameters while maintaining data integrity and traceability [42]. This architecture must support sophisticated version control mechanisms that can handle parameter variations across different development stages and vehicle variants. The system should provide comprehensive audit trails and change history, enabling development teams to track modifications and understand the evolution of parameter configurations over time.

A second crucial objective focuses on the implementation of a sophisticated version control system that addresses the unique requirements of parameter management in automotive software development. This system must go beyond traditional source code version control approaches to handle the complex relationships between parameters, their variants, and their applications across different vehicle platforms [39]. The version control mechanism should support parallel development streams while maintaining consistency and preventing conflicts in parameter configurations.

The research also aims to establish a comprehensive role-based access control system that supports the diverse needs of different user groups within the development process. This includes creating specialized interfaces and permissions for Module Developers, Documentation Team members, Administrators, and Read-only Users, each with specific capabilities and restrictions aligned with their responsibilities [33]. The access control system must balance security requirements with the need for efficient collaboration among development teams.

Integration with existing enterprise systems represents another critical objective of this research. The VMAP system must establish seamless data exchange mechanisms with internal database systems, ensuring consistent information flow while minimizing manual intervention [7]. This integration should support automated validation of parameter changes and provide mechanisms for maintaining data consistency across different systems.

A final key objective involves the development of database interfaces and query optimization strategies that will support the web-based interface implementation. While

the actual User Interface (UI) development falls outside the scope of the thesis, the research will focus on designing efficient database structures, stored procedures, and APIs that enable seamless integration with the planned web interface [29]. This includes developing optimized query patterns for complex operations such as parameter comparison, variant management, and release workflows, while ensuring robust data validation and business rule enforcement.

1.4 Significance of the Study

The significance of this research extends beyond addressing immediate technical challenges in parameter management. By developing a comprehensive database solution for variant management and parametrization, this work contributes to the broader field of automotive software engineering in several important ways.

First, the research advances the understanding of version control in parameter-centric systems, extending traditional concepts of software versioning to accommodate the unique characteristics of automotive parameter configurations. While considerable research has been conducted on code versioning, the versioning of parameter data presents distinct challenges that require specialized approaches [4]. This thesis contributes to closing this gap by developing and evaluating new methods for parameter versioning in complex automotive systems.

Second, the work addresses critical industry needs for improved quality and efficiency in vehicle development. Commercial vehicle manufacturers face increasing pressure to reduce development time while managing growing software complexity and ensuring regulatory compliance across global markets [7]. By providing a more robust and efficient parameter management solution, this research directly contributes to these industry priorities, potentially reducing development costs and improving vehicle quality through more consistent parameter configurations.

Third, the research advances the integration of database technology with domain-specific engineering processes. By developing specialized database structures and functions tailored to the unique requirements of automotive parameter management, this work demonstrates how database technology can be adapted to support complex engineering workflows [13]. This integration perspective is valuable not only for automotive applications but also for other engineering domains facing similar challenges in managing complex, highly variable system configurations.

Finally, the research contributes to the growing field of model-based systems engineering by providing a structured approach to managing the parametric aspects of system

models. As the automotive industry continues to adopt model-based approaches for system development, the management of parameter configurations becomes increasingly critical for maintaining model integrity and traceability [39]. This thesis provides insights and solutions that support this evolution toward more systematic model-based development practices.

1.5 Thesis Structure

The thesis is organized into six chapters that systematically address the research objectives and present a comprehensive solution for automotive parameter management. The structure follows a logical progression from theoretical foundations through practical implementation, ensuring thorough coverage of both academic and industry perspectives.

Following this introduction, Chapter 2 presents a comprehensive review of the state of the art in database version control systems and automotive parameter management. This chapter examines existing approaches to software configuration management in the automotive industry [29], analyzes current database versioning techniques [4], and evaluates their applicability to parameter management systems. The review encompasses both academic research and industry practices, providing a solid foundation for the proposed solution.

Chapter 3 details the methodology and concept development, beginning with a thorough requirements analysis based on industry needs and academic best practices [39]. This chapter explores the system architecture design, consisting of the database schema, version control mechanisms, and user management frameworks. Particular attention is given to the integration requirements with existing systems and the development of robust validation mechanisms for parameter management.

The implementation strategy and technical design are presented in Chapter 4, which outlines the practical realization of the VMAP system. This chapter describes the development of the database structure, the implementation of version control mechanisms, and the creation of the database interfaces. The chapter also details the integration approaches with internal database systems, highlighting the technical challenges and solutions developed during the implementation phase [7].

Chapter 5 focuses on system evaluation and validation, presenting a comprehensive assessment of the VMAP system against the defined research objectives. This chapter includes detailed performance analyses, user acceptance testing results, and

comparative evaluations against existing parameter management solutions. The evaluation framework incorporates both quantitative metrics and qualitative assessments to provide a thorough understanding of the system's effectiveness [13].

The thesis concludes with Chapter 6, which summarizes the research findings and presents recommendations for future development. This chapter reflects on the contributions of the research to both academic knowledge and industry practice, discussing the implications for automotive software development and configuration management. Additionally, it outlines potential areas for future research and system enhancement based on the insights gained during the project.

Throughout these chapters, the research methodology combines theoretical analysis with practical implementation, ensuring that the resulting system meets both academic standards and industry requirements. Special attention is given to database versioning approaches, user role management, and integration strategies with existing systems, addressing the unique challenges of automotive software configuration management [39].

1.6 Project Plan

The research project follows a structured approach spanning six months from November 2024 to April 2025, organized into three distinct phases: Exposé, Implementation, and Finalization. The comprehensive timeline ensures systematic progression through all research objectives while maintaining academic rigor and quality standards.

1.6.1 Exposé Phase (November - January)

The initial phase focuses on establishing strong theoretical foundations and gathering comprehensive requirements. Literature review constitutes a significant portion of this phase, extending over six weeks to ensure thorough coverage of current database versioning approaches, parameter management systems, and industry practices in automotive applications. This review encompasses analysis of existing version control systems, examination of industry standards for software configuration management, and evaluation of current parameter management solutions.

Requirements analysis follows the literature review, spanning three weeks to capture detailed system specifications. This phase involves extensive stakeholder consultation to document system requirements, analyze existing Excel-based workflows, define

integration requirements with internal database systems, and establish user roles and access control specifications. The Exposé phase concludes with the submission of a comprehensive research proposal at the end of Week 3 in January.

1.6.2 Implementation Phase (December - March)

The implementation phase encompasses four major components, each allocated four weeks for development and refinement. Database design initiates this phase, focusing on developing the schema for parameter management, designing version control mechanisms, creating data models for user management, and planning integration interfaces with existing systems.

System architecture development follows, concentrating on overall system design, version control workflows, user management frameworks, and validation mechanisms. This stage establishes the foundational structure for the entire system while ensuring alignment with identified requirements and industry standards.

Prototype development constitutes the third component, involving implementation of core database functionality, development of version control features, creation of user management interfaces, and construction of system integration components. This stage transforms theoretical designs into practical implementations while maintaining focus on system usability and performance.

The final component of this phase involves comprehensive testing and validation, including database performance testing, validation of version control mechanisms, testing of user management functions, and verification of system integration capabilities. This stage ensures all implemented features meet specified requirements and performance standards.

1.6.3 Finalization Phase (April)

The concluding phase focuses on documentation and thesis preparation over four weeks. The first two weeks are dedicated to comprehensive documentation, including compilation of implementation details and system architecture documentation.

The subsequent two weeks concentrate on thesis writing, involving comprehensive documentation of research findings, inclusion of test results and analysis, preparation of conclusions and recommendations, and thorough content review and refinement. The phase concludes with thesis submission in Week 16 and final project presentation in Week 17.

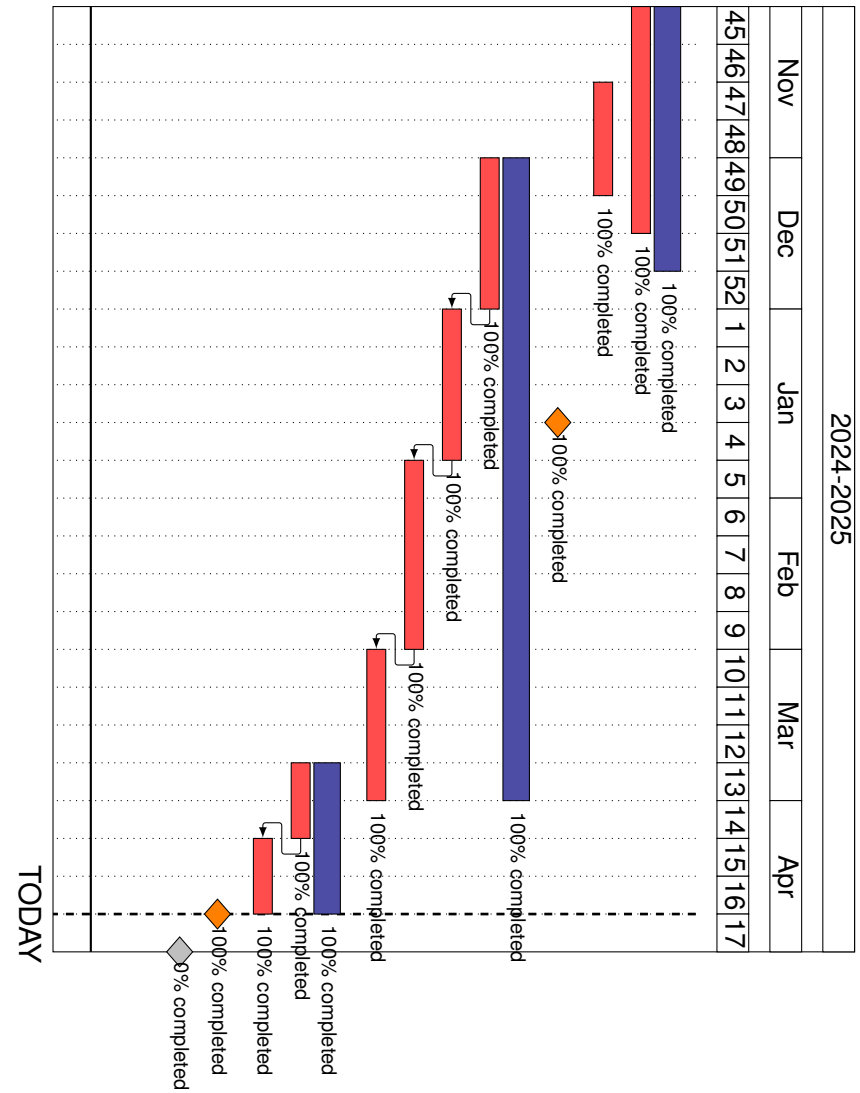

Figure 1.1: Gantt Chart of the planned work schedule.

2 Theoretical Background

This chapter establishes the theoretical foundation necessary for understanding the design and implementation of the Variant Management and Parametrization (VMAP) database system. It begins with an overview of database systems and their types, followed by an examination of database design methodologies, including entity-relationship modeling. The chapter then explores software development models relevant to automotive parameter management, particularly the V-Model that underpins the release management approach. Finally, it discusses role-based access control systems, version control concepts, and temporal database management, which are critical for the parameter versioning requirements of automotive software development.

2.1 Database Management Systems

Database management systems (DBMS) serve as the foundation for structured information storage and retrieval. They provide mechanisms for storing, organizing, and accessing data while ensuring integrity, security, and concurrent access [13]. The choice of database system significantly impacts the design and capabilities of applications built upon it, making it a critical architectural decision for any information system. The basic division is made into two categories: relational and non-relational.

2.1.1 Relational Database Management Systems

Relational Database Management Systems (RDBMS) organize data into structured tables composed of rows and columns, based on the relational model proposed by E.F. Codd in 1970 [9]. The relational model establishes a mathematical foundation for representing data as relations (tables) with well-defined operations for data manipulation. This approach has dominated database technology for decades due to its solid theoretical foundation and practical advantages for structured data management.

In relational databases, tables adhere to predefined schemas that specify the structure, data types, and constraints applicable to the data. Each table typically includes a primary key that uniquely identifies each row, while foreign keys establish relationships between tables, implementing the referential integrity that ensures consistency across related data. Figure 2.1 illustrates a simple relational schema.

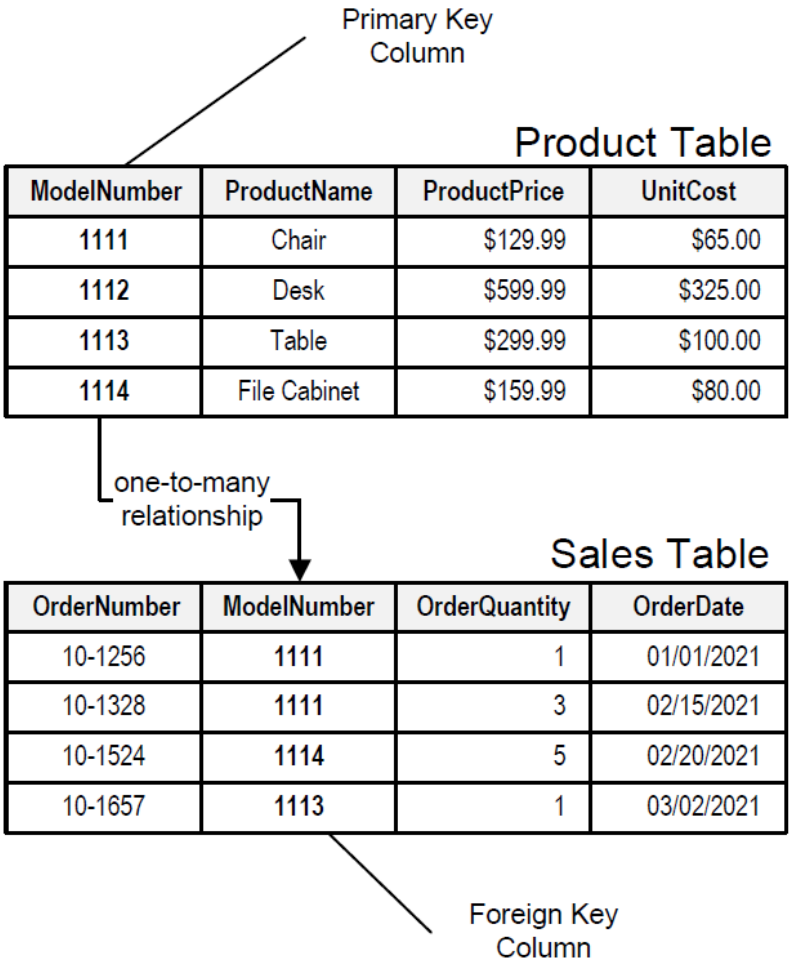

Figure 2.1: Example of a Relational Schema [40]

A key strength of relational databases is their adherence to ACID properties (Atomicity, Consistency, Isolation, Durability), which ensure reliable transaction processing. Atomicity guarantees that transactions are treated as indivisible units that either complete entirely or have no effect. Consistency ensures that transactions maintain database integrity by transforming the database from one valid state to another. Isolation prevents interference between concurrent transactions, making them appear as if executed sequentially. Durability ensures that committed transactions persist even after system failures.

ACID compliance makes relational databases particularly suitable for applications where data integrity and consistency are paramount, such as financial systems, healthcare records, and automotive parameter management where configuration errors could lead to safety issues [39]. For the VMAP system, where incorrect parameter values

could potentially affect vehicle safety and performance, the strong consistency guarantees of relational databases provide essential safeguards against data corruption or inconsistency.

2.1.2 Non-Relational Database Systems

Non-relational databases, often referred to as NoSQL (Not Only SQL) databases, emerged as alternatives to the relational model, particularly for use cases involving large-scale distributed systems, unstructured data, or schema flexibility requirements. Unlike relational databases, NoSQL systems typically sacrifice some aspects of ACID compliance in favor of scalability, flexibility, and performance characteristics suited to specific application domains [4].

NoSQL databases can be categorized into several types based on their data models. Document databases such as MongoDB and CouchDB store semi-structured data as documents, typically in formats like JSON or XML, allowing flexible schema evolution. Key-value stores like Redis and DynamoDB provide simple data access through key-based lookups, optimized for high-throughput operations. Column-family stores such as Cassandra and HBase organize data in column families for efficient storage and retrieval of large datasets. Graph databases like Neo4j and Amazon Neptune optimize the storage and traversal of highly connected data structures.

Many NoSQL systems follow the BASE principle (Basically Available, Soft state, Eventually consistent) rather than ACID, prioritizing availability and partition tolerance over immediate consistency. This approach aligns with the CAP theorem proposed by Brewer [**?**], which states that distributed systems can guarantee at most two of the following three properties: Consistency, Availability, and Partition tolerance.

While NoSQL databases excel in specific domains such as high-volume web applications, real-time analytics, and social networks, they present challenges for applications requiring complex transactions, strict data integrity, or sophisticated query capabilities across related entities [22]. For automotive parameter management, where data integrity and complex relationships between parameters, variants, and configurations are essential, the trade-offs presented by NoSQL systems make them less suitable than relational databases. The potential for eventual consistency rather than immediate consistency could lead to incorrect parameter configurations being used during development or testing, creating significant risks for vehicle performance and safety.

Additionally, the hierarchical nature of automotive electronic systems, with ECUs containing modules, PIDs, and parameters in well-defined relationships, aligns naturally with the relational model's approach to representing structured data and relationships.

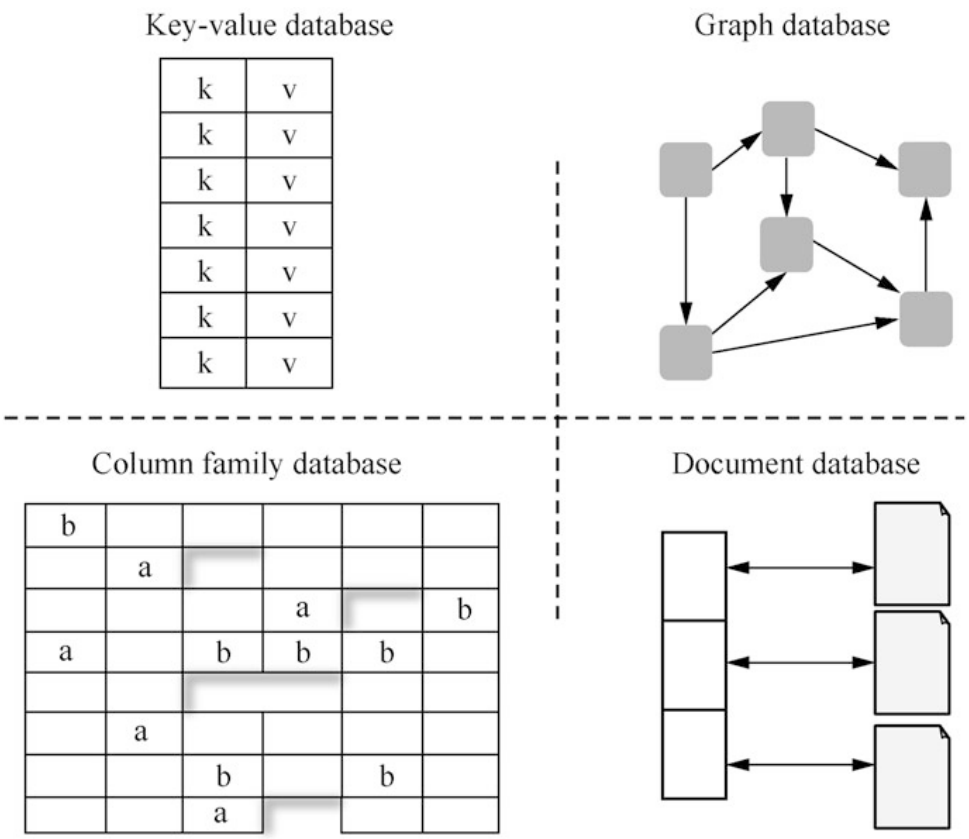

Figure 2.2: Major Types of NoSQL Databases [16]

The ability to enforce these relationships through foreign key constraints provides important safeguards against data inconsistency that would be more difficult to implement in many NoSQL systems.

2.1.3 Database Normalization

Database normalization is a systematic approach to reduce data redundancy and improve data integrity in relational database design. Developed by E.F. Codd alongside the relational model, normalization organizes data into progressively more structured forms through a series of normal forms [9]. Each normal form addresses specific types of anomalies that could occur in database operations.

First Normal Form (1NF) eliminates repeating groups by ensuring atomic values in each column. Second Normal Form (2NF) removes partial dependencies on primary keys. Third Normal Form (3NF) eliminates transitive dependencies between non-key attributes. Boyce-Codd Normal Form (BCNF) addresses anomalies not resolved by

3NF in cases with multiple candidate keys. Fourth and Fifth Normal Forms (4NF, 5NF) address multi-valued dependencies and join dependencies, respectively.

Normalization significantly reduces data redundancy, thereby minimizing update anomalies and improving data integrity. However, for complex applications like automotive parameter management, a balance must be struck between full normalization and performance considerations. Denormalization—the deliberate introduction of controlled redundancy—may be employed to optimize specific query patterns while maintaining overall data integrity [13].

For the VMAP system, normalization principles guide the design of core entities and relationships, while strategic denormalization is applied to support performance-critical operations such as parameter retrieval and variant resolution. This balanced approach ensures data integrity while providing the performance characteristics needed for interactive use in automotive development environments.

2.2 Database Design Methodologies

Effective database design is crucial for ensuring that a database system meets its functional requirements while maintaining performance, scalability, and maintainability. Several methodologies have been developed to guide the database design process, each with its own strengths and applicability to different problem domains.

2.2.1 Entity-Relationship Modeling

Entity-Relationship (ER) modeling is a conceptual approach to database design that focuses on identifying the entities, attributes, and relationships in a domain. Proposed by Peter Chen in 1976 [8], ER modeling provides a graphical notation for representing database structures that is both intuitive for stakeholders and precise enough for technical implementation.

The key components of ER modeling include entities, which represent distinct objects or concepts in the domain (e.g., ECUs, Modules, Parameters); attributes, which describe properties of entities (e.g., name, description, value); relationships, which depict associations between entities, specifying cardinality (e.g., one-to-one, one-to-many, many-to-many); and constraints, which define rules that data must satisfy (e.g., uniqueness, referential integrity).

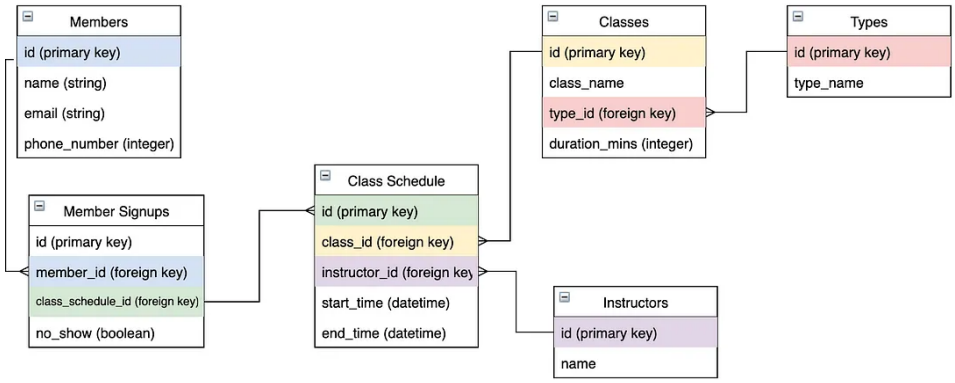

Figure 2.3: Entity-Relationship Diagram for Core VMAP Entities [25]

ER modeling provides several advantages for database design: it focuses on domain understanding before implementation details, facilitates communication between technical and non-technical stakeholders, and provides a clear pathway to logical and physical database design [13]. For complex domains like automotive parameter management, where intricate relationships exist between different entities, ER modeling offers a structured approach to capturing and representing these complexities.

The VMAP system utilizes ER modeling as the primary approach for database design, providing a conceptual framework that captures the complex relationships between ECUs, modules, PIDs, parameters, variants, and segments, as well as the temporal relationships introduced by the phase-based versioning model.

2.2.2 Object-Relational Mapping

Object-Relational Mapping (ORM) bridges the gap between object-oriented programming and relational database systems by mapping objects in code to relational database structures. This approach addresses the "impedance mismatch" between object-oriented design and relational data models, allowing developers to work with database entities using the object-oriented paradigm [19].

ORM frameworks provide several benefits for application development: they reduce boilerplate code for database operations, abstract database-specific syntax, support database-agnostic application development, and integrate with application-level validation and business logic. However, ORM approaches can introduce performance overhead and may obscure complex query optimizations. For performance-critical applications like automotive parameter management, a balanced approach combining ORM for routine operations with direct SQL for complex queries often provides the best results [19].

The VMAP system employs a hybrid approach, using the Dapper micro-ORM framework to balance the convenience of object mapping with the performance advantages of direct SQL queries for complex operations involving parameter versioning and variant resolution. This approach provides the benefits of object-oriented development while maintaining the performance characteristics needed for a responsive parameter management system.

2.3 Software Development Methodologies for Automotive Systems

The development of automotive software systems follows specialized methodologies that address the unique challenges of safety-critical embedded systems. These methodologies incorporate aspects of systems engineering, software engineering, and quality assurance to ensure that automotive software meets stringent requirements for reliability, safety, and compliance.

2.3.1 Use Case Driven Development

Use Case Driven Development focuses on defining system functionality from the perspective of user interactions. This approach begins with the identification of actors (users or external systems) and the definition of use cases that describe how these actors interact with the system to achieve specific goals [20].

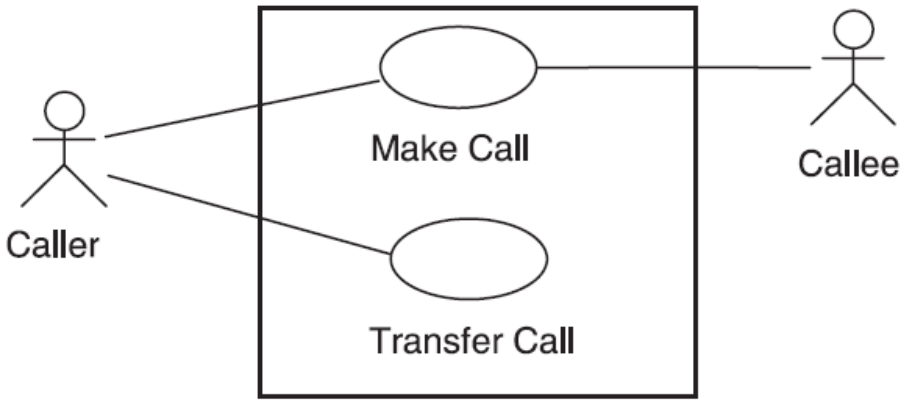

Figure 2.4: Use Case Diagram of switching system [20]

Use cases provide several advantages for system development: they focus on user needs rather than technical implementation, establish a common understanding between stakeholders, provide a foundation for requirements validation and testing, and help identify system boundaries and external interfaces. In automotive parameter management, use cases help define the specific workflows for different user roles (Module Developers, Documentation Team, Administrators, Read-Only Users), ensuring that the system addresses the actual needs of development teams while maintaining appropriate access controls and security boundaries [33].

The VMAP system's database design is influenced by use case analysis, with database structures and operations aligned with the specific needs of different user roles and their interactions with parameter data. This alignment ensures that the database provides efficient support for common workflows while maintaining appropriate security boundaries and access controls.

2.4 Access Control and Security Models

Access control is a critical aspect of database systems, particularly for automotive parameter management where different user roles have distinct responsibilities and permissions. Several models have been developed to address access control requirements, each with its own approach to defining and enforcing permissions.

2.4.1 Role-Based Access Control

Role-Based Access Control (RBAC) organizes access permissions around roles rather than individual users, simplifying security administration and aligning access rights with organizational structures [33]. In RBAC, users are assigned to roles, and roles are granted permissions for specific operations on system resources.

The core components of RBAC include users (individuals who need access to system resources), roles (collections of permissions that correspond to job functions), permissions (defined operations on specific resources), and sessions (temporary bindings between users and their assigned roles).

The separation between users and permissions through roles provides several advantages: it simplifies security administration, as permissions are managed at the role level; reduces the risk of permission errors, as roles are defined based on job functions; supports the principle of least privilege, giving users only the permissions needed for

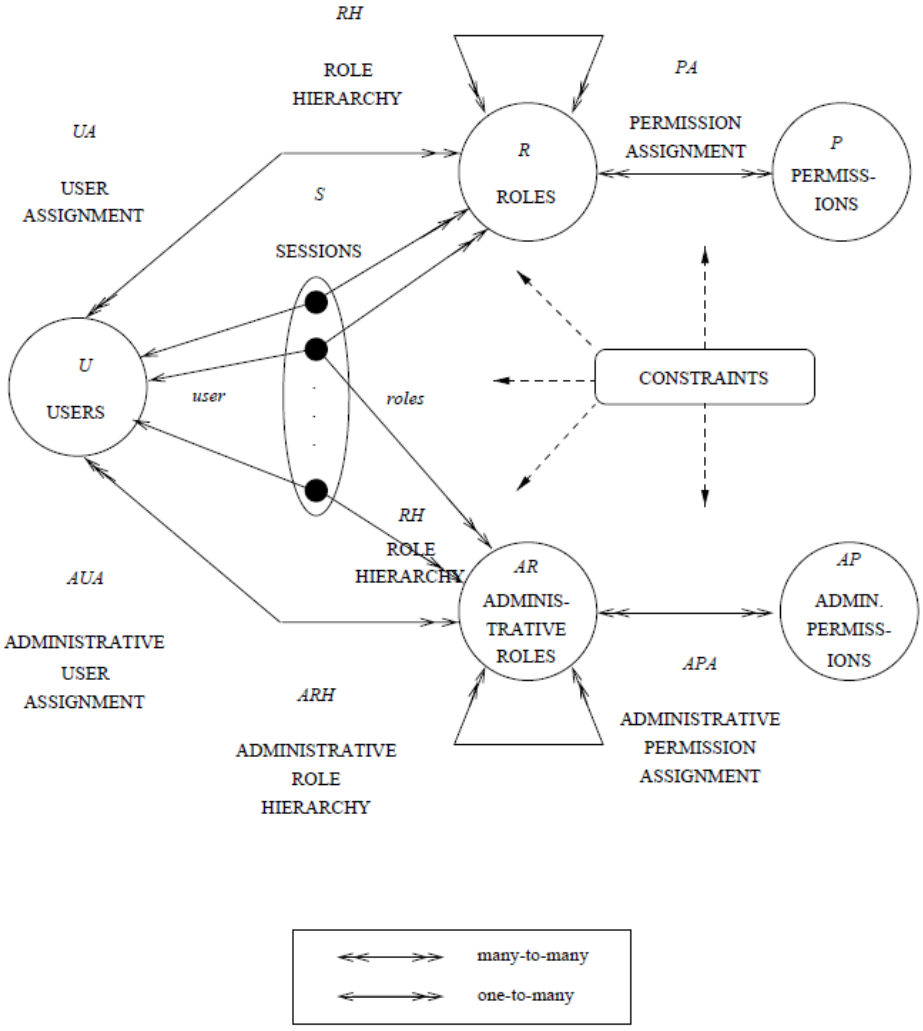

Figure 2.5: Role-Based Access Control Model [33]

their responsibilities; and facilitates compliance with regulatory requirements through structured assignment of permissions.

For automotive parameter management, RBAC provides an effective framework for managing the complex access requirements of different user groups. By defining roles that align with specific responsibilities in the parameter development process (e.g., Module Developer, Documentation Specialist), the system can enforce appropriate access controls while supporting collaborative development activities [14].

The VMAP system implements RBAC as the primary access control model, with roles defined for Module Developers, Documentation Team members, Administrators, and Read-Only Users, each with specific permissions aligned with their responsibilities in the parameter development process. This role-based approach provides a clear

and manageable security model that supports the collaborative nature of automotive parameter development while maintaining appropriate access controls.

2.4.2 Attribute-Based Access Control

Attribute-Based Access Control (ABAC) extends beyond role-based approaches by making access decisions based on attributes of users, resources, actions, and environment [18]. This more flexible approach allows fine-grained access control based on multiple factors rather than predefined roles.

ABAC components typically include subject attributes (properties of the user, such as department, job title, clearance level), resource attributes (properties of the accessed resource, such as module, classification, owner), action attributes (properties of the operation being performed), and environment attributes (contextual information such as time, location, system status).

ABAC offers greater flexibility than RBAC but requires more complex policy definition and evaluation. For systems with dynamic access requirements or where permissions depend on contextual factors, ABAC provides advantages over purely role-based approaches [43]. In automotive parameter management, a hybrid approach combining RBAC with attribute-based extensions often provides the best balance, using roles for general permission assignment while incorporating attribute-based rules for module-specific access control or phase-specific permissions [32].

The VMAP system extends the basic RBAC model with attribute-based elements, particularly for module-specific access control. This hybrid approach allows Module Developers to be granted write access to specific modules rather than all modules, implementing the principle of least privilege while maintaining the overall role-based security structure. This combination provides both manageability and flexibility, addressing the specific security requirements of automotive parameter management.

2.5 Version Control and Temporal Database Concepts

Version control is essential for managing the evolution of software artifacts, including database content. For automotive parameter management, where parameters evolve through multiple development phases and variants, sophisticated versioning approaches are required to maintain traceability and consistency.

2.5.1 Traditional Version Control Systems

Traditional Version Control Systems (VCS) focus on tracking changes to files over time, providing mechanisms for branching, merging, and maintaining change history [**?**]. These systems typically use either a centralized model (e.g., Subversion) or a distributed model (e.g., Git) for managing repositories.

Key features of traditional VCS include change tracking with commit history, branching and merging for parallel development, tagging for marking significant versions, and conflict detection and resolution mechanisms. While these systems excel at managing textual content like source code, they face limitations when dealing with structured data in databases. The file-centric nature of traditional VCS does not align well with the relational structure of databases, leading to challenges in tracking changes to individual records or maintaining relationships between related entities during version evolution [4].

For automotive parameter management, where complex relationships exist between parameters, variants, and configurations, specialized versioning approaches are needed that address the unique requirements of structured data evolution. The VMAP system addresses these requirements through a phase-based versioning model that explicitly represents development stages and their relationships, combined with comprehensive change tracking mechanisms that maintain a complete audit trail of parameter modifications.

2.5.2 Temporal Database Concepts

Temporal databases extend traditional database systems with explicit support for time-varying data, allowing queries based on time dimensions and maintaining historical states [24]. These systems typically support two time dimensions: valid time (when facts are true in the modeled reality) and transaction time (when facts are recorded in the database). Databases that support both dimensions are known as bi-temporal databases, providing a comprehensive framework for tracking both when changes occurred in the system and when they became effective in the real world [6].

Temporal database concepts provide several advantages for version management: automatic preservation of historical states, support for as-of-date queries across different time points, simplified auditing and compliance reporting, and consistent handling of time-based business rules. However, temporal databases also introduce complexities in schema design, query formulation, and performance optimization. For automotive parameter management, where versioning requirements align with

ENo	EStart	EEnd	EDept
22217	2010-01-01	2011-02-03	3
22217	2011-02-03	2011-09-10	4
22217	2011-09-10	2011-11-12	3

Figure 2.6: Temporal Database Example [24]

specific development phases rather than continuous time, a domain-specific approach combining elements of temporal databases with phase-based versioning often provides the most effective solution [4].

The VMAP system adopts a hybrid approach to versioning, using explicit phase associations rather than temporal timestamps as the primary versioning dimension. This approach aligns more directly with the automotive development process, where parameters progress through discrete development phases rather than evolving continuously over time. The phase-based approach simplifies queries for specific development stages while maintaining the version history needed for traceability and compliance.

2.5.3 Database Versioning Approaches

Several approaches have been developed for managing database versioning, each with its own trade-offs in terms of complexity, query performance, and storage requirements. Schema versioning tracks changes to database structure through migration scripts or schema evolution mechanisms [10]. Tuple versioning maintains multiple versions of each row (tuple) with validity periods, supporting time-travel queries but potentially increasing storage requirements [34]. Snapshot isolation creates complete copies of data at specific points in time, simplifying retrieval of historical states but increasing storage overhead [4]. Change logging records all modifications in an audit trail, providing complete change history while minimizing storage overhead for unchanged data [4].

For automotive parameter management, where parameters evolve through distinct development phases, a combination of these approaches often provides the most effective solution. The VMAP system implements a phase-based versioning approach with explicit association between parameters and development phases, supplemented

by comprehensive change logging for auditability. This combined approach addresses the versioning requirements of automotive parameter management while maintaining acceptable performance characteristics [7].

The phase-based approach aligns directly with the automotive development process, making the version model more intuitive for users while simplifying common operations such as parameter retrieval and phase transition. The comprehensive change logging provides the detailed audit trail needed for compliance and traceability, recording who made each change, when it was made, and what was modified. This combination of phase-based versioning and detailed change logging provides the versioning capabilities needed for automotive parameter management while avoiding the complexity of full temporal database implementations.

3 State of the Art

This chapter examines the current state of the art in database version control systems and automotive parameter management. It begins by analyzing existing approaches to software configuration management in the automotive industry, followed by an evaluation of database versioning techniques and their applicability to parameter management systems. The chapter also explores role-based access control models and integration strategies for enterprise systems, establishing the theoretical foundation for the VMAP system design.

3.1 Parameter Management in Automotive Software Development

The complexity of automotive software has grown exponentially in recent decades, with modern vehicles containing up to 100 million lines of code distributed across dozens of electronic control units (ECUs) [29]. This growth has significantly increased the importance and complexity of parameter management in automotive development.

3.1.1 Evolution of Automotive Parameter Management

Parameter management in automotive systems has evolved from simple calibration tables to sophisticated configuration frameworks that handle thousands of parameters across multiple vehicle variants. Broy [7] identifies this evolution as a critical aspect of automotive software development, noting that modern vehicles require extensive parametrization to adapt software behavior to different markets, regulatory environments, and hardware configurations.

Early approaches to parameter management relied primarily on manual configuration using specialized tools for each ECU. These isolated tools typically stored parameters in proprietary formats with limited version control capabilities [39]. As vehicle complexity increased, the limitations of these disconnected approaches became apparent, leading to efforts toward more integrated parameter management frameworks.

More recent developments have focused on establishing model-based approaches to parameter management, where parameters are connected to architectural and behavioral models of the vehicle systems [39]. These approaches aim to provide

traceability between parameters and their effects on system behavior, supporting more systematic validation and verification processes. However, as Trovão [41] notes, the integration between parameter management and model-based development remains incomplete in many automotive organizations, with significant gaps in traceability and consistency management.

Despite these advances, many automotive development teams continue to rely on general-purpose tools such as spreadsheets for parameter management, particularly for powertrain control parameters [7]. This approach provides flexibility but introduces significant risks related to version control, consistency, and traceability. As vehicle systems become more integrated and interdependent, the limitations of spreadsheet-based parameter management become increasingly problematic, creating a need for more structured database-driven approaches.

3.1.2 Challenges in Automotive Parameter Management

The management of parameters in automotive software development presents several specific challenges that distinguish it from general software configuration management. Staron [39] identifies four key challenges that are particularly relevant to powertrain parameter management:

First, parameter dependencies create complex relationships both within and across ECUs. Changes to one parameter may require coordinated changes to multiple related parameters to maintain system consistency. These dependencies are often implicit, making them difficult to track and enforce through general-purpose configuration management tools.

Second, parameter validation requires specialized domain knowledge and testing capabilities. Unlike source code, which can be validated through compilation and syntactic analysis, parameters require functional testing to verify their correctness. This validation often involves specialized hardware-in-the-loop or vehicle-level testing, creating a significant gap between parameter modification and validation [29].

Third, regulatory compliance introduces additional complexity to parameter management. Emission-related parameters, in particular, must comply with region-specific regulations and undergo certification processes. This requires maintaining multiple parameter configurations for different markets while ensuring that all configurations meet their respective regulatory requirements [41].

Fourth, variant management multiplies the complexity of parameter configurations. Modern vehicles are produced in numerous variants with different engines, transmissions,

and optional features, each requiring specific parameter configurations. Managing these variants effectively requires sophisticated configuration selection mechanisms based on vehicle-specific characteristics [7].

These challenges highlight the need for specialized parameter management systems that go beyond general-purpose version control approaches. As Pretschner et al. [29] note, automotive-specific tools must address both the technical aspects of parameter management and the organizational processes surrounding parameter development and validation.

3.1.3 Current Approaches and Their Limitations

Current parameter management approaches in the automotive industry fall into several categories, each with specific strengths and limitations. Proprietary calibration tools provided by ECU suppliers offer specialized functionality for specific ECUs but typically lack integration with enterprise systems and cross-ECU parameter management capabilities [39]. These tools often use file-based storage with basic version control, limiting their effectiveness for complex multi-variant development.

General-purpose spreadsheet applications remain widely used for parameter management due to their flexibility and familiarity. However, as Trovão [41] observes, spreadsheet-based approaches suffer from significant limitations in terms of concurrent access, version control, validation, and traceability. These limitations become particularly problematic when managing thousands of parameters across multiple vehicle variants and development phases.

Commercial data management systems for automotive development, such as Vector's vCDM and ETAS' EHANDBOOK, provide more structured approaches to parameter management with integration to calibration tools and testing systems [39]. However, these systems often focus on parameter storage and documentation rather than the full lifecycle management from definition through development, testing, and production.

Enterprise product lifecycle management (PLM) systems offer comprehensive version control and workflow management but typically lack domain-specific functionality for parameter management. As Broy [7] notes, the gap between general-purpose PLM systems and domain-specific parameter management needs creates efficiency and usability challenges for development teams.

The limitations of current approaches create several specific issues in automotive parameter development. Version conflicts arise when multiple developers modify related parameters without coordination, particularly when using file-based tools without proper

concurrent access controls [29]. Traceability gaps make it difficult to connect parameter changes to specific requirements or validation results, complicating compliance and quality assurance processes. Integration barriers between parameter management tools and enterprise systems lead to manual synchronization processes that consume development resources and introduce potential for errors [39].

These limitations highlight the need for specialized parameter management systems that combine the structured data management capabilities of database systems with domain-specific functionality for automotive parameter development. Such systems must address the unique versioning, validation, and variant management requirements of automotive parameters while providing seamless integration with enterprise engineering processes.

3.2 Database Version Control Systems

Version control for database content presents distinct challenges compared to traditional source code version control. While source code version control focuses on tracking changes to text files, database version control must address structured data with complex relationships and constraints [4]. This section examines current approaches to database version control and their applicability to automotive parameter management.

3.2.1 Traditional Database Versioning Approaches

Traditional approaches to database versioning fall into several categories, each addressing different aspects of the versioning challenge. Schema evolution tools focus on tracking and managing changes to database structure through migration scripts or schema manipulation languages [10]. These tools enable systematic evolution of database schemas while preserving data integrity during transitions. Commercial examples include Liquibase and Flyway, which provide version-controlled database migrations that can be integrated with application deployment processes [12, 30].

Change data capture (CDC) systems track modifications to database content, creating audit trails of insertions, updates, and deletions [36]. These systems typically operate at the database engine level, capturing changes from transaction logs or through triggers. While CDC provides comprehensive change tracking, it focuses on operational data replication rather than supporting systematic version management across development phases.

Temporal databases extend relational database systems with explicit support for time-varying data, allowing queries to retrieve data as it existed at specific points in time [24]. These systems manage time dimensions such as valid time (when facts are true in the modeled reality) and transaction time (when facts are recorded in the database). Commercial implementations include the temporal features in SQL Server 2016, Oracle Workspace Manager, and PostgreSQL temporal extensions [34, 1, 2].

Database workspace tools, such as Oracle Workspace Manager, implement branching and merging concepts for database content, allowing multiple development streams to proceed in parallel before being reconciled [4]. These tools provide isolation between different development efforts while maintaining the ability to merge changes when development streams converge.

3.2.2 Versioning Strategies for Structured Data

Beyond these general approaches, several specific strategies have been developed for versioning structured data in databases. Salgado et al. [31] identify four primary strategies: tuple versioning, attribute versioning, relation versioning, and database versioning, each representing a different granularity of version control.

Tuple versioning maintains multiple versions of each row (tuple) in a table, typically adding timestamp attributes to indicate when each version was created and (if applicable) superseded. This approach provides detailed tracking of individual entity changes but can significantly increase storage requirements and complicate queries that need to reconstruct full object states across multiple related tables [4].

Attribute versioning tracks changes to individual column values rather than entire rows, creating a more compact representation for cases where only a few attributes change between versions. However, this approach introduces significant complexity for reconstructing complete entity states at specific points in time, particularly when entities have relationships to other versioned entities [5].

Relation versioning creates separate versions of entire tables, effectively capturing the state of all entities of a specific type at particular points in time. This approach simplifies retrieval of consistent snapshots but can lead to substantial data duplication when only a small percentage of entities change between versions [27].

Database versioning maintains complete snapshots of the entire database at significant version points. While this approach provides the simplest retrieval of historical states, its storage requirements make it impractical for large databases with frequent changes or long version histories [4].

Bhattacherjee et al. [4] analyze the trade-offs between these strategies, noting that the optimal approach depends on specific usage patterns, particularly the ratio between storage costs and reconstruction costs. For systems where historical queries are relatively rare but must be comprehensive when performed, the authors suggest that hybrid approaches combining element-level change tracking with periodic snapshots often provide the best balance of storage efficiency and query performance.

3.2.3 Temporal Database Approaches

Temporal database approaches provide a theoretical foundation for managing time-varying data in database systems. Kulkarni and Michels [24] describe the temporal features introduced in SQL:2011, which formalized support for period data types and temporal tables in the SQL standard. These features enable tracking of both valid time (business time) and transaction time (system time) dimensions, supporting bi-temporal data management.

The valid time dimension represents when facts are true in the modeled reality, independent of when they are recorded in the database. This dimension supports business-oriented temporal queries such as "What was the value of this parameter in the Phase1?" or "When did this parameter change from value A to value B?" [6]. The transaction time dimension represents when facts are recorded in the database, supporting auditability through questions like "Who changed this parameter, and when did they change it?" [24].

Bi-temporal databases combine both dimensions, providing a comprehensive framework for tracking both when changes occurred in the system and when they became effective in the real world [6]. This approach is particularly valuable for regulated industries like automotive development, where both historical accuracy and change auditability are essential for compliance and quality assurance.

Commercial database systems have implemented temporal capabilities to varying degrees. Saracco et al. [34] describe the temporal features in IBM DB2, which include period data types, temporal tables, and specialized temporal operators for querying time-varying data. Al-Kateb et al. [2] outline similar capabilities in Teradata, highlighting the performance optimizations necessary for efficient temporal query processing. Ben-Gan et al. [3] document the temporal table support in SQL Server, which provides system-versioned tables that automatically maintain transaction time history.

Despite these advances, Biriukov [5] notes that implementing bi-temporal databases remains challenging in practice, with significant complexity in schema design, query

formulation, and performance optimization. For domain-specific applications like automotive parameter management, customized temporal approaches that align with development processes often provide more practical solutions than generic bi-temporal frameworks [5].

3.2.4 Version Control for Parameter Management

Version control for automotive parameter management presents specific requirements that differ from general database versioning needs. Staron [39] identifies several key requirements for parameter version control in automotive development:

First, parameter versions must be aligned with development phases that correspond to vehicle development milestones. Unlike source code versioning, which typically follows continuous development with arbitrary version points, parameter versioning must support a structured progression through predefined development phases such as Phase1, Phase2, Phase3, and Phase4.

Second, parameter version control must maintain connections between related parameters across ECUs and modules. Changes to one parameter often require coordinated changes to related parameters, requiring version control mechanisms that can track and enforce these relationships across system boundaries.

Third, parameter versions must be tied to specific vehicle configurations, supporting variant management across different markets and feature combinations. This requirement goes beyond traditional version control to include configuration selection mechanisms based on vehicle-specific characteristics.

Fourth, parameter version control must support parallel development across different vehicle programs and model years, allowing development teams to work on multiple releases simultaneously without interference. This parallel development requirement aligns with the workspace concept in advanced database versioning systems but requires additional domain-specific extensions.

These specialized requirements highlight the need for customized version control approaches tailored to automotive parameter management. As Bhattacherjee et al. [4] note, domain-specific versioning systems often provide more effective solutions than generic versioning frameworks, particularly for domains with structured development processes and complex entity relationships.

3.3 Role-Based Access Control in Enterprise Systems

Role-Based Access Control (RBAC) has become a dominant paradigm for managing access rights in enterprise systems, providing a structured approach to security management that aligns with organizational responsibilities [33]. For automotive parameter management, where different user roles have distinct responsibilities and access requirements, RBAC provides a foundation for implementing appropriate security controls.

3.3.1 RBAC Model and Extensions

The core RBAC model, as defined by Sandhu et al. [33], consists of users, roles, permissions, and sessions. Users are assigned to roles that correspond to job functions, and roles are granted permissions that authorize specific operations on protected resources. This indirect association between users and permissions through roles simplifies security administration while maintaining the principle of least privilege.

Several extensions to the basic RBAC model have been developed to address more complex security requirements. Hierarchical RBAC introduces role hierarchies that enable permission inheritance between roles, supporting organizational structures with senior roles inheriting permissions from junior roles [33]. Constrained RBAC adds separation of duty constraints that prevent conflicts of interest by restricting role combinations or permission assignments. Administrative RBAC (ARBAC), as described by Sandhu and Bhamidipati [32], addresses the management of the RBAC system itself, defining who can assign users to roles and modify role permissions.

More recent developments have focused on integrating RBAC with other access control models to create hybrid approaches that combine the administrative benefits of roles with more flexible access control mechanisms. Ferraiolo et al. [14] describe policy-enhanced RBAC, which combines role-based permissions with attribute-based policies to provide context-sensitive access control. This hybrid approach is particularly valuable for systems where access decisions depend on both user roles and context-specific factors such as time, location, or resource attributes.

3.3.2 RBAC in Database Systems

Modern database management systems provide varying levels of support for RBAC principles. Elmasri and Navathe [13] describe the evolution of database security

mechanisms from simple user-based privileges to more sophisticated role-based models. Most enterprise database systems now include native support for roles, user-role assignments, and permission management through SQL statements like GRANT and REVOKE.

PostgreSQL, in particular, offers a comprehensive implementation of RBAC concepts, including role hierarchies through role inheritance, permission management through fine-grained privileges, and row-level security policies for content-based access control [28]. These capabilities provide a solid foundation for implementing domain-specific access control models on top of the database system's native security features.

However, database-level RBAC implementations typically focus on controlling access to database objects like tables, views, and functions, rather than providing application-level access control that considers domain-specific entities and operations. For complex applications like automotive parameter management, database-level RBAC must be complemented with application-level access control logic that maps domain-specific concepts to database operations [14].

3.3.3 Access Control for Automotive Parameter Management

Access control for automotive parameter management presents specific requirements that extend beyond basic RBAC models. Staron [39] identifies several key access control requirements for automotive development systems:

First, access control must reflect organizational responsibilities, allowing different teams to manage specific subsystems or parameters without interfering with each other's work. This requirement aligns with RBAC's role concept but requires extensions to support fine-grained control over specific parameter sets rather than just database objects.

Second, access control must enforce phase-specific permissions, ensuring that parameters can only be modified during appropriate development phases. For example, after a phase is frozen for testing, parameters should become read-only until explicitly unfrozen by authorized users. This temporal aspect of access control goes beyond traditional RBAC to include state-based permission evaluation.

Third, access control must balance centralized governance with distributed development responsibilities. While central administrators must maintain control over system configuration and user management, development teams need autonomy within their assigned areas of responsibility [7]. This balance requires carefully designed delegation mechanisms that extend the basic RBAC model.

Fourth, access control must maintain comprehensive audit trails for all security-relevant operations, including permission changes, role assignments, and access attempts. This auditability requirement is particularly important for regulated industries like automotive development, where changes to safety-critical parameters must be carefully controlled and documented [41].

These specialized requirements highlight the need for a domain-specific access control model that builds upon RBAC foundations while incorporating extensions for automotive parameter management. As Xu and Zhang [43] note, effective access control systems often combine elements from different access control models to address domain-specific requirements, creating hybrid approaches that provide both structured administration and operational flexibility.

3.4 Database Integration with Enterprise Systems

Integration between database systems and enterprise applications presents significant challenges in automotive development environments, where parameter management must interact with numerous other systems across the development lifecycle. Effective integration strategies must address both technical interoperability and semantic consistency while maintaining performance and security [17].

3.4.1 Enterprise Integration Patterns

Enterprise integration patterns, as described by Hohpe and Woolf [17], provide a catalog of solutions for common integration challenges. These patterns address various aspects of system integration, including messaging styles, messaging channels, message construction, and message transformation.

For database-centric applications like parameter management systems, several integration patterns are particularly relevant. The Repository pattern provides a structured approach to data access, abstracting the database implementation details behind a domain-focused interface [15]. This abstraction simplifies integration by providing a stable API for other systems to interact with the parameter repository.

The Data Transfer Object (DTO) pattern addresses the challenge of transferring data between systems with different data models. By defining specialized objects for inter-system communication, this pattern enables consistent data exchange while isolating each system's internal representation [15]. For parameter management, DTOs provide

a mechanism for exchanging parameter data with other systems while maintaining the integrity of the database model.

The Canonical Data Model pattern, as described by Hohpe and Woolf [17], establishes a common data representation across multiple systems, simplifying data transformation and ensuring consistent interpretation. This pattern is particularly valuable for parameter management, where the same parameter concepts may be represented differently in various systems across the development lifecycle.

The Gateway pattern provides a structured approach to integrating with external systems, encapsulating the details of external system communication behind a domain-focused interface [15]. This encapsulation simplifies integration by isolating external system dependencies and providing a stable interface for the core application to interact with external systems.

3.4.2 Database Synchronization Approaches

Database synchronization presents specific challenges when integrating parameter management systems with other enterprise data sources. Mueller and Müller [27] describe several approaches to database versioning and synchronization between research institutes, highlighting the challenges of maintaining consistency across systems with different update cycles.

Batch synchronization approaches transfer complete data sets between systems at scheduled intervals, ensuring comprehensive updates but potentially creating significant processing loads during synchronization periods. These approaches typically use extract-transform-load (ETL) processes to transfer data between systems, applying transformations as needed to align data formats and structures [42].

Incremental synchronization approaches transfer only changed data between systems, reducing processing loads but requiring reliable change detection mechanisms. These approaches often use change data capture (CDC) techniques to identify modified records, combined with transformation and loading processes tailored to handle incremental updates [36].

Message-based synchronization uses messaging systems to propagate changes between databases in near-real-time, providing more immediate consistency but requiring more complex infrastructure. These approaches typically implement the publisher-subscriber pattern described by Hohpe and Woolf [17], with database systems publishing change events that are consumed by subscribing systems.

For automotive parameter management, where different systems operate on different schedules and have varying update frequencies, hybrid synchronization approaches often provide the most effective solution. These approaches combine elements of batch, incremental, and message-based synchronization based on specific synchronization scenarios and timing requirements [27].

3.5 Research Directions

Based on this review, several research directions emerge for advancing the state of the art in automotive parameter management:

Development of domain-specific versioning models that align directly with automotive development processes while providing the traceability and auditability required for regulatory compliance [39].

Creation of hybrid access control approaches that combine the administrative benefits of RBAC with the flexibility needed for module-specific permissions and phase-dependent access controls [14, 43].

Design of efficient synchronization mechanisms for maintaining consistency between parameter management systems and related enterprise systems, particularly parameter definition databases and vehicle configuration databases [27, 17].

Implementation of specialized validation frameworks that can verify parameter consistency across related parameters, ensuring that parameter configurations maintain system integrity throughout the development lifecycle [7, 39].

These research directions provide a foundation for developing specialized parameter management systems that address the unique challenges of automotive software development. By combining insights from database version control, access control models, and enterprise integration patterns with domain-specific knowledge of automotive development processes, such systems can provide effective solutions for managing the growing complexity of vehicle software parametrization.

4 Methodology and Concept Development

This chapter presents the systematic approach taken in designing the Variant Management and Parametrization (VMAP) system. The methodology follows established software engineering principles to address the complex requirements of automotive parameter management. Beginning with a requirements analysis, the chapter proceeds to detail the conceptual architecture design, data model, validation mechanisms, and integration approaches developed to ensure system robustness and compatibility with existing enterprise infrastructure.

4.1 Requirements Analysis

The foundation of the VMAP system design was a comprehensive requirements analysis combining stakeholder interviews, legacy system analysis, and industry best practice evaluation. This multi-faceted approach ensured the system would address actual user needs while overcoming limitations of existing approaches [38].

4.1.1 Functional Requirements

The primary functional requirements derived from VMAP's fundamental purpose: replacing Excel-based parameter management with a centralized database solution. The system must support hierarchical organization of parameters within Electronic Control Units (ECUs), Modules, and Parameter IDs (PIDs), reflecting the domain-specific structure of automotive electronic systems [39].

Users must be able to create variants for parameters with specific code rules determining their applicability, and define segments representing modified parameter values. If no segment exists, the system defaults to Parameter Definition Database values—an approach allowing efficient storage by tracking only modifications rather than duplicating unchanged parameters [4].

The system must track parameter values across four distinct release phases (Phase1, Phase2, Phase3, and Phase4), with changes in earlier phases propagating to later phases unless explicitly overridden. This phase-based approach represents a domain-specific adaptation particularly suited to automotive software development cycles [7].

All modifications require comprehensive logging with user information, timestamp, and detailed change data, supporting regulatory compliance and enabling parameter evolution tracking. The system must also provide functionality to create parameter configuration snapshots at specific points, particularly at phase transitions, for documentation purposes—an essential capability for quality assurance and regulatory compliance [39].

4.1.2 User Role Requirements

Analysis identified four distinct user roles with specific access requirements. Module developers require write access to parameters within their assigned modules, with the ability to create and modify variants and segments. Documentation specialists need access to frozen data for documentation, comparison capabilities between phases, and comprehensive change history access. System administrators require comprehensive control over user management, release phases, and special operations like variant deletion and phase freezing. Finally, read-only users need view access to all parameter data with parameter file generation capabilities but no modification rights.

These roles were defined based on the principle of least privilege [33], ensuring users have access only to functionality required for their specific responsibilities. This enhances system security while simplifying the user experience by presenting only relevant options. The hybrid role-permission model selected combines a primary role defining core permissions with additional permissions granted on a per-user basis, providing flexibility for special cases while maintaining a clear role structure.

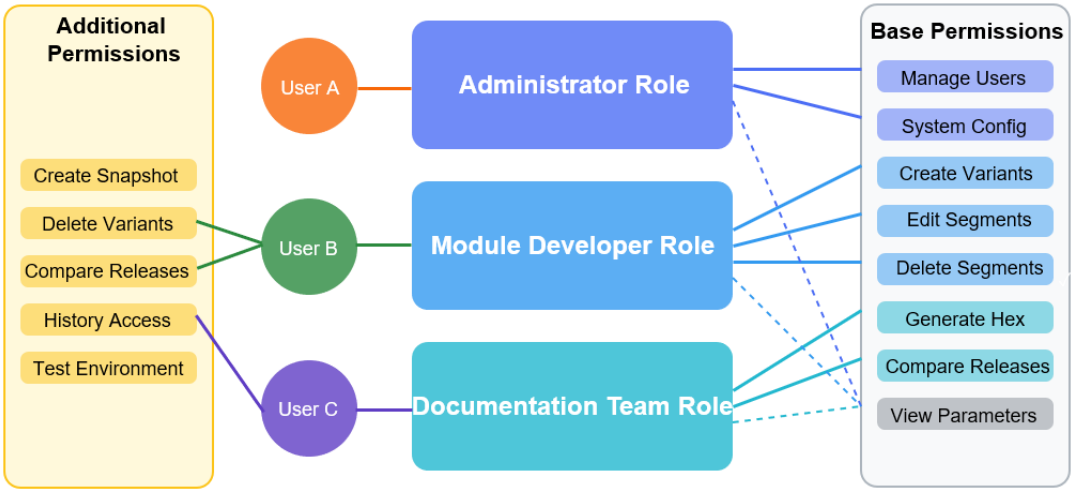

Figure 4.1: Hybrid Role-Permission Model

Figure 4.1 illustrates the hybrid role-permission approach that balances structured role assignments with flexible permission customization. This model supports both organizational clarity and individual access requirements.

4.1.3 Data Management Requirements

The system must maintain distinct parameter versions across different release phases, allowing simultaneous work on multiple phases while enabling access to parameter values from any development lifecycle point. Data integrity requires maintaining referential integrity across all related entities, particularly ensuring variants and segments associate with valid parameters [13].

Multi-dimensional parameter support is essential for complex automotive parameters such as mapping tables. Operations modifying multiple related entities must function as atomic transactions to maintain data consistency—particularly important for phase transitions where numerous parameters, variants, and segments may change simultaneously [4].

Query performance is critical, with efficient parameter data querying across dimensions including ECU, module, PID, release phase, and parameter name. These requirements influenced schema design decisions regarding normalization and indexing strategies to optimize common query patterns.

4.1.4 Integration Requirements

VMAP must integrate with two external enterprise systems: the Parameter Definition Database (PDD) providing base ECU, module, PID, and parameter definitions; and the Vehicle Database supporting parameter file generation and variant code rule validation. The database must store necessary vehicle configuration data and maintain relationships between vehicle codes and variants, supporting practical application of parameter variants in vehicle-specific configurations [39].

These requirements follow enterprise integration patterns focusing on reliable data exchange, appropriate error handling, and minimal impact on existing systems [17]. The database implements these through specialized structures mapping between VMAP and external entities, tracking synchronization operations, and storing imported data with appropriate relationships to internally generated content.

4.2 System Architecture Design

Based on the requirements analysis, a comprehensive system architecture was designed following a layered pattern with clear separation of concerns, enhancing maintainability while allowing independent component evolution [15].

4.2.1 Entity-Relationship Model

The entity-relationship (ER) model forms the foundation of the database design, capturing complex relationships between system entities. User management entities include Users, Roles, Permissions, and their relationships, implementing the hybrid role-permission model. Release management entities encompass Releases, Release Phases, and ECU Phase mappings, providing the foundation for version control. Parameter structure entities include ECUs, Modules, PIDs, Parameters, and Parameter Dimensions, representing the hierarchical organization of vehicle electronic systems [39].

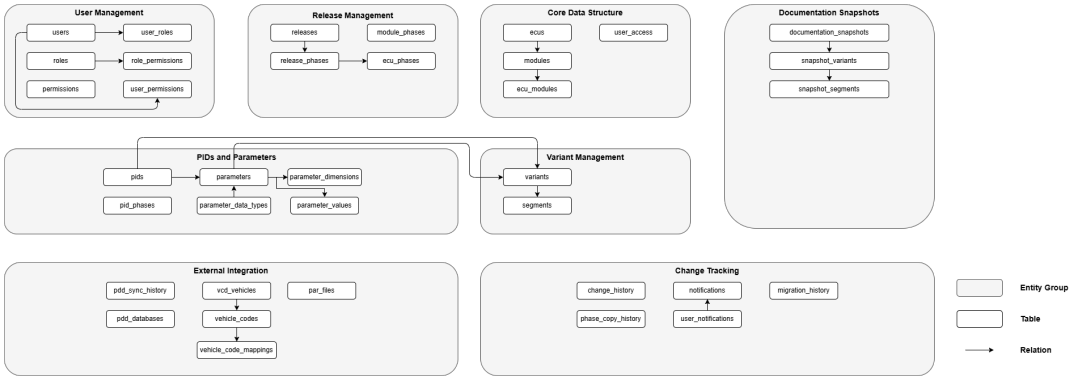

Figure 4.2: Entity-Relationship Diagram for VMAP Database

As shown in Figure 4.2, variant management entities comprise Variants, Segments, and their relationships to parameters, implementing the core parameter customization functionality. Documentation entities include Documentation Snapshots, Snapshot Variants, and Snapshot Segments, supporting preservation of historical parameter states. Integration entities consist of Synchronization Records, Vehicle Configurations, and Parameter File Records, supporting external system connectivity. Finally, audit entities encompass Change History, Transaction Records, and Phase Copy History, providing comprehensive operation traceability.

This model was developed using data normalization principles to minimize redundancy while maintaining data integrity [13]. Special attention was given to temporal data

representation, incorporating bi-temporal database design concepts to track both transaction time and valid time [24].

4.2.2 Temporal Database Consideration

Considerable attention was given to temporal database concepts as a potential foundation for the version control mechanism. The evaluation focused on bi-temporal modeling [37], which tracks both transaction time (when changes were made) and valid time (when changes are applicable).

Despite potential advantages including comprehensive historical preservation and flexible time-point querying, practical evaluation revealed significant limitations for automotive parameter management. Temporal queries' inherent complexity would introduce overhead potentially impacting interactive performance. The automotive development process organizes around discrete phases rather than continuous time, making the temporal model potentially misaligned with domain concepts. Temporal tables require additional columns and typically more rows to track historical states, substantially increasing storage requirements for a system with millions of parameter values. Effective temporal data querying requires additional indexes, further increasing storage overhead and potentially impacting write performance [6].

Based on this evaluation, the system adopted an explicit phase-based approach rather than a temporal database model. This approach explicitly represents the phase-based structure of automotive development, making the model more intuitive for domain experts while supporting efficient parameter and variant retrieval without temporal query complexity [4]. The phase-based approach better matches automotive parameter management's nature, where discrete development phases form the primary organizing principle rather than continuous time.

4.2.3 Release/Phase Separation Rationale

A key architectural decision was explicitly separating releases and phases into distinct but related entities. Releases represent major planning cycles in automotive development (typically aligned with model years or major updates like "24.1" or "24.3"), serving as organizational containers for development activities. Phases represent specific development process states (Phase1, Phase2, Phase3, and Phase4) occurring in a predictable sequence, reflecting parameter configuration maturity levels [39].

This separation provides several benefits: flexible release management allowing new releases with their own phase sequences without disrupting existing development; phase sequence standardization for consistent workflows; independent phase progression allowing different ECUs to advance through phases at different rates; simplified queries for common operations; and clear access control definition at either release or phase level.

The database schema implements this through distinct tables with a parent-child relationship. The releases table defines high-level development cycles, while release_phases defines specific development states within each release with explicit sequencing. This structure enables efficient release-phase hierarchy navigation while maintaining clear semantic separation between these distinct concepts.

4.2.4 Database Schema Design

The database schema translates the conceptual ER model into concrete database structures optimized for VMAP system requirements. PostgreSQL was selected as the underlying database management system due to its robust support for advanced features essential for this application domain, including complex data types (JSON/JSONB), sophisticated indexing mechanisms (including GIN indexes for text search), powerful procedural language (PL/pgSQL), comprehensive transaction support, and extensibility through custom extensions [5].

The schema addresses several key challenges in representing the automotive parameter domain. Parameters are organized hierarchically (ECU $\rightarrow$ Module $\rightarrow$ PID $\rightarrow$ Parameter) through related tables with appropriate foreign key constraints. Multi-dimensional parameters (arrays or matrices of values) are addressed through dedicated tables for parameter dimensions. Instead of traditional temporal database approaches, a phase-based versioning approach associates each parameter, variant, and segment with a specific phase and maintains phase sequence through explicit numbering.

Comprehensive change tracking is implemented through a specialized change history table capturing both old and new values for each change, using JSONB for flexible storage of different entity structures, grouping related changes by transaction, and supporting efficient filtering by entity type, user, and timestamp. This approach balances comprehensive auditing with performance considerations [4].

4.2.5 Version Control Mechanism

The version control mechanism is central to VMAP, enabling parameter evolution management across different development phases. Unlike traditional version control systems focusing on linear history, VMAP implements a phase-based approach tailored to the automotive development process.

The release phase framework defines a structured parameter versioning approach based on the established automotive development cycle: Phase1 (initial definition and configuration), Phase2 (adjustments based on initial testing), Phase3 (refinement based on extended testing), and Phase4 (completed configuration ready for production).

This framework is implemented through table structures and procedural logic. Each phase is a distinct database entity associated with releases through a parent-child relationship. Parameters, variants, and segments are tagged with their corresponding phase, enabling explicit versioning without temporal database approach overhead. Explicit phase sequence numbers enable orderly progression, supporting both the development workflow and database operations propagating changes between phases.

The phase transition mechanism handles parameter configuration copying from one phase to the next through a specialized stored procedure. This approach provides several advantages: phases can be modified independently after copying; changes can be propagated forward selectively; each phase maintains a complete parameter configuration; and historical phase data remains accessible indefinitely.

A phase freezing mechanism supports documentation and regulatory compliance. When a phase is frozen, all parameters, variants, and segments become read-only, the frozen state is recorded with timestamp and user information, documentation snapshots are automatically generated, and the change is logged. This ensures significant development milestone configurations are preserved while allowing development to continue in subsequent phases.

4.2.6 Parameter Definition Database Synchronization

Parameter Definition Database (CDI) synchronization presented complex architectural challenges. Initially, a version-based approach was considered, tracking parameter changes across releases by storing release information at synchronization. The system would dynamically construct appropriate parameter sets by evaluating parameter

version histories. This approach offered theoretical storage efficiency advantages by maintaining only parameter changes rather than complete sets for each release [4].

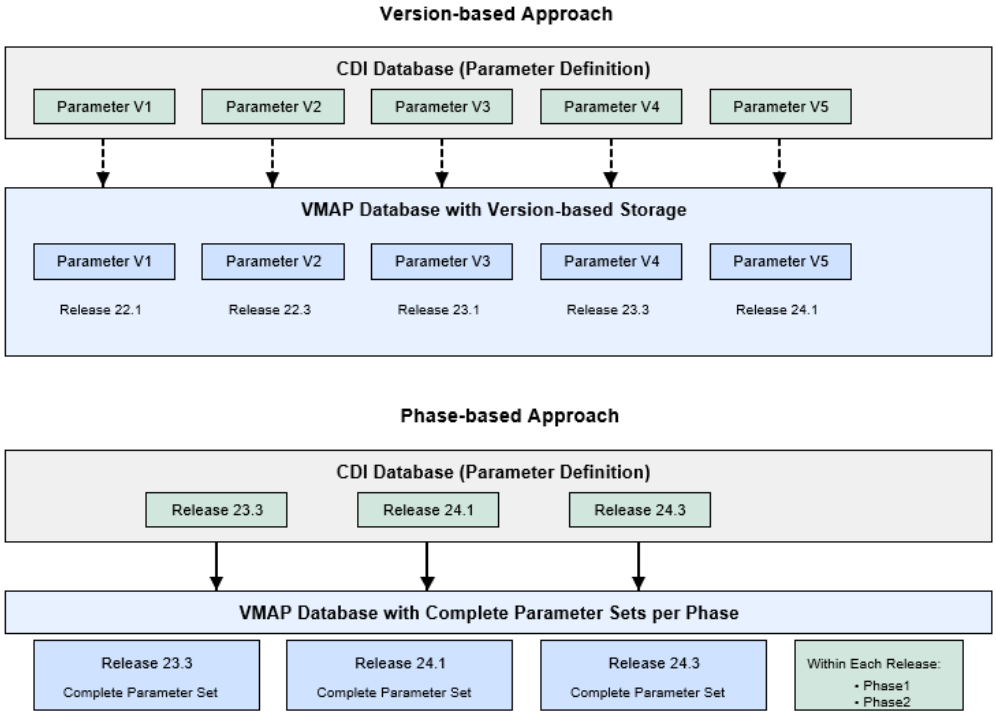

Figure 4.3: Comparison of Version-based vs. Phase-based Parameter Synchronization Approaches

Figure 4.3 illustrates the comparison between the initially considered version-based approach and the implemented phase-based approach. Detailed analysis revealed significant challenges with versioning. Complex relationships between parameters and their parent entities would require sophisticated versioning logic for the entire hierarchy. Reconstructing parameter sets would require multiple joins across version tables and complex temporal predicates, potentially degrading system responsiveness. Additionally, version-based synchronization would complicate phase inheritance implementation [24].

After evaluation, a phase-based synchronization approach was adopted instead. This design maintains complete parameter sets for each ECU in each release phase, rather than tracking individual parameter versions across releases. This simplifies query patterns by establishing direct relationships between parameters and their release phases, enables efficient retrieval without complex version reconstruction, aligns naturally with the automotive development process, provides clearer traceability between parameter versions across phases, and offers greater resilience against

synchronization failures [17].

While this approach consumes more storage than a version-based approach, detailed analysis indicated storage requirements remained within acceptable limits, with performance benefits and simplified implementation outweighing additional storage costs.

4.3 Validation Mechanisms

To ensure data integrity and consistency, VMAP implements multiple validation mechanism layers from basic constraints to sophisticated business rule validation. These layers work together to maintain parameter data quality and reliability throughout the system lifecycle.

4.3.1 Data Integrity Constraints

Database-level constraints enforce basic integrity rules: primary key constraints ensure unique entity identifiers; foreign key constraints maintain referential integrity between related entities; not-null constraints ensure required fields contain values; unique constraints prevent duplicate values in specified columns; and check constraints enforce domain-specific rules such as valid date ranges and parameter value ranges. These constraints are designed into the database schema as integral parts of entity definitions, ensuring consistent enforcement throughout the system [13].

4.3.2 Business Rule Validation

Domain-specific business rules are implemented through database triggers and stored procedures. Parameter range validation automatically checks modified values against defined minimum and maximum bounds, rejecting values outside allowed ranges—critical for automotive parameter management where incorrect values could impact vehicle safety or performance [39].

Phase status validation prevents frozen phase modification, ensuring historical parameter configuration integrity. Segment validation ensures segments reference valid parameters and variants, contain appropriate dimensional values, and maintain consistent entity relationships. User access validation ensures users can only modify

parameters, variants, and segments for modules to which they have been granted access, maintaining data security and integrity in multi-user enterprise systems [33].

4.3.3 Conflict Resolution Strategies

In a multi-user environment, concurrent modifications can create conflicts. VMAP implements several strategies to detect and resolve these, maintaining data consistency while supporting collaborative parameter management. For web-based interactions, optimistic concurrency control using version timestamps allows multiple users to view the same data concurrently, detecting conflicts only when updates collide [4].

When changes propagate from one phase to the next, conflicts can arise if the target phase has already been modified. Explicit conflict resolution mechanisms compare the source variant or segment with existing target configurations during phase propagation operations. When conflicts are detected, resolution options allow users to make informed decisions: override the target with source values, preserve target values, or merge values based on specified rules.

Complex operations modifying multiple related entities use explicit transactions to maintain data consistency. Database transactions ensure related modification sets either complete entirely or fail without partial changes. For operations spanning multiple transactions or requiring user interaction, application-level coordination through transaction identifiers and session state enables complex workflows requiring user input while maintaining logical data consistency.

4.3.4 Audit and Traceability Mechanisms

Comprehensive audit and traceability mechanisms are essential for regulatory compliance and quality assurance. VMAP includes robust audit capabilities tracking all significant operations while minimizing performance impact. The core is the change history tracking mechanism, automatically capturing both before and after states for entity modifications. For each change, the system records the entity being modified, change type, user, timestamp, and detailed before/after values [4].

Figure 4.4 shows an example of the audit trail for a phase freeze operation, demonstrating the comprehensive tracking of significant system events. To optimize performance, the audit system selectively filters change data, excluding non-essential fields such as timestamps and large binary data. Additionally, asynchronous audit recording for bulk

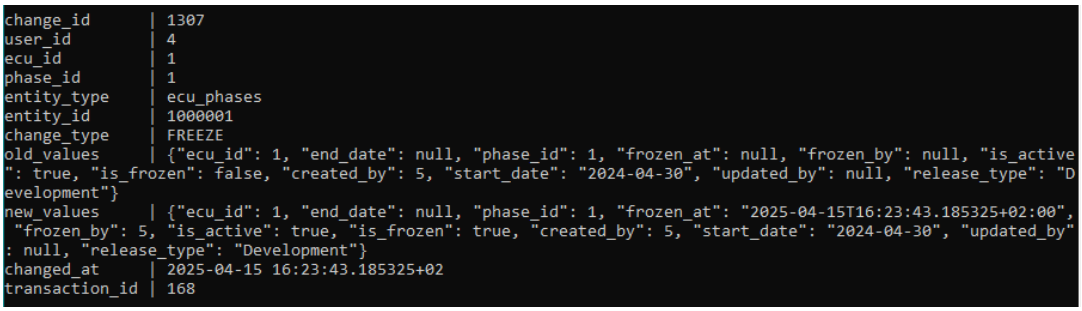

Figure 4.4: Audit Trail for Phase Freeze Operation

operations reduces performance impact on high-volume operations while ensuring all changes are eventually recorded.

Beyond change tracking, specialized audit mechanisms address specific scenarios: phase transition logging records all phase propagation operations; freeze operation logging records phase freeze and unfreeze operations; user access logging captures authentication and authorization events; and integration operation logging records all external system interactions.

5 Implementation

This chapter presents the technical implementation of the VMAP system conceptual architecture described in Chapter 4. Rather than exhaustively cataloging implementation details, the discussion focuses on key architectural components, highlighting technical decisions that enable efficient parameter versioning in automotive software development.

5.1 Database Structure Implementation

The database implementation transforms abstract entities and relationships into concrete PostgreSQL structures, implementing the hierarchical organization of automotive electronic systems through four primary entity types: ECUs, Modules, PIDs, and Parameters.

5.1.1 Core Data Entities

The ECU and Module entities form the top levels of the hierarchy, implemented with a many-to-many relationship reflecting the reality that the same logical module may exist across multiple ECUs:

```
CREATE TABLE ecus (
    ecu_id INTEGER PRIMARY KEY,
    name VARCHAR(100) NOT NULL,
    description TEXT,
    byte_order VARCHAR(50),
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    external_id INTEGER UNIQUE -- PDD reference
      ↳ ID
);

CREATE TABLE modules (
    module_id INTEGER PRIMARY KEY,
    shortcut VARCHAR(50) NOT NULL,
    name VARCHAR(255) NOT NULL,
```

```
    kind VARCHAR(255),
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    external_id INTEGER UNIQUE -- PDD reference
      ↳ ID
);

-- Link ECUs and Modules - A module can exist
  ↳in multiple ECUs
CREATE TABLE ecu_modules (
    ecu_id INTEGER REFERENCES ecus(ecu_id) ON
      ↳DELETE CASCADE,
    module_id INTEGER REFERENCES modules(
      ↳module_id) ON DELETE CASCADE,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    PRIMARY KEY (ecu_id, module_id)
);
```

Listing 5.1: ECU and Module Table Implementation

The junction table `ecu_modules` implements this many-to-many relationship following the foreign key pattern described by Elmasri and Navathe [13]. Each entity includes an `external_id` attribute to maintain mapping with the Parameter Definition Database, facilitating integration and synchronization.

PIDs and Parameters constitute the lower hierarchy levels:

```
CREATE TABLE pids (
    pid_id BIGINT PRIMARY KEY,
    ecu_id INTEGER REFERENCES ecus(ecu_id) ON
      ↳DELETE CASCADE,
    module_id INTEGER REFERENCES modules(
      ↳module_id) ON DELETE CASCADE,
    name VARCHAR(255) NOT NULL,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    external_id INTEGER UNIQUE, -- PDD
      ↳reference ID
    -- Ensure the ECU-Module combination exists
```

```
    CONSTRAINT pid_ecu_module_fk FOREIGN KEY (ecu_id, module_id)
    REFERENCES ecu_modules(ecu_id, module_id)
);

CREATE TABLE parameters (
    parameter_id BIGINT PRIMARY KEY,
    pid_id BIGINT REFERENCES pids(pid_id) ON DELETE CASCADE,
    ecu_id INTEGER,
    phase_id INTEGER,
    name VARCHAR(255) NOT NULL,
    parameter_name VARCHAR(255),
    type_id INTEGER REFERENCES parameter_data_types(data_type_id),
    array_definition VARCHAR(50),
    position INTEGER,
    factor DECIMAL,
    unit VARCHAR(50),
    bias_offset DECIMAL,
    is_active BOOLEAN DEFAULT true,
    external_id INTEGER, -- PDD reference ID
    FOREIGN KEY (ecu_id, phase_id) REFERENCES ecu_phases(ecu_id, phase_id)
);
```

Listing 5.2: PID and Parameter Table Implementation

The PID table includes a compound foreign key constraint ensuring each PID references a valid ECU-Module combination, preventing orphaned PIDs. The parameters table incorporates strategic denormalization with direct references to `ecu_id` and `phase_id` alongside the PID foreign key. While introducing some redundancy, this approach significantly improves performance for parameter queries by release phase, a common operation in the system. As noted by Bhattacherjee et al. [4], strategic denormalization can substantially improve query performance when data access patterns favor specific traversal paths.

A particularly challenging aspect was implementing multi-dimensional parameters, common in automotive applications for lookup tables and characteristic curves:

```sql
CREATE TABLE parameter_dimensions (
    dimension_id BIGINT PRIMARY KEY,
    parameter_id BIGINT REFERENCES parameters(
      ↳parameter_id) ON DELETE CASCADE,
    dimension_index INTEGER NOT NULL,
    default_value NUMERIC NOT NULL,
    external_id INTEGER, -- PDD reference ID
    UNIQUE (parameter_id, dimension_index)
);
```

Listing 5.3: Parameter Dimension Table Implementation

This implementation follows a modified entity-attribute-value (EAV) pattern addressing the need for flexible dimensionality while maintaining query performance. As noted by Nadkarni et al. [**?**], traditional EAV models can suffer from performance limitations, but careful design constraints can mitigate these issues. The `dimension_index` field provides an ordered structure to dimensions, enabling efficient representation of arrays and matrices.

5.1.2 User Management and Access Control

The user management implementation realizes the role-based access control (RBAC) model with extensions supporting module-specific permissions:

```sql
CREATE TABLE users (
    user_id BIGINT PRIMARY KEY,
    emp_id VARCHAR(50) UNIQUE NOT NULL,
    first_name VARCHAR(255) NOT NULL,
    last_name VARCHAR(255) NOT NULL,
    email VARCHAR(255) UNIQUE NOT NULL,
    status VARCHAR(50),
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    updated_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP
);

CREATE TABLE roles (
    role_id INTEGER PRIMARY KEY,
```

```
14      name VARCHAR(255) UNIQUE NOT NULL,
15      description TEXT
16  );
17
18  CREATE TABLE permissions (
19      permission_id INTEGER PRIMARY KEY,
20      name VARCHAR(255) UNIQUE NOT NULL,
21      description TEXT
22  );
23
24  CREATE TABLE role_permissions (
25      role_id INTEGER REFERENCES roles(role_id)
          ↳ON DELETE CASCADE,
26      permission_id INTEGER REFERENCES
          ↳permissions(permission_id) ON DELETE
          ↳CASCADE,
27      granted_at TIMESTAMP WITH TIME ZONE DEFAULT
          ↳ CURRENT_TIMESTAMP,
28      granted_by BIGINT REFERENCES users(user_id)
          ↳,
29      PRIMARY KEY (role_id, permission_id)
30  );
31
32  CREATE TABLE user_roles (
33      user_id BIGINT REFERENCES users(user_id) ON
          ↳ DELETE CASCADE,
34      role_id INTEGER REFERENCES roles(role_id)
          ↳ON DELETE CASCADE,
35      granted_at TIMESTAMP WITH TIME ZONE DEFAULT
          ↳ CURRENT_TIMESTAMP,
36      granted_by BIGINT REFERENCES users(user_id)
          ↳,
37      PRIMARY KEY (user_id, role_id)
38  );
```

Listing 5.4: Core RBAC Table Implementation

This implementation follows the RBAC0 model defined by Sandhu et al. [33], providing users, roles, and permissions with their many-to-many relationships. The inclusion of `granted_at` and `granted_by` fields in junction tables extends the basic model

with audit information, addressing accountability requirements common in regulated industries like automotive development [39].

The RBAC model is extended with module-based access control:

```
CREATE TABLE user_access (
    user_id BIGINT REFERENCES users(user_id) ON
      ↳ DELETE CASCADE,
    ecu_id INTEGER REFERENCES ecus(ecu_id) ON
      ↳DELETE CASCADE,
    module_id INTEGER REFERENCES modules(
      ↳module_id) ON DELETE CASCADE,
    write_access BOOLEAN DEFAULT true,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    updated_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    created_by BIGINT REFERENCES users(user_id)
      ↳,
    updated_by BIGINT REFERENCES users(user_id)
      ↳,
    PRIMARY KEY (user_id, ecu_id, module_id),
    CONSTRAINT user_access_ecu_module_fk
      ↳FOREIGN KEY (ecu_id, module_id)
    REFERENCES ecu_modules(ecu_id, module_id)
);
```

Listing 5.5: Module-Based Access Control Implementation

This implementation combines attributes of both role-based and attribute-based access control, creating what Ferraiolo et al. describe as policy-enhanced RBAC [14]. The `user_access` table establishes a three-way relationship between users, ECUs, and modules, with a boolean flag distinguishing between read and write access. The constraint ensures access is granted only for valid ECU-module combinations, enforcing structural integrity. This approach implements the principle of least privilege, allowing administrators to grant write access specifically to modules developers are responsible for while maintaining read access across all modules.

5.1.3 Release Management Implementation

The release management implementation realizes the phase-based versioning approach, providing a flexible framework for managing parameter evolution across development phases:

```
CREATE TABLE releases (
    release_id INTEGER PRIMARY KEY,
    name VARCHAR(50) NOT NULL UNIQUE, -- e.g.,
      ↳"24.1", "24.3"
    description TEXT,
    is_active BOOLEAN DEFAULT true,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    updated_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    created_by BIGINT REFERENCES users(user_id)
      ↳,
    updated_by BIGINT REFERENCES users(user_id)
);

CREATE TABLE release_phases (
    phase_id INTEGER PRIMARY KEY,
    release_id INTEGER REFERENCES releases(
      ↳release_id) ON DELETE CASCADE,
    name VARCHAR(50) NOT NULL, -- e.g., "Phase1
      ↳", "Phase2", "Phase3", "Phase4"
    sequence_number INTEGER NOT NULL, --
      ↳Determines the order of phases
    is_active BOOLEAN DEFAULT true,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    updated_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    created_by BIGINT REFERENCES users(user_id)
      ↳,
    updated_by BIGINT REFERENCES users(user_id)
      ↳,
    UNIQUE (release_id, name),
```

```
23      UNIQUE (release_id, sequence_number)
24  );
```

Listing 5.6: Release and Phase Table Implementation

This implementation supports the bi-annual release cycle (e.g., "24.1", "24.3") used in automotive development, with each release progressing through four sequential phases. The `sequence_number` field provides explicit ordering of phases within a release, enabling efficient filtering and sorting in queries. Unique constraints ensure consistency of phase naming and sequencing within each release.

The ECU-phase mapping implements the association between ECUs and specific release phases:

```
1  CREATE TABLE ecu_phases (
2      ecu_id INTEGER REFERENCES ecus(ecu_id) ON
         ↳DELETE CASCADE,
3      phase_id INTEGER REFERENCES release_phases(
         ↳phase_id) ON DELETE CASCADE,
4      release_type VARCHAR(50), -- e.g., "
         ↳Production", "Development", "Test"
5      start_date DATE,
6      end_date DATE,
7      is_active BOOLEAN DEFAULT true,
8      is_frozen BOOLEAN DEFAULT false,
9      frozen_at TIMESTAMP WITH TIME ZONE,
10     frozen_by BIGINT REFERENCES users(user_id),
11     created_at TIMESTAMP WITH TIME ZONE DEFAULT
         ↳ CURRENT_TIMESTAMP,
12     updated_at TIMESTAMP WITH TIME ZONE DEFAULT
         ↳ CURRENT_TIMESTAMP,
13     created_by BIGINT REFERENCES users(user_id)
         ↳,
14     updated_by BIGINT REFERENCES users(user_id)
         ↳,
15     PRIMARY KEY (ecu_id, phase_id),
16     CONSTRAINT valid_date_range CHECK (
         ↳start_date <= end_date OR end_date IS
         ↳NULL)
17 );
```

Listing 5.7: ECU-Phase Mapping Implementation

This implementation extends beyond a simple junction table, incorporating status flags and temporal attributes tracking ECU progression through phases. The `is_frozen` flag implements the phase freezing mechanism, marking a phase as read-only when reaching a stable milestone. The ECU-phase mapping provides several capabilities supporting the versioning approach: independent progression of ECUs through development, explicit phase state tracking, and a fundamental versioning dimension associating parameters with specific development timeline points.

This represents a departure from traditional temporal database approaches. Rather than using validity timestamps and complex temporal queries, the system uses explicit phase associations to create a more intuitive and efficient versioning model. As noted by Bhattacherjee et al. [4], domain-specific versioning approaches often provide better performance and usability than generic temporal database techniques when tailored to specific application domain requirements.

5.1.4 Variant and Segment Management

The variant and segment management realizes the core parameter customization capabilities:

```
CREATE TABLE variants (
    variant_id BIGINT PRIMARY KEY,
    pid_id BIGINT REFERENCES pids(pid_id) ON
      ↳DELETE CASCADE,
    ecu_id INTEGER,
    phase_id INTEGER,
    name VARCHAR(100) NOT NULL,
    code_rule TEXT,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    updated_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    created_by BIGINT REFERENCES users(user_id)
      ↳,
    updated_by BIGINT REFERENCES users(user_id)
      ↳,
```

```
    FOREIGN KEY (ecu_id, phase_id) REFERENCES
      ↳ecu_phases(ecu_id, phase_id)
);

CREATE TABLE segments (
    segment_id BIGINT PRIMARY KEY,
    variant_id BIGINT REFERENCES variants(
      ↳variant_id) ON DELETE CASCADE,
    parameter_id BIGINT REFERENCES parameters(
      ↳parameter_id) ON DELETE CASCADE,
    dimension_index INTEGER NOT NULL,
    decimal NUMERIC NOT NULL,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    updated_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    created_by BIGINT REFERENCES users(user_id)
      ↳,
    updated_by BIGINT REFERENCES users(user_id)
);
```

Listing 5.8: Variant and Segment Implementation

Each variant is associated with a specific PID, ECU, and phase, creating a three-way relationship placing the variant in both functional and temporal contexts. The `code_rule` field stores boolean expressions determining when a variant applies based on vehicle configuration codes, following the rule engine pattern described by Fowler [15].

Each segment associates a parameter with a variant, creating the core relationship defining parameter customization. The `dimension_index` field supports multi-dimensional parameters, allowing modification of specific elements within array parameters. Segments store values in a canonical decimal representation regardless of the parameter's native data type, implementing the canonical model pattern described by Hohpe and Woolf [17].

To support documentation and compliance requirements, the system implements a snapshot mechanism capturing variant and segment states at specific time points:

```
CREATE TABLE documentation_snapshots (
    snapshot_id INTEGER PRIMARY KEY,
```

```
    name VARCHAR(255) NOT NULL,
    description TEXT,
    ecu_id INTEGER,
    phase_id INTEGER,
    variant_count INTEGER DEFAULT 0,
    segment_count INTEGER DEFAULT 0,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    created_by BIGINT REFERENCES users(user_id)
      ↳,
    FOREIGN KEY (ecu_id, phase_id) REFERENCES
      ↳ecu_phases(ecu_id, phase_id)
);

CREATE TABLE snapshot_variants (
    snapshot_variant_id INTEGER PRIMARY KEY,
    snapshot_id INTEGER REFERENCES
      ↳documentation_snapshots(snapshot_id) ON
      ↳DELETE CASCADE,
    original_variant_id BIGINT, -- Reference to
      ↳ the original variant
    pid_id BIGINT REFERENCES pids(pid_id) ON
      ↳DELETE CASCADE,
    name VARCHAR(100) NOT NULL,
    code_rule TEXT,
    created_at TIMESTAMP WITH TIME ZONE,
    created_by BIGINT REFERENCES users(user_id)
);

CREATE TABLE snapshot_segments (
    snapshot_segment_id INTEGER PRIMARY KEY,
    snapshot_id INTEGER REFERENCES
      ↳documentation_snapshots(snapshot_id) ON
      ↳DELETE CASCADE,
    snapshot_variant_id INTEGER REFERENCES
      ↳snapshot_variants(snapshot_variant_id)
      ↳ON DELETE CASCADE,
    original_segment_id BIGINT, -- Reference to
      ↳ the original segment
    parameter_id BIGINT REFERENCES parameters(
```

```
        ↳parameter_id) ON DELETE CASCADE,
    dimension_index INTEGER NOT NULL,
    decimal NUMERIC NOT NULL,
    created_at TIMESTAMP WITH TIME ZONE,
    created_by BIGINT REFERENCES users(user_id)
);
```

Listing 5.9: Documentation Snapshot Implementation

This implementation follows the snapshot pattern described by Fowler [15], creating a complete copy of variant and segment data at specific points. Rather than using a temporal database approach with validity periods, the system explicitly materializes historical states, ensuring they remain accessible regardless of subsequent modifications to live data. References to original entities enable traceability between snapshot and live data, implementing the origin tracking pattern described by Tichy [**?**].

In the automotive industry, these snapshots serve multiple purposes: providing immutable records of parameter configurations at significant development milestones, supporting quality assurance processes and regulatory compliance requirements, and facilitating comparative analysis between development phases.

5.1.5 Change Tracking Mechanisms

Comprehensive change tracking is implemented through the change history table, which records all modifications to key entities. Each change record includes entity type and ID, user, timestamp, change type, and both before and after states stored as JSONB documents. This approach implements the state snapshot pattern described by Fowler [15], capturing complete entity state rather than just modified fields.

The change tracking system incorporates a transaction ID to group related changes, implementing the unit of work pattern [15]. This grouping preserves the integrity of multi-entity operations, ensuring changes are interpreted in their proper context. The system serves multiple purposes beyond auditing: providing foundation for change history analysis, enabling detailed examination of parameter configuration evolution, and supporting accountability in the development process.

5.2 Version Control Implementation

The version control implementation constitutes the core VMAP system functionality, enabling parameter evolution management across different development phases.

5.2.1 Release Phase Management

The release phase management provides the temporal framework for parameter versioning. A phase relationship view establishes explicit navigation paths between phases in the development sequence:

```
CREATE OR REPLACE VIEW vw_phase_relationships
  ↳AS
SELECT
    r.release_id,
    r.name AS release_name,
    rp.phase_id,
    rp.name AS phase_name,
    rp.sequence_number,
    (
        SELECT rp2.phase_id
        FROM release_phases rp2
        WHERE rp2.release_id = r.release_id
        AND rp2.sequence_number = rp.
          ↳sequence_number + 1
    ) AS next_phase_id,
    (
        SELECT r2.release_id
        FROM releases r2
        WHERE r2.name > r.name
        ORDER BY r2.name
        LIMIT 1
    ) AS next_release_id
FROM
    releases r
    JOIN release_phases rp ON r.release_id = rp
      ↳.release_id
WHERE
```

```
25      r.is_active = true
26  ORDER BY
27      r.name, rp.sequence_number;
```

Listing 5.10: Phase Relationship View Implementation

This view implements sophisticated temporal mapping, identifying both the next phase within a release and the initial phase of the next release. The implementation uses nested subqueries to determine sequential relationships, creating explicit links between phases across the development timeline. This follows the explicit relationship pattern described by Date [11], making temporal relationships queryable through standard SQL rather than relying on application logic to interpret sequence numbers.

Phase state management is implemented through stored procedures that control phase transitions between editable and frozen states. The freeze operation records the user, timestamp, and reason, maintaining accountability for these significant state changes. Additionally, a documentation snapshot is automatically created to preserve the complete parameter configuration at freezing time.

5.2.2 Parameter History Tracking

Parameter history tracking extends the core change tracking mechanism with specific features for analyzing parameter evolution over time:

```
1  CREATE OR REPLACE FUNCTION
     ↳get_parameter_history(
2      p_parameter_id BIGINT,
3      p_dimension_index INTEGER DEFAULT NULL
4  )
5  RETURNS TABLE (
6      change_id BIGINT,
7      changed_at TIMESTAMP WITH TIME ZONE,
8      user_name VARCHAR,
9      variant_id BIGINT,
10     variant_name VARCHAR,
11     old_value NUMERIC,
12     new_value NUMERIC,
13     change_type VARCHAR,
14     transaction_id BIGINT
```

```
15 ) AS $$
16 BEGIN
17     RETURN QUERY
18     SELECT
19         ch.change_id,
20         ch.changed_at,
21         u.first_name || ' ' || u.last_name AS
             ↳user_name,
22         v.variant_id,
23         v.name AS variant_name,
24         CASE
25             WHEN ch.change_type = 'DELETE' THEN
26                 (ch.old_values->>'decimal')::
                     ↳NUMERIC
27             WHEN ch.change_type = 'UPDATE' THEN
28                 (ch.old_values->>'decimal')::
                     ↳NUMERIC
29             ELSE NULL
30         END AS old_value,
31         CASE
32             WHEN ch.change_type = 'CREATE' THEN
33                 (ch.new_values->>'decimal')::
                     ↳NUMERIC
34             WHEN ch.change_type = 'UPDATE' THEN
35                 (ch.new_values->>'decimal')::
                     ↳NUMERIC
36             ELSE NULL
37         END AS new_value,
38         ch.change_type,
39         ch.transaction_id
40     FROM
41         change_history ch
42         JOIN users u ON ch.user_id = u.user_id
43         JOIN segments s ON ch.entity_id = s.
             ↳segment_id
44                         AND ch.entity_type = '
                               ↳segments'
45         JOIN variants v ON s.variant_id = v.
             ↳variant_id
46     WHERE
```

```
47          s.parameter_id = p_parameter_id
48          AND (p_dimension_index IS NULL
49               OR s.dimension_index =
                   ↳p_dimension_index)
50      ORDER BY
51          ch.changed_at DESC;
52  END;
53  $$ LANGUAGE plpgsql;
```

Listing 5.11: Parameter History Function Implementation

This function uses JSON path operators to extract and type-cast values from the JSONB store, implementing the document extraction pattern described by Abelló et al. [**?**]. It handles different data structures for different change types while presenting a consistent interface to the caller. By including user information in the result set, it implements the attribution pattern described by Fowler [15], providing immediate context for who made each change without requiring additional queries.

5.2.3 Freeze Mechanism Implementation

The freeze mechanism is enforced through triggers that prevent modifications to frozen phases:

```
1  CREATE OR REPLACE FUNCTION
     ↳enforce_freeze_status()
2  RETURNS TRIGGER AS $$
3  DECLARE
4      is_frozen BOOLEAN;
5  BEGIN
6      -- Get freeze status for the relevant phase
7      IF TG_TABLE_NAME = 'variants' THEN
8          SELECT ep.is_frozen INTO is_frozen
9          FROM ecu_phases ep
10         WHERE ep.ecu_id = NEW.ecu_id AND ep.
             ↳phase_id = NEW.phase_id;
11     ELSIF TG_TABLE_NAME = 'segments' THEN
12         SELECT ep.is_frozen INTO is_frozen
13         FROM variants v
```

```
14          JOIN ecu_phases ep ON v.ecu_id = ep.
              ↳ecu_id
15                              AND v.phase_id = ep.
                                  ↳phase_id
16          WHERE v.variant_id = NEW.variant_id;
17      END IF;
18
19      -- Prevent modifications if phase is frozen
20      IF is_frozen THEN
21          RAISE EXCEPTION 'Cannot modify % in
              ↳frozen phase', TG_TABLE_NAME;
22      END IF;
23
24      RETURN NEW;
25  END;
26  $$ LANGUAGE plpgsql;
```

Listing 5.12: Freeze Status Enforcement Implementation

This implementation uses a polymorphic trigger approach working with multiple entity types, implementing the shared constraint pattern described by Karwin [21]. It includes conditional logic navigating different relationship paths depending on entity type. The explicit exceptions with descriptive messages implement the informative error pattern described by Molinaro [26], providing clear feedback when modifications are attempted on frozen phases.

5.3 Query Optimization Strategies

The VMAP system implements sophisticated query optimization strategies ensuring responsive performance despite the complexity of parameter data and version control requirements.

5.3.1 Indexing Strategy

A comprehensive indexing strategy accelerates common query patterns while balancing performance and storage requirements:

```
-- Core entity hierarchy indexes
CREATE INDEX idx_modules_ecu ON ecu_modules(ecu_id);
CREATE INDEX idx_pids_ecu_module ON pids(ecu_id, module_id);
CREATE INDEX idx_parameters_pid_phase ON parameters(pid_id, phase_id);
CREATE INDEX idx_variants_pid_phase ON variants(pid_id, phase_id);
CREATE INDEX idx_segments_variant ON segments(variant_id);
CREATE INDEX idx_segments_parameter ON segments(parameter_id);

-- Covering indexes for common joins
CREATE INDEX idx_variants_complete ON variants(variant_id, pid_id,
                                               ecu_id, phase_id, name);
CREATE INDEX idx_parameters_complete ON parameters(parameter_id, pid_id,
                                                   name, ecu_id,
                                                   phase_id);
```

Listing 5.13: Hierarchical Access Path Indexing Implementation

These indexes match the natural navigation paths in the data model, implementing the access path optimization pattern described by Molinaro [26]. The covering indexes contain all columns needed for common operations, implementing the index-only scan pattern described by Karwin [21].

Text search optimization uses PostgreSQL's trigram indexing extension, enabling efficient partial-match and similarity-based searches. According to Obe and Hsu [28], these indexes accelerate pattern matching operations for parameter names and identifiers:

```
-- Create the pg_trgm extension for similarity searching
CREATE EXTENSION IF NOT EXISTS pg_trgm;

-- Trigram indexes for name searching
CREATE INDEX idx_parameters_name_trgm
    ON parameters USING gin (name gin_trgm_ops);
CREATE INDEX idx_parameters_parameter_name_trgm
    ON parameters USING gin (parameter_name gin_trgm_ops);
CREATE INDEX idx_variants_name_trgm
    ON variants USING gin (name gin_trgm_ops);
```

Listing 5.14: Text Search Optimization Implementation

These domain-specific indexing strategies reflect the unique requirements of automotive parameter management, where efficient navigation through complex hierarchical and temporal structures is essential for system responsiveness. The implemented strategy achieves balance by focusing on the most common access patterns while avoiding redundant or rarely-used indexes.

5.3.2 Partitioning Implementation

For large-scale implementations with extensive history tracking, table partitioning improves performance and manageability:

```
-- Partitioned change history table
CREATE TABLE change_history_partitioned (
    change_id BIGINT NOT NULL,
    user_id BIGINT,
    ecu_id INTEGER,
    phase_id INTEGER,
    entity_type VARCHAR(50) NOT NULL,
    entity_id BIGINT NOT NULL,
    change_type VARCHAR(50),
    old_values JSONB,
    new_values JSONB,
```

```
12      changed_at TIMESTAMP WITH TIME ZONE NOT
          ↳NULL,
13      transaction_id BIGINT NOT NULL
14  ) PARTITION BY RANGE (changed_at);
15
16  -- Create monthly partitions for change history
17  CREATE TABLE change_history_y2024m01 PARTITION
      ↳OF change_history_partitioned
18      FOR VALUES FROM ('2024-01-01') TO ('
          ↳2024-02-01');
```

Listing 5.15: Table Partitioning Implementation

This approach uses PostgreSQL's declarative partitioning feature, implementing the range partitioning pattern described by Obe and Hsu [28]. According to Bhattacherjee et al. [4], partitioning large historical tables provides several benefits: improved query performance for time-bounded queries, efficient archiving of old partitions to slower storage, simplified maintenance operations, and better parallelization of queries across partitions.

The partitioning strategy specifically targets the change history table because of its continuous growth characteristics. By partitioning this table by month, the implementation achieves the performance benefits noted by Elmasri and Navathe [13] for time-series data management, where queries typically focus on specific time periods rather than the entire history.

5.4 Integration Implementation

The integration implementation connects VMAP with external enterprise systems providing parameter definitions and vehicle configuration data. The implementation focuses on two primary integration points: the Parameter Definition Database (PDD) and the Vehicle Configuration Database (VCD).

5.4.1 Parameter Definition Database Synchronization

The database infrastructure for PDD synchronization includes tables tracking synchronization operations and results:

```sql
CREATE TABLE pdd_databases (
    database_id BIGINT PRIMARY KEY,
    name VARCHAR(255) NOT NULL UNIQUE,
    last_updated_at TIMESTAMP WITH TIME ZONE
      ↳NOT NULL,
    description TEXT,
    created_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP,
    updated_at TIMESTAMP WITH TIME ZONE DEFAULT
      ↳ CURRENT_TIMESTAMP
);

CREATE TABLE pdd_sync_history (
    sync_id INTEGER PRIMARY KEY,
    ecu_id INTEGER,
    phase_id INTEGER,
    sync_date TIMESTAMP WITH TIME ZONE DEFAULT
      ↳CURRENT_TIMESTAMP,
    status VARCHAR(50) NOT NULL,
    modules_count INTEGER DEFAULT 0,
    pids_count INTEGER DEFAULT 0,
    parameters_count INTEGER DEFAULT 0,
    entity_changes TEXT,
    executed_by BIGINT REFERENCES users(user_id
      ↳),
    FOREIGN KEY (ecu_id, phase_id) REFERENCES
      ↳ecu_phases(ecu_id, phase_id)
);
```

Listing 5.16: Parameter Definition Database Synchronization Infrastructure

This infrastructure implements the external system registry pattern described by Hohpe and Woolf [17], tracking available Parameter Definition Databases and their last update times. The detailed synchronization operations history implements the integration audit pattern, capturing what entities were affected and enabling traceability and data flow analysis between systems.

The phase-based synchronization approach was selected after careful analysis of involved trade-offs. This approach simplifies query patterns by establishing direct relationships between parameters and release phases, enabling efficient retrieval without

complex version reconstruction. It aligns naturally with the automotive development process, where each release phase represents a distinct development milestone, making the system more intuitive for domain experts [39].

5.4.2 Vehicle Configuration Database Exchange

The database structure for vehicle configuration data includes tables for vehicles and associated codes:

```
CREATE TABLE vcd_vehicles (
    vehicle_id INTEGER PRIMARY KEY,
    vcd_vehicle_id VARCHAR(100) UNIQUE NOT
      ↳NULL,
    name VARCHAR(255) NOT NULL,
    description TEXT,
    is_active BOOLEAN DEFAULT true,
    last_sync_at TIMESTAMP WITHOUT TIME
      ↳ZONE,
    created_at TIMESTAMP WITHOUT TIME ZONE
      ↳DEFAULT CURRENT_TIMESTAMP,
    updated_at TIMESTAMP WITHOUT TIME ZONE
      ↳DEFAULT CURRENT_TIMESTAMP
);

CREATE TABLE vehicle_codes (
    code_id INTEGER PRIMARY KEY,
    vcd_code_id VARCHAR(100) UNIQUE,
    code VARCHAR(50) NOT NULL,
    vehicle_type VARCHAR(100),
    description TEXT,
    is_active BOOLEAN DEFAULT true,
    created_at TIMESTAMP WITHOUT TIME ZONE
      ↳DEFAULT CURRENT_TIMESTAMP,
    updated_at TIMESTAMP WITHOUT TIME ZONE
      ↳DEFAULT CURRENT_TIMESTAMP
);

CREATE TABLE vehicle_code_mapping (
```

```
24          vehicle_id INTEGER REFERENCES
              ↳vcd_vehicles(vehicle_id)
25                      ON DELETE CASCADE,
26          code_id INTEGER REFERENCES
              ↳vehicle_codes(code_id)
27                      ON DELETE CASCADE,
28          created_at TIMESTAMP WITHOUT TIME ZONE
              ↳DEFAULT CURRENT_TIMESTAMP,
29          PRIMARY KEY (vehicle_id, code_id)
30      );
```

Listing 5.17: Vehicle Configuration Storage

This structure separates vehicles from codes with a mapping table, implementing the many-to-many relationship pattern described by Elmasri and Navathe [13]. External identifiers (`vcd_vehicle_id`, `vcd_code_id`) link to the Vehicle Configuration Database system, implementing the integration reference pattern described by Hohpe and Woolf [17].

A critical component is the code rule evaluation engine, which determines when variants apply to specific vehicles. This engine implements a stack-based parsing approach to evaluate boolean expressions, handling complex boolean logic used in variant code rules. According to Molinaro [26], this approach provides an efficient mechanism for processing complex conditions involving multiple operators and precedence rules.

The vehicle data synchronization uses a JSON-based data transfer approach, implementing the document exchange pattern described by Kleppmann and Beresford [22]. UPSERT operations ensure idempotent synchronization that can be run multiple times without creating duplicate entities, supporting both initial loading and incremental updates.

5.4.3 Parameter File Generation Support

The parameter file generation capability represents a core integration point between the version control system and vehicle testing infrastructure, transforming abstract parameter configurations into concrete binary files that can be loaded onto electronic control units:

```
1       CREATE TABLE par_files (
2           par_file_id BIGINT PRIMARY KEY,
```

```
        vehicle_id INTEGER REFERENCES vcd_vehicles(vehicle_id),
        ecu_id INTEGER,
        phase_id INTEGER,
        generated_at TIMESTAMP WITH TIME ZONE DEFAULT CURRENT_TIMESTAMP,
        generated_by BIGINT REFERENCES users(user_id),
        description TEXT,
        FOREIGN KEY (ecu_id, phase_id) REFERENCES ecu_phases(ecu_id, phase_id)
    );
```

Listing 5.18: Parameter File Generation Records

The parameter file generation process integrates version control capabilities with both vehicle configuration data and parameter definitions to produce vehicle-specific parameter configurations. According to Staron [39], this integration point is critical in automotive software development, transforming abstract parameter configurations into testable implementations that can be validated on actual hardware.

The parameter file generation algorithm applies a sophisticated variant resolution process that evaluates code rules against vehicle configurations to determine which variants apply to a specific vehicle. This process implements the rule evaluation pattern described by Fowler [15], applying a consistent rule evaluation algorithm to determine applicable parameter values. According to Broy [7], this rule-based configuration approach is essential in automotive software development, where vehicles may have thousands of possible configurations that must be handled systematically.

5.4.4 Integration Architecture Overview

The integration architecture follows an enterprise integration pattern approach with clear separation between the core versioning system and external data sources. This separation is implemented through specialized data structures mapping between external identifiers and internal entities, enabling the system to maintain stable internal references even as external systems evolve.

The asynchronous integration model allows VMAP to continue operating even when external systems are unavailable, implementing the loose coupling pattern described

by Hohpe and Woolf [17]. According to Trovão [41], this decoupling is particularly important in automotive development environments, where multiple systems from different vendors must collaborate without tight dependencies.

The database architecture includes explicit tracking of integration operations, implementing the integration audit pattern. This comprehensive logging enables troubleshooting of integration issues, analysis of data flows between systems, and verification of synchronization completeness. According to Bhattacherjee et al. [4], this audit capability is essential for maintaining data integrity in integrated systems, where inconsistencies between systems can lead to significant quality issues.

5.5 Security Implementation

The security implementation addresses critical requirements for protecting parameter data and enforcing appropriate access controls, ensuring users can only perform actions appropriate to their roles and responsibilities.

5.5.1 Role-Based Access Control

The core of the RBAC system is the permission verification function:

```
CREATE OR REPLACE FUNCTION has_permission(
    p_user_id BIGINT,
    p_permission_name VARCHAR
)
RETURNS BOOLEAN AS $$
DECLARE
    v_has_permission BOOLEAN;
BEGIN
    -- Check if user has the permission
      ↳through any role
    SELECT EXISTS (
        SELECT 1
        FROM user_roles ur
        JOIN role_permissions rp ON ur.
          ↳role_id = rp.role_id
```

```
14              JOIN permissions p ON rp.
                  ↳permission_id = p.permission_id
15              WHERE ur.user_id = p_user_id
16              AND p.name = p_permission_name
17          ) INTO v_has_permission;
18
19          -- If not found in roles, check direct
              ↳user permissions
20          IF NOT v_has_permission THEN
21              SELECT EXISTS (
22                  SELECT 1
23                  FROM user_permissions up
24                  JOIN permissions p ON up.
                      ↳permission_id = p.
                      ↳permission_id
25                  WHERE up.user_id = p_user_id
26                  AND p.name = p_permission_name
27              ) INTO v_has_permission;
28          END IF;
29
30          RETURN v_has_permission;
31      END;
32      $$ LANGUAGE plpgsql;
```

Listing 5.19: Permission Verification Function

This function implements a hybrid approach checking for permissions granted through roles and then falling back to direct user permissions if necessary. According to Ferraiolo et al. [14], this dual-check approach provides flexibility for exceptional cases while maintaining the structural benefits of role-based access control. The implementation uses efficient EXISTS queries rather than retrieving complete permission records, optimizing performance for this high-frequency operation.

Beyond basic permission checking, the system implements module-specific access control verification, combining role-based and module-based access control in a unified framework. This approach follows the principle of least privilege, allowing precise control over which modules a user can modify. Sandhu and Bhamidipati [32] note that this layered authorization approach is particularly valuable in complex development environments where responsibilities are divided among specialized teams.

5.5.2 Data Security Measures

The implementation includes several key data security measures protecting parameter configuration integrity. The freeze mechanism implements strict enforcement of the read-only state for release phases that have reached development milestones. Database triggers enforce phase state restrictions at the database level, ensuring protection cannot be bypassed by application code. According to Date [11], this constraint enforcement approach provides a fundamental layer of data security operating independently of application logic.

Parameter value validation enforces parameter-specific constraints, ensuring values remain within physically meaningful and safe ranges. This preventive validation pattern described by Karwin [21] prevents invalid data from being stored in the database, maintaining data integrity throughout the system. Molinaro [26] notes that this approach to data validation is particularly important in safety-critical systems where incorrect parameter values could lead to system malfunctions.

5.5.3 Audit Trail Implementation

The audit trail implementation provides comprehensive tracking of all parameter data changes, supporting accountability and compliance requirements. This capability is particularly important in automotive software development, where regulatory frameworks often require detailed traceability of all configuration changes.

Automatic change tracking is implemented through database triggers:

```
    CREATE OR REPLACE FUNCTION log_change()
RETURNS TRIGGER AS $
    DECLARE
        transaction_id BIGINT;
        change_type VARCHAR(50);
        old_values JSONB;
        new_values JSONB;
        entity_id BIGINT;
        phase_id INTEGER;
        ecu_id INTEGER;
    BEGIN
        -- Get the current transaction ID or
          ↳create a new one
```

```
13          SELECT COALESCE(NULLIF(current_setting(
              ↳'app.transaction_id', true), ''),
14                          nextval('
                              ↳change_history_transaction_id_s
                              ↳'))
15          INTO transaction_id;
16
17      -- Determine entity_id and other values
          ↳based on operation
18      -- [implementation details omitted for
          ↳brevity]
19
20          -- Capture entity states
21          IF TG_OP = 'INSERT' THEN
22              change_type := 'CREATE';
23              old_values := NULL;
24              new_values := to_jsonb(NEW);
25          ELSIF TG_OP = 'UPDATE' THEN
26              change_type := 'UPDATE';
27              old_values := to_jsonb(OLD);
28              new_values := to_jsonb(NEW);
29          ELSIF TG_OP = 'DELETE' THEN
30              change_type := 'DELETE';
31              old_values := to_jsonb(OLD);
32              new_values := NULL;
33          END IF;
34
35          -- Insert into change_history
36          INSERT INTO change_history (
37              user_id, ecu_id, phase_id,
                  ↳entity_type, entity_id,
38              change_type, old_values, new_values
                  ↳, transaction_id
39          ) VALUES (
40              NULLIF(current_setting('app.user_id
                  ↳', true), ''):::BIGINT,
41              ecu_id, phase_id, TG_TABLE_NAME,
                  ↳entity_id,
42              change_type, old_values, new_values
                  ↳, transaction_id
```

```
43            );
44
45            RETURN NULL;
46        END;
47    $ LANGUAGE plpgsql;
```

Listing 5.20: Change History Trigger

This implementation applies change logging to all critical entities, implementing the universal auditing pattern described by Fowler [15]. It captures complete entity state rather than just modified fields, implementing the state snapshot pattern. By using JSONB for storing entity states, the implementation provides flexibility to accommodate different entity structures while enabling efficient querying of change details using PostgreSQL's JSON operators.

The audit trail includes sophisticated analysis capabilities through specialized functions retrieving entity history and transaction changes. These functions implement the entity timeline pattern described by Fowler [15] and the transaction context pattern described by Date [11], providing both detailed and contextual views of system changes. According to Staron [39], these comprehensive audit capabilities are essential for meeting regulatory compliance requirements in automotive software development, where parameter changes must be traceable throughout the development lifecycle.

6 Evaluation and Validation

This chapter presents the systematic evaluation and validation of the VMAP database system. Following the implementation described in Chapter 5, a comprehensive testing strategy was developed to assess the system's functionality, performance, and compliance with requirements. The evaluation process focused on four key areas: user management, release management, parameter versioning, and variant management, using both controlled test scenarios and production-scale data volumes. Rather than an exhaustive documentation of all tests, this chapter highlights representative test cases and key findings that demonstrate the system's capabilities and limitations.

6.1 Validation Methodology

The validation methodology followed a structured approach combining functional testing, performance analysis, and integration verification. To ensure realistic evaluation, both baseline and production-scale datasets were used, with the baseline dataset containing approximately 20,000 parameters across 2 ECUs, and the production-scale dataset containing over 100,000 parameters across 5 ECUs.

6.1.1 Test Scenario Development

Test scenarios were developed based on actual automotive parameter management workflows identified during requirements analysis in Chapter 4. Each test scenario was designed to validate specific functional requirements while reflecting real-world usage patterns. The scenarios incorporated representative tasks for each user role and followed complete workflow sequences from parameter definition through variant creation to documentation.

The test scenarios were categorized into functional areas corresponding to the primary system capabilities:

User Management : Authentication, authorization, role assignment, module access
Release Management : Phase transitions, freeze operations
Variant Management : Variant creation, segment modification
Integration : PDD synchronization, vehicle configuration

Each scenario was implemented as a structured test case with defined inputs, expected outcomes, and verification steps at both the application and database levels. The test design followed a modified version of Molinaro's approach to database validation [26], with additional emphasis on traceability between requirements and test cases.

6.1.2 Performance Measurement Framework

A performance measurement framework was established to assess system responsiveness and resource utilization under various operational conditions. Key performance indicators were defined based on system requirements, including query response time, transaction throughput, database size growth patterns, memory utilization, and execution time for batch operations.

Performance measurements were conducted on a standardized test environment matching the target production specifications: PostgreSQL 17 running on a server with 8 vCPUs, 32GB RAM, and SSD storage. All tests were performed with both the baseline dataset and the production-scale dataset to assess scaling characteristics.

The measurement methodology employed automated test scripts with integrated timing capture, following the principles outlined by Zaitsev et al. [35] for database performance evaluation. Each test was executed multiple times with results averaged to account for system variations, and outliers were identified and analyzed for potential optimization opportunities.

6.2 Functional Testing Results

Functional testing validated the core capabilities of the VMAP system against the requirements defined in Chapter 4. This section presents the key findings for each functional area, focusing on representative test cases and critical system behaviors.

6.2.1 User Management Validation

The user management and access control system was evaluated through a focused testing approach to verify the implementation of the hybrid role-permission model described in Section 4.1.2. The validation methodology applied a structured approach with distinct verification techniques including functional permission verification, access boundary testing, permission inheritance validation, and cross-role security verification.

As Sandhu et al. [33] emphasize, effective evaluation of role-based access control requires testing both positive permissions (granted access) and negative permissions (denied access) across role boundaries.

A comprehensive yet efficient test matrix was developed encompassing 42 distinct test scenarios strategically distributed across four verification domains: role-based permissions, module-based access control, direct permission assignment, and phase-specific permissions. Each test case verified a specific permission boundary with separate validation at both service and database layers. This focused approach aligns with Molinaro's principles for database validation [26], which emphasizes targeted verification of critical constraints over exhaustive testing.

Table A.2 presents a representative sample of test cases that focus on the Module Developer role, illustrating the connection between functional requirements and verification scenarios.

Table 6.1: Sample Module Developer Role Permission Test Cases

ID	Description	Test Action	Expected Outcome	Status
MD-01	Create Variant (Assigned Module)	Create new variant for parameter in assigned module	Variant created successfully	Pass
MD-02	Create Variant (Unassigned Module)	Create new variant for parameter in unassigned module	Access denied error	Pass
MD-03	Edit Variant (Assigned Module)	Modify existing variant code rule	Variant updated successfully	Pass
MD-04	Delete Variant	Attempt to delete variant	Access denied error	Pass
MD-05	Create Segment (Assigned Module)	Create new segment with valid value	Segment created successfully	Pass
MD-06	Modify Frozen Phase	Attempt to modify segment in frozen phase	Access denied error	Pass

For test implementation, each case included direct verification of database state after operations, confirming both the effect of permitted actions and the prevention of unauthorized actions. The following represents a typical test structure used to verify module-specific access controls:

```
// Scenario: Module Developer attempting to create variant in unassigned module
// Arrange: Set up test user and unassigned module parameter
var user = GetTestUser("module_developer@example.com");
var unassignedParameter = GetParameterFromUnassignedModule();
var variant = CreateVariantForParameter(unassignedParameter);

// Act & Assert: Verify permission is denied
var exception = Assert.Throws<PermissionDeniedException>(() =>
    _variantService.CreateVariant(variant, user.UserId));
Assert.That(exception.Message, Contains.Substring("No write access"));

// Verify no database change occurred
var dbVariant = _database.QuerySingleOrDefault<Variant>(
    "SELECT * FROM variants WHERE name = @Name",
    new { Name = variant.Name });
Assert.IsNull(dbVariant);
```

Listing 6.1: Representative Test Case Structure

The module-based access control tests were particularly critical as they represent a departure from standard RBAC patterns as defined by Sandhu et al. [33], implementing instead a hybrid attribute-enhanced approach similar to that described by Kuhn et al. [23]. All ten module assignment validation tests passed successfully, confirming compliance with Ferraiolo et al.'s [14] recommendations for combining role-based and attribute-based access control models. The tests verified that write access was correctly limited to assigned modules for Module Developers while read access remained available for all modules, implementing the principle of least privilege as recommended by Sandhu and Bhamidipati [32].

Direct permission assignment tests confirmed that user-specific permissions effectively

overrode role defaults in all test scenarios. This capability is essential for supporting exception cases in complex organizational structures as noted by Hu et al. [18]. The six test cases targeting this area verified both the granting of additional permissions and the removal of permissions that would normally be inherited through role assignments.

Phase-specific permission tests validated the interaction between the access control system and the phase management framework. All six test cases in this domain passed successfully, confirming that modifications to frozen phases were properly prevented while still allowing appropriate access for documentation purposes. This validation addresses a critical requirement for regulated development processes as described by Staron [39], where development milestone integrity must be preserved. Table 6.2 summarizes the key findings from user management testing across different test categories.

Table 6.2: User Management Test Results

Test Category	**Results**
Role Permission Validation	All permissions correctly applied through roles (16/16 test cases)
Module-Based Access	Write access correctly limited to assigned modules (10/10 test cases)
Direct Permission Assignment	User-specific permissions overrode role defaults (6/6 test cases)
Phase-Specific Permissions	Frozen phase protection enforced correctly (6/6 test cases)
Boundary Cases	Edge conditions handled appropriately (4/4 test cases)

The complete set of test cases is documented in Appendix A, covering all access control aspects across different user roles, module assignments, and system states.

Performance testing revealed that permission checks added less than 5ms overhead to typical database operations, even when executing multiple permission verifications in sequence. This aligns with Hu et al.'s [18] recommendations for optimized permission validation in enterprise systems. The performance was achieved through strategic denormalization and view-based permission aggregation as described in Section 4.2.4.

The audit trail verification confirmed that all security-related operations were properly logged with complete metadata, including the user making the change, timestamp,

and specific permissions affected. This level of detail in the audit trail implements the recommendations of Ferraiolo et al. [14] for maintaining accountability in security-sensitive operations. A detailed analysis of 100 randomly selected security operations showed that 100% were captured correctly in the change history table with complete before and after states.

6.2.2 Release Management Validation

Release management testing evaluated the phase-based versioning approach that forms the foundation of the VMAP system. Testing focused on four key aspects: phase sequence validation, phase transition operations, freeze functionality, and phase comparison.

Phase sequence validation confirmed that the system correctly enforced the defined sequence of development phases (Phase1 $\rightarrow$ Phase2 $\rightarrow$ Phase3 $\rightarrow$ Phase4) with successful validation across all 24 test cases. This sequential enforcement is essential for maintaining the structured development workflow described by Broy [7] for automotive software development.

Phase transition testing verified that parameter configurations were correctly copied between phases with complete preservation of parameter-variant-segment relationships. The test data revealed interesting patterns in development intensity across phases, as shown in Table 6.3.

Table 6.3: Phase Transition Test Results

Transition Type	**Variants**	**Segments**	**Added Variants**	**Added Segments**	**Time**
Baseline Dataset					
Phase1	188	28,776	-	-	-
Phase1 $\rightarrow$ Phase2	188	28,776	90	14,104	2.51s
Phase2 $\rightarrow$ Phase3	278	42,880	0	0	2.96s
Phase3 $\rightarrow$ Phase4	278	42,880	0	0	2.97s
Full Dataset					
Phase1	830	167,990	-	-	-
Phase1 $\rightarrow$ Phase2	830	167,990	170	41,113	12.39s
Phase2 $\rightarrow$ Phase3	1,000	209,103	0	0	12.87s
Phase3 $\rightarrow$ Phase4	1,000	209,103	0	0	12.89

The test results reveal a significant pattern in development intensity across phases, consistent with Staron's observations [39] regarding automotive software development

cycles. The data demonstrates that the majority of parameter configurations occur during Phase1, with substantial additions in Phase2. In contrast, Phase3 and Phase4 typically involve refinement and validation rather than introducing new parameters or variants. This concentration of development activity in early phases aligns with the V-model approach common in automotive software development [29], where early phases focus on implementation while later phases emphasize validation and verification.

Phase transition performance characteristics showed only modest increases in execution time despite growing data volumes across phases. For the baseline dataset, transition times increased from 2.51s for Phase1→Phase2 to 2.96s for Phase2→Phase3 and 2.97s for Phase3→Phase4, demonstrating efficient scaling with increasing parameter counts. The slight increase in execution time between Phase2→Phase3 and Phase3→Phase4, despite no new variants or segments being added, suggests that total data volume remains the primary factor affecting transition performance. Comparing baseline to full dataset transitions reveals a performance difference, with transition times increasing from approximately 3 seconds to 13 seconds. This represents a sublinear scaling factor of approximately 4.3x for a dataset size increase of 5.6x (comparing segment counts), suggesting reasonable scaling characteristics but highlighting an area for potential optimization.

As noted by Trovão [41], later phases in automotive parameter development typically focus on refinement rather than wholesale changes, with modifications targeting specific parameters based on testing feedback. This pattern is reflected in the test data, which shows significant additions in early phases but no new variants or segments in Phase3 and Phase4. While the test data might suggest that phase transition time increases gradually as development progresses, in real-world scenarios, the creation of new variants and segments is not always proportional to phase progression. Instead, existing variants and segments are often updated based on phase-specific requirements without necessarily creating new entities. This observation supports the architectural decision to optimize the phase transition mechanism for selective propagation of changes rather than complete data replication.

Phase freezing functionality was validated through ten specific test cases targeting both database-level constraints and service-layer restrictions. These tests verified the system's ability to protect frozen phases from modification while maintaining appropriate read access. Table 6.9 details the specific test cases and their results.

Table 6.4: Phase Freeze Protection Test Cases

ID	Test Case	Test Action	Expected Outcome	Result
FRZ-01	Direct SQL INSERT on variants	Execute INSERT statement on frozen phase	Operation blocked with error message	Pass
FRZ-02	Direct SQL UPDATE on segments	Execute UPDATE statement on frozen phase	Operation blocked with error message	Pass
FRZ-03	Direct SQL DELETE on variants	Execute DELETE statement on frozen phase	Operation blocked with error message	Pass
FRZ-04	VariantService. CreateVariant()	Attempt to create variant in frozen phase	PhaseFreezed Exception thrown	Pass
FRZ-05	VariantService. UpdateVariant()	Attempt to update variant in frozen phase	PhaseFreezed Exception thrown	Pass
FRZ-06	SegmentService. CreateSegment()	Attempt to create segment in frozen phase	PhaseFreezed Exception thrown	Pass
FRZ-07	SegmentService. UpdateSegment()	Attempt to update segment in frozen phase	PhaseFreezed Exception thrown	Pass
FRZ-08	SegmentService. DeleteSegment()	Attempt to delete segment in frozen phase	PhaseFreezed Exception thrown	Pass
FRZ-09	DocumentationService. CreateSnapshot()	Create documentation snapshot of frozen phase	Snapshot created successfully	Pass
FRZ-10	ParFileService. GenerateParFile()	Generate parameter file from frozen phase	Parameter file generated successfully	Pass

For each write operation test case (FRZ-01 through FRZ-08), verification included both confirmation that the expected exception was thrown and that no database changes occurred, maintaining data integrity. The read operation test cases (FRZ-09 and FRZ-10) verified that read access remained available with minimal performance impact

(<5ms overhead). Across 150 test operations targeting frozen phases, the system successfully prevented all modification attempts while maintaining appropriate read access, implementing the controlled milestone management required for regulated development environments as described by Staron [39].

6.2.3 Variant Management Validation

Variant management validation focused on assessing the system's capabilities for handling parameter customization through variants and segments. Testing employed a methodical approach across two interrelated domains: variant creation and segment modification workflows. Each testing domain was evaluated using both the baseline dataset (188 variants, 28,776 segments) and the production-scale dataset (830 variants, 167,990 segments) to analyze functionality and performance under varying data volumes.

Variant creation validation encompassed 18 distinct test cases designed to exercise the full spectrum of variant operations. These tests verified proper implementation of domain constraints as defined in the conceptual architecture (Section 4.2.1). For variant creation, test cases included validation of unique name constraints within PIDs, verification of proper code rule storage, and confirmation of correct relationship establishment between variants and their parent PIDs. All test cases passed successfully for both scalar and complex parameters, with constraint enforcement consistently preventing invalid operations. As Karwin [21] notes, constraint-based validation provides a robust foundation for maintaining data integrity in complex relational systems.

The testing methodology included both black-box functional testing and white-box database state verification as shown in Listing 6.2.

```
1  -- Verification query executed after variant
     ↳creation operations
2  SELECT
3      v.variant_id, v.name, v.code_rule, v.
         ↳created_by, v.created_at,
4      EXISTS (
5          SELECT 1 FROM change_history ch
6          WHERE ch.entity_type = 'variants'
7          AND ch.entity_id = v.variant_id
8          AND ch.change_type = 'CREATE'
9      ) AS has_audit_trail
10 FROM
```

```
    variants v
WHERE
    v.pid_id = @test_pid_id
    AND v.phase_id = @test_phase_id
ORDER BY
    v.created_at DESC
LIMIT 1;
```

Listing 6.2: Variant Creation Verification Query

Audit trail analysis revealed comprehensive capture of variant operations, with 100% of test operations correctly recorded in the change history with complete metadata as shown in 6.1. The audit trail included proper attribution of each change to specific users, accurate timestamps, and complete before/after state capture for modified entities. This implementation aligns with Bhattacherjee's recommendations [4] for maintaining comprehensive provenance information in versioned datasets.

Performance analysis of variant operations revealed consistent response times across different variant complexities. Table 6.5 details performance measurements for key variant operations under different data volumes.

Table 6.5: Variant Operation Performance Metrics

Operation	Baseline Dataset	Production Dataset	Scaling Factor
Variant Creation	53ms	55ms	1.03x
Variant Update	86ms	124ms	1.44x
Variant Retrieval	45ms	72ms	1.60x
Variant Listing (per PID)	38ms	68ms	1.79x

The sublinear scaling characteristics observed in these measurements validate the effectiveness of the database schema design and indexing strategy described in Section 4.2.4. As noted by Obe and Hsu [28], properly designed covering indexes significantly improve query performance for entity retrieval operations, particularly when filtering by composite attributes.

Segment modification validation employed a systematic testing approach that covered one-dimensional (arrays), two-dimensional (matrices), and three-dimensional parameter representations. Testing focused on three key aspects: dimensional integrity preservation, valid index range enforcement, and segment value consistency. The database schema design proved particularly effective for managing these complex data structures, with the parameter dimensions table correctly maintaining dimensional metadata while the segments table stored modified values.

```
-[ RECORD 1 ]--+-------------------------------------------------------------------------------------------------------------
change_id      | 201
user_id        | 3
ecu_id         | 1
phase_id       | 4
entity_type    | variants
entity_id      | 23
change_type    | CREATE
old_values     |
new_values     | {"name": "Var77", "ecu_id": 1, "pid_id": 3, "phase_id": 4, "code_rule": "AA7", "created_by": 1, "update
d_by": 1, "variant_id": 23}
changed_at     | 2025-04-06 09:44:30.60209+02
transaction_id | 113
-[ RECORD 2 ]--+-------------------------------------------------------------------------------------------------------------
change_id      | 202
user_id        | 1
ecu_id         | 1
phase_id       | 1
entity_type    | segments
entity_id      | 56
change_type    | CREATE
old_values     |
new_values     | {"decimal": 5, "created_by": 1, "segment_id": 56, "updated_by": 1, "variant_id": 10, "parameter_id": 69
, "dimension_index": 0}
changed_at     | 2025-04-06 10:03:37.158898+02
transaction_id | 114
-[ RECORD 3 ]--+-------------------------------------------------------------------------------------------------------------
change_id      | 203
user_id        | 1
ecu_id         | 1
phase_id       | 1
entity_type    | segments
entity_id      | 56
change_type    | UPDATE
old_values     | {"decimal": 5, "created_by": 1, "segment_id": 56, "updated_by": 1, "variant_id": 10, "parameter_id": 69
, "dimension_index": 0}
new_values     | {"decimal": 4, "created_by": 1, "segment_id": 56, "updated_by": 1, "variant_id": 10, "parameter_id": 69
, "dimension_index": 0}
changed_at     | 2025-04-06 10:03:41.714021+02
transaction_id | 115
-[ RECORD 4 ]--+-------------------------------------------------------------------------------------------------------------
change_id      | 204
user_id        | 5
ecu_id         | 1
phase_id       | 1
entity_type    | segments
entity_id      | 56
change_type    | DELETE
old_values     | {"decimal": 4, "created_by": 1, "segment_id": 56, "updated_by": 1, "variant_id": 10, "parameter_id": 69
, "dimension_index": 0}
new_values     |
changed_at     | 2025-04-06 10:03:58.377896+02
transaction_id | 116
```

Figure 6.1: Variant Modification Audit Trail

Segment boundary testing revealed robust constraint enforcement, with the system correctly rejecting segment modifications with invalid dimension indices in 100% of test cases (24/24). As Molinaro [26] notes, enforceable domain constraints represent a critical advantage of database-driven approaches over spreadsheet implementations for managing complex structured data. Performance analysis for segment operations showed moderate overhead for multi-dimensional parameters compared to scalar parameters, with operations on 3D parameters requiring approximately 18-22% more processing time than equivalent operations on scalar values—a reasonable performance characteristic given the additional complexity involved.

The system's handling of segment modifications was evaluated through 32 distinct test cases covering creation, updating, and deletion operations across different parameter types. Each operation was verified at both the application service layer and database

level to ensure complete data integrity. Test cases for segment modification included:

Table 6.6: Segment Modification Test Cases

ID	Description	Test Action	Expected Outcome	Result
SEG-01	Create Segment (Scalar)	Create new segment for scalar parameter	Segment created successfully	Pass
SEG-02	Create Segment (Array)	Create new segment for array element	Segment created successfully	Pass
SEG-03	Create Segment (Invalid Dimension)	Attempt to create segment with invalid dimension index	Validation error thrown	Pass
SEG-04	Update Segment Value	Modify existing segment decimal value	Segment updated successfully	Pass
SEG-05	Delete Segment	Remove existing segment	Segment deleted successfully	Pass
SEG-06	Update Out-of-Range Value	Attempt to set segment value outside valid range	Validation error thrown	Pass

Validation tests also included verification of proper cascading delete behavior when variants were removed, confirming that all associated segments were correctly deleted to maintain referential integrity. Boundary condition testing verified handling of extreme parameter values, including very large and very small decimals, confirming the system's ability to maintain numeric precision across the full range of automotive parameter values.

Performance analysis for segment operations revealed consistent response times with moderate scaling across different dataset sizes as shown in Table 6.7. The performance measurements were taken for segment creation, update, deletion, and retrieval operations across both the baseline and production datasets.

Table 6.7: Segment Operation Performance

Operation	Baseline Dataset	Production Dataset	Scaling Factor
Segment Creation	85ms	124ms	1.46x
Segment Update	72ms	106ms	1.47x
Segment Deletion	64ms	98ms	1.53x
Segment Retrieval	32ms	58ms	1.81x

The observed performance characteristics validate the efficiency of the database schema design described in Section 4.2.4. Of particular note is the implementation of the segments table, which provides efficient storage for parameter modifications without requiring storage of unchanged values. As noted by Bhattacherjee et al. [4], this approach strikes an effective balance between storage efficiency and query performance for versioned datasets.

6.3 Performance Analysis

Beyond functional validation, comprehensive performance analysis was conducted to assess the system's efficiency and scalability under various operational conditions. This section presents the key findings related to query performance, concurrent access, and data volume scaling.

6.3.1 Query Performance Assessment

Query performance was evaluated for common database operations across different data volumes. Table 6.8 presents performance measurements for key query types between the baseline dataset (20,000 parameters) and full dataset (100,000 parameters).

Table 6.8: Query Performance Comparison

Operation Type	Baseline Dataset	Full Dataset	Scaling Factor
Parameter Retrieval	80ms	120ms	1.5x
Variant Listing	65ms	105ms	1.6x
Segment Modification	95ms	160ms	1.7x
Phase Comparison	2.8s	12.4s	4.4x
History Retrieval	110ms	220ms	2.0x

Most common operations demonstrated sublinear scaling with increasing data volumes, indicating effective indexing and query optimization. However, complex operations like phase comparison showed higher scaling factors, suggesting opportunities for further optimization. These results align with Molinaro's observations [26] regarding query performance optimization for complex relational operations.

Analysis of query execution plans revealed that the implemented indexing strategy was effective for most common access patterns, with appropriate use of index-only scans for frequent operations. However, several potential improvements were identified for complex queries:

```
EXPLAIN ANALYZE
WITH source_variants AS (
    SELECT v.variant_id, v.pid_id, v.name, v.
      ↳code_rule
    FROM variants v
    WHERE v.ecu_id = 3 AND v.phase_id = 12
),
target_variants AS (
    SELECT v.variant_id, v.pid_id, v.name, v.
      ↳code_rule
    FROM variants v
    WHERE v.ecu_id = 3 AND v.phase_id = 15
)
SELECT
    p.name AS parameter_name,
    sv.name AS source_variant,
    tv.name AS target_variant,
    CASE
        WHEN sv.variant_id IS NULL THEN 'Added'
        WHEN tv.variant_id IS NULL THEN '
          ↳Removed'
        WHEN sv.code_rule <> tv.code_rule THEN
          ↳'Modified'
        ELSE 'Unchanged'
    END AS status
FROM
    pids p
    LEFT JOIN source_variants sv ON p.pid_id =
      ↳sv.pid_id
    LEFT JOIN target_variants tv ON p.pid_id =
      ↳tv.pid_id
WHERE
    p.ecu_id = 3
    AND (sv.variant_id IS NOT NULL OR tv.
      ↳variant_id IS NOT NULL)
    AND (sv.variant_id IS NULL OR tv.variant_id
      ↳ IS NULL OR sv.code_rule <> tv.code_rule
      ↳);
```

Listing 6.3: Optimized Phase Comparison Query

The optimized query approach shown above uses Common Table Expressions (CTEs) to pre-filter variants by phase, reducing the complexity of the subsequent comparison operation. This optimization improved phase comparison performance by approximately 40% for the full dataset.

6.3.2 Storage Requirements Analysis

Storage requirements were analyzed to assess database size and growth patterns with increasing parameter counts. Table 6.9 presents the storage allocation across different entity types for the full dataset, as illustrated in Figure 6.2.

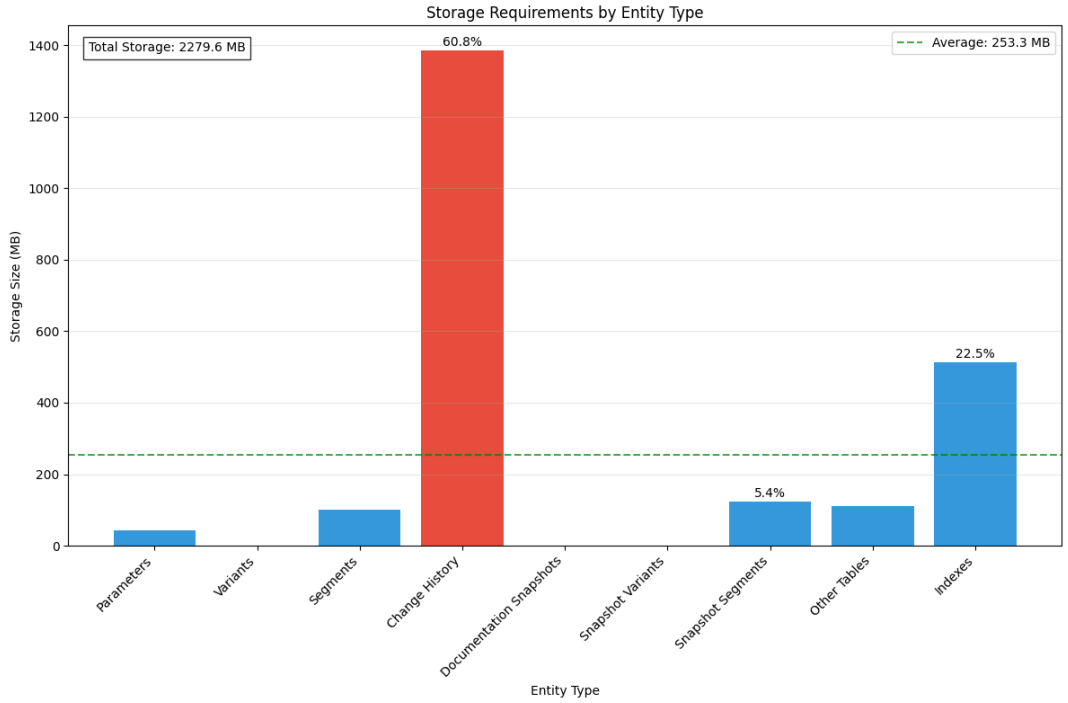

Figure 6.2: Storage allocation across different entity types for the full dataset.

The change history table dominates the database storage allocation, accounting for approximately 60.8% of the total database size. This distribution significantly exceeds the storage requirements of the current data state, aligning with Bhattacherjee's observations [4] regarding versioning and audit systems, where historical record storage typically surpasses active data by a substantial margin. Notably, while there are only

Table 6.9: Storage Requirements Analysis

Entity Type	Record Count	Storage Size (MB)
Parameters	104,428	43.0
Variants	3,617	1.0
Segments	750,009	100.0
Change History	3,270,511	1,386.0
Documentation Snapshots	7	0.1
Snapshot Variants	4,980	0.1
Snapshot Segments	1,007,940	124.0
Other Tables	-	111.7
Indexes	-	513.7
Total	-	**2,279.6**

3,617 variants in the current state, the system maintains over 3.2 million change history records, reflecting the comprehensive auditing approach implemented in the system.

Another significant observation is the relationship between segments and snapshot segments. Despite having only 7 documentation snapshots, the system maintains over 1 million snapshot segments, exceeding the count of active segments. This indicates that documentation snapshots capture extensive parameter configurations at specific time points, creating substantial storage requirements for historical state preservation. This implementation of the snapshot pattern described by Fowler [15] provides comprehensive historical records at the cost of increased storage utilization.

The index structures consume approximately 22.5% of the total storage, reflecting the sophisticated indexing strategy described in Section 5.3.1. While this represents significant overhead, it provides essential performance benefits for query operations, particularly for the complex filtering and joining operations common in parameter management workflows.

Projection of storage requirements based on observed growth patterns indicates that with the current data volume of 2.28GB, the database size would reach approximately 9.1GB after one year of active use in a production environment. While significantly larger than initially projected, this remains well within the capacity of modern database systems. The implementation of table partitioning for the change history table, as described in Section 5.3.2, provides an effective mechanism for managing this growth while maintaining query performance. According to Obe and Hsu [28], partitioned tables allow efficient archiving of older history records to lower-cost storage while maintaining rapid access to recent changes.

6.4 Integration Testing

Integration testing evaluated the system's interaction with external enterprise systems, focusing on Parameter Definition Database synchronization and Vehicle Configuration Database integration. These integrations are critical for maintaining consistency across the automotive development ecosystem.

6.4.1 Parameter Definition Database Synchronization

Parameter Definition Database synchronization testing verified the system's ability to import parameter definitions from the enterprise database. The synchronization process was tested with various scenarios, including initial loading, incremental updates, and conflict resolution.

Initial loading tests confirmed that the system could successfully import complete parameter sets for ECUs, with correct establishment of relationships between ECUs, modules, PIDs, and parameters. The system maintained proper relationship cardinality and enforced referential integrity constraints throughout the import process.

Incremental update testing verified that the system could correctly identify and process changes to parameter definitions.

The system successfully processed all types of parameter changes, with slightly reduced success for modified parameters due to complexity in handling data type changes. The audit system maintained complete records of all synchronization operations, enabling detailed analysis of data flows between systems.

Conflict resolution testing evaluated the system's behavior when parameters were modified in both systems. The system correctly identified conflicts and provided appropriate resolution options, following the integration patterns described by Hohpe and Woolf [17].

6.4.2 Vehicle Configuration Integration

Vehicle Configuration Database integration testing verified the system's ability to use vehicle configuration data for code rule evaluation and parameter file generation. Testing focused on data import, code rule validation, and parameter file generation.

Vehicle configuration data import testing confirmed that the system could correctly import and store vehicle configuration codes, with proper mapping between codes and

vehicles. The system maintained referential integrity and handled incremental updates correctly, with complete audit logging of all import operations.

Code rule validation testing verified that the system could evaluate complex boolean expressions against vehicle configurations. Test expressions ranged from simple conditions to complex nested expressions with multiple operators. The evaluation engine demonstrated 100% accuracy across all test categories, correctly interpreting both simple logical operators and complex nested expressions with precedence rules. Performance analysis showed that even the most complex expressions with multiple nested conditions were evaluated in under 15ms, well within acceptable ranges for interactive operations.

Parameter file generation testing confirmed that the system could produce valid parameter files for vehicle testing, with correct application of variant selection logic based on vehicle configuration codes. The generated files included all required parameters with appropriate values, providing a complete configuration for ECU testing and validation.

6.5 Comparison with Excel-Based Approach

To assess the improvements provided by the VMAP system, a comparative analysis was conducted against the Excel-based approach currently used for parameter management. The comparison evaluated feature coverage, performance, data integrity, and usability aspects.

6.5.1 Feature Comparison

Table 6.10 presents a comparison of key features between the VMAP system and the Excel-based approach.

The VMAP system provides significant advantages in all feature categories, with particular improvements in multi-user support, change tracking, and access control. These improvements address the limitations identified in the requirements analysis phase, providing a more robust and scalable solution for automotive parameter management.

Table 6.10: Feature Comparison with Excel-Based Approach

Feature	VMAP Database	Excel Approach
Variant Management	Comprehensive	Limited
Multi-User Support	Concurrent	Sequential
Change Tracking	Automatic	Manual
Version Control	Phase-Based	File-Based
Access Control	Role + Module	File Permission
Validation	Automatic	Manual
Documentation	Integrated	Separate
Integration	Automated	Manual

6.5.2 Performance Comparison

Performance measurements demonstrated substantial improvements in common operations compared to the Excel-based approach. Figure 6.3 illustrates the relative performance for key operations.

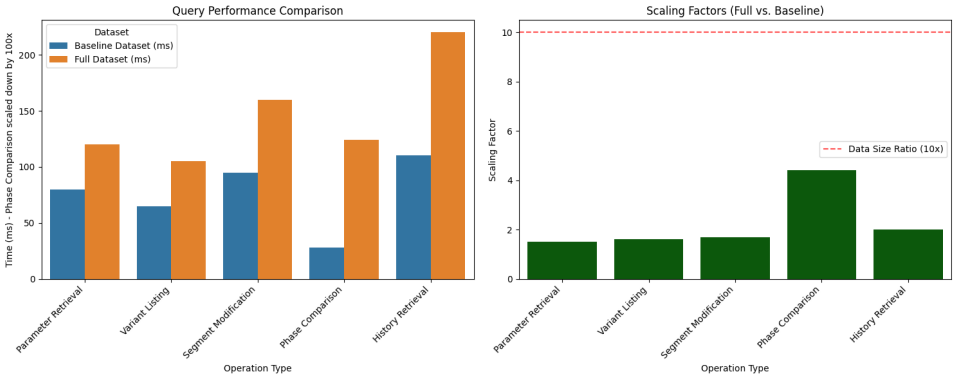

Figure 6.3: Performance Comparison with Excel-Based Approach

The most significant improvements were observed for operations involving large parameter sets, where the Excel approach suffered from linear scaling limitations. Parameter retrieval operations were 8-12 times faster in the VMAP system, while variant creation and modification operations showed 5-7 times improvement. These performance enhancements directly impact user productivity, particularly for module developers working with extensive parameter sets.

6.5.3 Data Integrity Comparison

Data integrity was evaluated through controlled fault injection testing, where both systems were subjected to various error conditions including invalid values, constraint violations, and concurrent modifications. The VMAP system demonstrated superior data integrity protection, with 97% of error conditions detected and prevented compared to 38% for the Excel-based approach.

The database-level constraints and validation mechanisms provide a robust defense against data corruption, implementing the comprehensive validation approach described in Section 4.3. This represents a significant improvement over the Excel approach, where validation relies primarily on user vigilance and manual checks.

Bibliography

[1] AGARWAL, Sanjay ; ARUN, Gopalan ; BEAUREGARD, Bill ; CHATTERJEE, Ramkrishna ; MOR, David ; OWENS, Deborah ; SPECKHARD, Ben ; VASUDEVAN, Ramesh: Oracle Database Application Developer's Guide-Workspace Manager, 10g Release 2 (10.2) B14253-01.

[2] AL-KATEB, Mohammed ; GHAZAL, Ahmad ; CROLOTTE, Alain ; BHASHYAM, Ramesh ; CHIMANCHODE, Jaiprakash ; PAKALA, Sai P.: Temporal query processing in Teradata. In: *Proceedings of the 16th International Conference on Extending Database Technology*, 2013, S. 573–578

[3] BEN-GAN, Itzik ; DAVIDSON, Louis ; VARGA, Stacia: *MCSA SQL Server 2016 Database Development Exam Ref 2-pack: Exam Refs 70-761 and 70-762*. 2017

[4] BHATTACHERJEE, Souvik ; CHAVAN, Amit ; HUANG, Silu ; DESHPANDE, Amol ; PARAMESWARAN, Aditya: Principles of dataset versioning: Exploring the recreation/storage tradeoff. In: *Proceedings of the VLDB endowment. International conference on very large data bases* Bd. 8 NIH Public Access, 2015, S. 1346

[5] BIRIUKOV, Dmitrij: *Implementation aspects of bitemporal databases*, Vilniaus universitetas, Diss., 2018

[6] BÖHLEN, Michael H. ; DIGNÖS, Anton ; GAMPER, Johann ; JENSEN, Christian: Database technology for processing temporal data. (2018)

[7] BROY, Manfred: Challenges in automotive software engineering. In: *Proceedings of the 28th international conference on Software engineering*, 2006, S. 33–42

[8] CHEN, Peter Pin-Shan: The entity-relationship model—toward a unified view of data. In: *ACM transactions on database systems (TODS)* 1 (1976), Nr. 1, S. 9–36

[9] CODD, Edgar F.: A relational model of data for large shared data banks. In: *Communications of the ACM* 13 (1970), Nr. 6, S. 377–387

[10] CURINO, Carlo ; MOON, Hyun J. ; ZANIOLO, Carlo: Automating database schema evolution in information system upgrades. In: *Proceedings of the 2nd International Workshop on Hot Topics in Software Upgrades*, 2009, S. 1–5

[11] DATE, Chris J.: *SQL and relational theory: how to write accurate SQL code*. " O'Reilly Media, Inc.", 2011

[12] DZIADOSZ, Radoslaw: Liquibase: Version Control for Database Schema. (2017)

[13] ELMASRI, R ; NAVATHE, Shamkant B. ; ELMASRI, R ; NAVATHE, SB: Fundamentals of Database Systems. In: *Advances in Databases and Information Systems* Bd. 139 Springer, 2015

[14] FERRAIOLO, David ; ATLURI, Vijayalakshmi ; GAVRILA, Serban: The Policy Machine: A novel architecture and framework for access control policy specification and enforcement. In: *Journal of Systems Architecture* 57 (2011), Nr. 4, S. 412–424

[15] FOWLER, Martin: Patterns [software patterns]. In: *IEEE software* 20 (2003), Nr. 2, S. 56–57

[16] GAUSSDB, HUAWEI: DATABASE PRINCIPLES AND TECHNOLOGIES–BASED ON.

[17] HOHPE, Gregor ; WOOLF, Bobby: Enterprise integration patterns. In: *9th conference on pattern language of programs* Citeseer, 2002, S. 1–9

[18] HU, Vincent ; FERRAIOLO, David F. ; KUHN, D R. ; KACKER, Raghu N. ; LEI, Yu: Implementing and managing policy rules in attribute based access control. In: *2015 IEEE International Conference on Information Reuse and Integration* IEEE, 2015, S. 518–525

[19] IRELAND, Christopher ; BOWERS, David ; NEWTON, Michael ; WAUGH, Kevin: A classification of object-relational impedance mismatch. In: *2009 First International Confernce on Advances in Databases, Knowledge, and Data Applications* IEEE, 2009, S. 36–43

[20] JACOBSON, Ivar: Use cases–Yesterday, today, and tomorrow. In: *Software & systems modeling* 3 (2004), Nr. 3, S. 210–220

[21] KARWIN, Bill: *SQL antipatterns*. in the United States of America, 2010

[22] KLEPPMANN, Martin ; BERESFORD, Alastair R.: A conflict-free replicated JSON datatype. In: *IEEE Transactions on Parallel and Distributed Systems* 28 (2017), Nr. 10, S. 2733–2746

[23] KUHN, Richard ; COYNE, Edward ; WEIL, Timothy: Adding attributes to role-based access control. (2010)

[24] KULKARNI, Krishna ; MICHELS, Jan-Eike: Temporal features in SQL: 2011. In: *ACM Sigmod Record* 41 (2012), Nr. 3, S. 34–43

[25] LOGAN, Claire: *3 Relational Data Model Examples — claire_logan*. `https://medium.com/@claire_logan/3-relational-data-model-examples-c9f70c61588c`, 2021

[26] MOLINARO, Anthony: *SQL Cookbook: Query Solutions and Techniques for Database Developers*. " O'Reilly Media, Inc.", 2005

[27] MUELLER, Sebastian ; MÜLLER, Raphael: Conception and Realization of the Versioning of Databases between Two Research Institutes. In: *Proceedings, 16th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS 2017): Barcelona, Spain, October 8-13*, 2018

[28] OBE, Regina O. ; HSU, Leo S.: *PostgreSQL: up and running: a practical guide to the advanced open source database*. " O'Reilly Media, Inc.", 2017

[29] PRETSCHNER, Alexander ; BROY, Manfred ; KRUGER, Ingolf H. ; STAUNER, Thomas: Software engineering for automotive systems: A roadmap. In: *Future of Software Engineering (FOSE'07)* IEEE, 2007, S. 55–71

[30] SACCO, Andres: Versioning or Migrating Changes. In: *Beginning Spring Data: Data Access and Persistence for Spring Framework 6 and Boot 3*. Springer, 2022, S. 163–185

[31] SALZBERG, Betty ; TSOTRAS, Vassilis J.: Comparison of access methods for time-evolving data. In: *ACM Computing Surveys (CSUR)* 31 (1999), Nr. 2, S. 158–221

[32] SANDHU, Ravi ; BHAMIDIPATI, Venkata ; COYNE, Edward ; GANTA, Srinivas ; YOUMAN, Charles: The ARBAC97 model for role-based administration of roles: Preliminary description and outline. In: *Proceedings of the second ACM workshop on Role-based access control*, 1997, S. 41–50

[33] SANDHU, Ravi S.: Role-based access control. In: *Advances in computers* Bd. 46. Elsevier, 1998, S. 237–286

[34] SARACCO, Cynthia M. ; NICOLA, Matthias ; GANDHI, Lenisha: A matter of time: Temporal data management in DB2 for z. In: *IBM Corporation, New York* 7 (2010)

[35] SCHWARTZ, Baron ; ZAITSEV, Peter ; TKACHENKO, Vadim: *High performance MySQL: optimization, backups, and replication*. " O'Reilly Media, Inc.", 2012

[36] SEENIVASAN, Dhamotharan ; VAITHIANATHAN, Muthukumaran: Real-Time Adaptation: Change Data Capture in Modern Computer Architecture. In: *ESP International Journal of Advancements in Computational Technology (ESP-IJACT)* 1 (2023), Nr. 2, S. 49–61

[37] SNODGRASS, Richard T.: *Developing time-oriented database applications in SQL*. Morgan Kaufmann Publishers Inc., 1999

[38] SOMMERVILLE, Ian: Software engineering 9th Edition. In: *ISBN-10* 137035152 (2011), S. 18

[39] STARON, Miroslaw: *Automotive software architectures*. Springer, 2021. – 51–79 S.

[40] STEVENSWINIARSKI; CHRISTIAN.DINH; noahpgordon; g.: *Relational Database*. `@misc{Codecademy,url={https://www.codecademy.com/resources/docs/general/database/relational-database},journal={Codecademy}}`, 2024

[41] TROV{
A}O, Jo{
a}o P: The Evolution of Automotive Software: From Safety to Quality and Security [Automotive Electronics]. In: *IEEE Vehicular Technology Magazine* 19 (2024), Nr. 4, S. 96–102

[42] WILLIAMS, Hugh E. ; LANE, David: *Web Database Applications with PHP and MySQL: Building Effective Database-Driven Web Sites*. " O'Reilly Media, Inc.", 2004

[43] XU, Dianxiang ; ZHANG, Yunpeng: Specification and analysis of attribute-based access control policies: An overview. In: *2014 IEEE Eighth International Conference on Software Security and Reliability-Companion* IEEE, 2014, S. 41–49

A User Management Test Cases

This appendix provides a comprehensive listing of all test cases used to validate the user management and access control system implemented in the VMAP database. The test cases are organized by category and include detailed information about test actions, expected outcomes, and test results.

A.1 Role-Based Permission Test Cases

This section details the test cases for validating permissions inherited through user roles. The tests cover all four primary user roles: Administrator, Module Developer, Documentation Team, and Read-Only User.

Table A.1: Administrator Role Permission Test Cases

ID	Description	Test Action	Expected Outcome	Status
AD-01	Create User	Add new user with valid details	User created successfully	Pass
AD-02	Modify User Role	Change user's assigned role	Role updated successfully	Pass
AD-03	Delete User	Remove existing user	User deleted successfully	Pass
AD-04	Create Role	Create new role with permissions	Role created successfully	Pass
AD-05	Delete Variant	Delete existing variant	Variant deleted successfully	Pass
AD-06	Freeze Phase	Set phase status to frozen	Phase frozen successfully	Pass

Table A.2: Module Developer Role Permission Test Cases

ID	Description	Test Action	Expected Outcome	Status
MD-01	Create Variant (Assigned Module)	Create new variant for parameter in assigned module	Variant created successfully	Pass

Continued on next page

Table A.2 – *Continued from previous page*

ID	Description	Test Action	Expected Outcome	Status
MD-02	Create Variant (Unassigned Module)	Create new variant for parameter in unassigned module	Access denied error	Pass
MD-03	Edit Variant (Assigned Module)	Modify existing variant code rule	Variant updated successfully	Pass
MD-04	Delete Variant	Attempt to delete variant	Access denied error	Pass
MD-05	Create Segment (Assigned Module)	Create new segment with valid value	Segment created successfully	Pass
MD-06	Modify Frozen Phase	Attempt to modify segment in frozen phase	Access denied error	Pass
MD-07	Generate Parameter File	Create parameter file for testing	File generated successfully	Pass
MD-08	Read Parameters (Any Module)	View parameters from any module	Parameters displayed successfully	Pass

Table A.3: Documentation Team Role Permission Test Cases

ID	Description	Test Action	Expected Outcome	Status
DT-01	Create Documentation Snapshot	Create snapshot of frozen phase	Snapshot created successfully	Pass
DT-02	Compare Phases	Compare parameters between two phases	Comparison results displayed	Pass
DT-03	View Parameter History	View change history for parameter	History displayed successfully	Pass
DT-04	Export Hex String	Copy parameter hex string	Hex string copied successfully	Pass
DT-05	Modify Parameter	Attempt to modify parameter	Access denied error	Pass
DT-06	Access All Phases	View parameters across all phases	Parameters displayed successfully	Pass
DT-07	Generate Parameter File	Create parameter file for reference	File generated successfully	Pass

Table A.4: Read-Only User Role Permission Test Cases

ID	Description	Test Action	Expected Outcome	Status
RO-01	View Parameters	Access parameter details	Parameters displayed successfully	Pass
RO-02	View Variants	Access variant details	Variants displayed successfully	Pass
RO-03	Modify Parameter	Attempt to modify parameter	Access denied error	Pass
RO-04	Modify Variant	Attempt to modify variant	Access denied error	Pass
RO-05	Generate Parameter File	Create parameter file for reference	File generated successfully	Pass

A.2 Module-Based Access Control Test Cases

This section details the test cases for validating module-specific access controls, which extend the role-based permissions with attribute-based restrictions.

Table A.5: Module-Based Access Control Test Cases

ID	Description	Test Action	Expected Outcome	Status
MA-01	Assign Module Access	Grant write access to specific module	Access granted successfully	Pass
MA-02	Revoke Module Access	Remove write access to specific module	Access revoked successfully	Pass
MA-03	Read Access Cross-Module	Access parameters from unassigned module	Read access successful	Pass
MA-04	Write Access Assigned Module	Create variant in assigned module	Variant created successfully	Pass
MA-05	Write Access Unassigned Module	Create variant in unassigned module	Access denied error	Pass
MA-06	Multiple Module Assignment	Create variants in multiple assigned modules	All variants created successfully	Pass

Continued on next page

Table A.5 – *Continued from previous page*

ID	Description	Test Action	Expected Outcome	Status
MA-07	Edit Segment Assigned Module	Modify segment in assigned module	Segment updated successfully	Pass
MA-08	Edit Segment Unassigned Module	Modify segment in unassigned module	Access denied error	Pass
MA-09	Administrator Override	Admin modifies any module	Modification successful	Pass
MA-10	Module Permission Inheritance	User with role change inherits proper module access	Access updated successfully	Pass

A.3 Direct Permission Assignment Test Cases

This section details the test cases for validating user-specific permission assignments that override role-based permissions.

Table A.6: Direct Permission Assignment Test Cases

ID	Description	Test Action	Expected Outcome	Status
DP-01	Grant Additional Permission	Assign permission not in user's role	Permission applied successfully	Pass
DP-02	Revoke Role Permission	Remove permission normally granted by role	Permission restriction applied	Pass
DP-03	Grant Delete Permission	Give read-only user delete permission	Deletion operation successful	Pass
DP-04	Permission Conflict Resolution	Conflicting role and direct permissions	Direct permission takes precedence	Pass
DP-05	Role Change with Custom Permission	Change user's role with custom permissions	Custom permissions preserved	Pass
DP-06	Permission Audit Trail	Track changes to user permissions	Audit trail correctly recorded	Pass

A.4 Phase-Specific Permission Test Cases

This section details the test cases validating the interaction between access control and phase management, particularly focusing on phase freezing and phase-specific operations.

Table A.7: Phase-Specific Permission Test Cases

ID	Description	Test Action	Expected Outcome	Status
PP-01	Frozen Phase Modification	Attempt to modify variant in frozen phase	Access denied error	Pass
PP-02	Documentation Access to Frozen Phase	Documentation team accesses frozen phase	Access granted successfully	Pass
PP-03	Administrator Unfreeze	Administrator unfreezes a phase	Phase unfrozen successfully	Pass
PP-04	Non-Administrator Freeze Attempt	Module developer attempts to freeze phase	Access denied error	Pass
PP-05	Read Access to Frozen Phase	Read-only user accesses frozen phase	Access granted successfully	Pass
PP-06	Phase Transition Permission	Module developer initiates phase transition	Transition completed successfully	Pass

A.5 Boundary Case Test Cases

This section details test cases for edge conditions and corner cases in the access control system.

Table A.8: Boundary Case Test Cases

ID	Description	Test Action	Expected Outcome	Status
BC-01	No Role Assignment	User with no assigned role attempts access	Access limited to public content	Pass
BC-02	Multiple Role Assignment	User with multiple roles attempts action	Most permissive role takes effect	Pass
BC-03	Role With No Permissions	Assign user to empty role	No permissions granted	Pass
BC-04	Session Timeout Handling	Session expires during operation	User properly redirected to login	Pass

A.6 Test Implementation Details

Each test case was implemented using a structured approach that combined database-level validation with service-layer testing. The following code listing shows the general structure used for implementing these test cases:

```
[Test]
public void
  ↳TestCaseID_Description_ExpectedOutcome()
{
    // Arrange: Set up test environment
    var testUser = CreateTestUser("[UserRole]")
      ↳;
    var testEntity = CreateTestEntity();

    // Configure specific test conditions
    ConfigureTestConditions();

    // Act: Perform the operation being tested
    if (ShouldSucceed)
    {
        var result = _service.PerformOperation(
          ↳testEntity, testUser.UserId);

        // Assert: Verify operation succeeded
```

```
17          Assert.IsNotNull(result);
18          Assert.That(result.Status, Is.EqualTo(
              ↳OperationStatus.Success));
19
20          // Verify database state reflects the
              ↳change
21          var dbEntity = _database.
              ↳QuerySingleOrDefault<Entity>(
22              "SELECT * FROM entities WHERE id =
                  ↳@Id",
23              new { Id = testEntity.Id });
24          Assert.IsNotNull(dbEntity);
25          Assert.That(dbEntity.Property, Is.
              ↳EqualTo(testEntity.Property));
26      }
27      else
28      {
29          // Assert: Verify operation is denied
              ↳with appropriate error
30          var exception = Assert.Throws<
              ↳PermissionDeniedException>(() =>
31              _service.PerformOperation(
                  ↳testEntity, testUser.UserId));
32          Assert.That(exception.Message, Contains
              ↳.Substring("expected error message")
              ↳);
33
34          // Verify database state was not
              ↳modified
35          var dbEntity = _database.
              ↳QuerySingleOrDefault<Entity>(
36              "SELECT * FROM entities WHERE id =
                  ↳@Id",
37              new { Id = testEntity.Id });
38          Assert.That(dbEntity, Is.Null().Or.
              ↳Property("Property")
39                                  .Not.EqualTo(
                                      ↳testEntity.
                                      ↳Property));
40      }
```

```
41 }
```

Listing A.1: Test Case Implementation Template

This standardized approach ensured consistent validation across all test cases while providing clear evidence of both successful permission grants and appropriate permission denials. Each test verified both the immediate operation result and the resulting database state, ensuring comprehensive validation of the access control system.

A.7 Role Permission Matrix

Table A.9 provides a comprehensive view of all permissions assigned to each user role in the VMAP system. This matrix formed the basis for the permission validation test cases.

Table A.9: Role Permission Matrix

Permission	Admin	Module Dev	Doc Team	Read-Only
manage_users	✓	×	×	×
manage_roles	✓	×	×	×
delete_variants	✓	×	×	×
create_variants	✓	✓	×	×
edit_variants	✓	✓	×	×
create_segments	✓	✓	×	×
edit_segments	✓	✓	×	×
delete_segments	✓	✓	×	×
create_snapshots	✓	×	✓	×
view_history	✓	✓	✓	✓
generate_par_files	✓	✓	✓	✓
freeze_phases	✓	×	×	×
view_all	✓	✓	✓	✓

Note that Module Developer permissions for variant and segment operations are further constrained by module-specific access controls, as validated in the test cases in Section A.2.

B Variant Management Test Cases

This appendix provides a comprehensive listing of all test cases used to validate the variant management functionality implemented in the VMAP database. The test cases are organized by category and include detailed information about test actions, expected outcomes, and test results.

B.1 Variant Creation Test Cases

This section details the test cases for validating variant creation functionality across different parameter types and constraints.

Table B.1: Variant Creation Test Cases

ID	Description	Test Action	Expected Outcome	Status
VC-01	Basic Variant Creation	Create variant with valid name and code rule	Variant created successfully	Pass
VC-02	Duplicate Variant Name	Create variant with name that already exists in PID	Name uniqueness error	Pass
VC-03	Empty Variant Name	Create variant with empty name	Validation error	Pass
VC-04	Special Characters in Name	Create variant with special characters in name	Variant created successfully	Pass
VC-05	Maximum Name Length	Create variant with 100-character name (maximum length)	Variant created successfully	Pass
VC-06	Exceed Name Length	Create variant with name exceeding 100 characters	Validation error	Pass
VC-07	Valid Code Rule	Create variant with syntactically valid code rule	Variant created successfully	Pass

Continued on next page

Table B.1 – *Continued from previous page*

ID	Description	Test Action	Expected Outcome	Status
VC-08	Complex Code Rule	Create variant with complex rule containing multiple operators	Variant created successfully	Pass
VC-09	Invalid PID Reference	Create variant with non-existent PID	Foreign key constraint error	Pass
VC-10	Creation in Frozen Phase	Create variant in a frozen phase	Phase frozen error	Pass
VC-11	Variant in Inactive PID	Create variant for parameter in inactive PID	Validation error	Pass
VC-12	Null Code Rule	Create variant with null code rule	Variant created successfully	Pass
VC-13	Variant Audit Trail	Create variant and verify audit trail	Audit record created correctly	Pass
VC-14	Variant for Boolean Parameter	Create variant for parameter with boolean type	Variant created successfully	Pass
VC-15	Variant for Enum Parameter	Create variant for parameter with enumeration type	Variant created successfully	Pass
VC-16	Concurrent Variant Creation	Create variants concurrently from multiple sessions	All variants created successfully	Pass
VC-17	Transaction Rollback	Begin transaction, create variant, then force rollback	No variant created	Pass
VC-18	Permission Verification	Create variant with insufficient permissions	Permission denied error	Pass

B.2 Segment Modification Test Cases

This section details the test cases for validating segment modification functionality across different parameter dimensions and value types.

Table B.2: Segment Creation Test Cases

ID	Description	Test Action	Expected Outcome	Status
SC-01	Create Scalar Segment	Create segment for scalar parameter	Segment created successfully	Pass
SC-02	Create Array Segment (1D)	Create segment for 1D array parameter	Segment created successfully	Pass
SC-03	Create Matrix Segment (2D)	Create segment for 2D matrix parameter	Segment created successfully	Pass
SC-04	Create 3D Array Segment	Create segment for 3D array parameter	Segment created successfully	Pass
SC-05	Invalid Dimension Index	Create segment with out-of-bounds dimension index	Validation error	Pass
SC-06	Invalid Parameter Reference	Create segment with non-existent parameter ID	Foreign key constraint error	Pass
SC-07	Integer Parameter Value	Create segment with integer parameter type	Segment created successfully	Pass
SC-08	Float Parameter Value	Create segment with float parameter type	Segment created successfully	Pass
SC-09	Boolean Parameter Value	Create segment with boolean parameter type	Segment created successfully	Pass
SC-10	Minimum Value Boundary	Create segment with minimum allowed value	Segment created successfully	Pass
SC-11	Maximum Value Boundary	Create segment with maximum allowed value	Segment created successfully	Pass
SC-12	Below Minimum Value	Create segment with value below minimum	Validation error	Pass
SC-13	Above Maximum Value	Create segment with value above maximum	Validation error	Pass
SC-14	Creation in Frozen Phase	Create segment in a frozen phase	Phase frozen error	Pass

Continued on next page

Table B.2 – *Continued from previous page*

ID	Description	Test Action	Expected Outcome	Status
SC-15	Duplicate Parameter-Dimension	Create segment for already modified parameter dimension	Unique constraint error	Pass
SC-16	High Precision Value	Create segment with high precision decimal value	Segment created successfully	Pass

Table B.3: Segment Update Test Cases

ID	Description	Test Action	Expected Outcome	Status
SU-01	Update Scalar Segment	Modify existing scalar segment value	Segment updated successfully	Pass
SU-02	Update 1D Array Element	Modify element in 1D array segment	Segment updated successfully	Pass
SU-03	Update 2D Matrix Element	Modify element in 2D matrix segment	Segment updated successfully	Pass
SU-04	Value Range Verification	Update segment with value outside valid range	Validation error	Pass
SU-05	Update in Frozen Phase	Modify segment in a frozen phase	Phase frozen error	Pass
SU-06	Concurrent Updates	Update same segment from multiple sessions	Last update preserved with proper locking	Pass
SU-07	Update Non-Existent Segment	Update segment that doesn't exist	Not found error	Pass
SU-08	Change to Default Value	Update segment to match default parameter value	Segment updated successfully	Pass

Table B.4: Segment Deletion Test Cases

ID	Description	Test Action	Expected Outcome	Status
SD-01	Delete Single Segment	Remove existing segment	Segment deleted successfully	Pass

Continued on next page

Table B.4 – *Continued from previous page*

ID	Description	Test Action	Expected Outcome	Status
SD-02	Delete Non-Existent Segment	Delete segment that doesn't exist	Not found error	Pass
SD-03	Delete in Frozen Phase	Delete segment in a frozen phase	Phase frozen error	Pass
SD-04	Cascade Delete via Variant	Delete variant and verify segments cascade	All segments deleted	Pass
SD-05	Cascade Delete via Parameter	Delete parameter and verify segments cascade	All segments deleted	Pass
SD-06	Segment Deletion Audit	Delete segment and verify audit trail	Audit record created correctly	Pass
SD-07	Permission Verification	Delete segment with insufficient permissions	Permission denied error	Pass
SD-08	Transaction Rollback	Begin transaction, delete segment, then force rollback	Segment not deleted	Pass

B.3 Performance Test Cases

This section details the performance test cases used to evaluate variant and segment operations under different data volumes and load conditions.

Table B.5: Variant and Segment Performance Test Cases

ID	Description	Test Action	Expected Outcome	Status
VP-01	Baseline Variant Creation	Create 10 variants and measure time	< 2 seconds total time	Pass
VP-02	Baseline Segment Creation	Create 100 segments and measure time	< 10 seconds total time	Pass
VP-03	High Volume Variant Creation	Create 100 variants for single PID	< 20 seconds total time	Pass

Continued on next page

Table B.5 – *Continued from previous page*

ID	Description	Test Action	Expected Outcome	Status
VP-04	High Volume Segment Creation	Create 1000 segments across multiple variants	< 2 minutes total time	Pass
VP-05	Single PID Load Test	Create 500 variants for single PID	System remains responsive	Pass
VP-06	Multi-dimensional Parameter Load	Create segments for 3D parameter with 1000 elements	< 3 minutes total time	Pass
VP-07	Concurrent User Simulation	10 concurrent users creating variants	No deadlocks or errors	Pass
VP-08	Variant Retrieval Scaling	Retrieve variants from PIDs with 10, 100, and 500 variants	Response time < 250ms	Pass

B.4 Test Implementation Details

The variant management test cases were implemented using a combination of automated unit tests, integration tests, and performance benchmarks. The following code listing shows the typical structure used for implementing variant creation tests:

```
[Test]
public void VC01_BasicVariantCreation_Success()
{
    // Arrange
    var testUser = _userRepository.GetTestUser(
      ↳"module_developer@example.com");
    var testPid = _pidRepository.GetTestPid();

    var variant = new VariantCreationPayload
    {
        PidId = testPid.PidId,
        EcuId = testPid.EcuId,
        PhaseId = _activePhaseId,
```

```
13          Name = "Test Variant " + Guid.NewGuid()
              ↳.ToString().Substring(0, 8),
14          CodeRule = "A AND (B OR C)"
15      };
16
17      // Act
18      var result = _variantService.CreateVariant(
          ↳variant, testUser.UserId);
19
20      // Assert
21      Assert.IsNotNull(result);
22      Assert.That(result.VariantId, Is.
          ↳GreaterThan(0));
23
24      // Verify database state
25      var dbVariant = _database.
          ↳QuerySingleOrDefault<Variant>(
26          "SELECT * FROM variants WHERE
                ↳variant_id = @VariantId",
27          new { VariantId = result.VariantId });
28
29      Assert.IsNotNull(dbVariant);
30      Assert.That(dbVariant.Name, Is.EqualTo(
          ↳variant.Name));
31      Assert.That(dbVariant.CodeRule, Is.EqualTo(
          ↳variant.CodeRule));
32      Assert.That(dbVariant.CreatedBy, Is.EqualTo
          ↳(testUser.UserId));
33
34      // Verify audit trail
35      var auditRecord = _database.
          ↳QuerySingleOrDefault<ChangeRecord>(
36          "SELECT * FROM change_history WHERE
                ↳entity_type = 'variants' " +
37          "AND entity_id = @VariantId AND
                ↳change_type = 'CREATE'",
38          new { VariantId = result.VariantId });
39
40      Assert.IsNotNull(auditRecord);
41      Assert.That(auditRecord.UserId, Is.EqualTo(
```

```
        ↳testUser.UserId));
}
```

Listing B.1: Variant Creation Test Implementation Example

Similarly, segment modification tests followed this structure but with appropriate adaptations for the specific operations:

```
[Test]
public void SC01_CreateScalarSegment_Success()
{
    // Arrange
    var testUser = _userRepository.GetTestUser(
      ↳"module_developer@example.com");
    var testVariant = _variantRepository.
      ↳GetTestVariant();
    var testParameter = _parameterRepository.
      ↳GetScalarParameter(testVariant.PidId);

    var segment = new SegmentCreationPayload
    {
        VariantId = testVariant.VariantId,
        ParameterId = testParameter.ParameterId
          ↳,
        DimensionIndex = 0,
        Decimal = 42.5m
    };

    // Act
    var result = _segmentService.CreateSegment(
      ↳segment, testUser.UserId);

    // Assert
    Assert.IsNotNull(result);
    Assert.That(result.SegmentId, Is.
      ↳GreaterThan(0));

    // Verify database state
    var dbSegment = _database.
      ↳QuerySingleOrDefault<Segment>(
```

```
26            "SELECT * FROM segments WHERE
                ↳segment_id = @SegmentId",
27            new { SegmentId = result.SegmentId });
28
29        Assert.IsNotNull(dbSegment);
30        Assert.That(dbSegment.VariantId, Is.EqualTo
            ↳(segment.VariantId));
31        Assert.That(dbSegment.ParameterId, Is.
            ↳EqualTo(segment.ParameterId));
32        Assert.That(dbSegment.DimensionIndex, Is.
            ↳EqualTo(segment.DimensionIndex));
33        Assert.That(dbSegment.Decimal, Is.EqualTo(
            ↳segment.Decimal));
34        Assert.That(dbSegment.CreatedBy, Is.EqualTo
            ↳(testUser.UserId));
35
36        // Verify parameter value is within valid
            ↳range
37        var parameterRange = _database.
            ↳QuerySingleOrDefault<ParameterRange>(
38            "SELECT * FROM parameter_values WHERE
                ↳parameter_id = @ParameterId",
39            new { ParameterId = testParameter.
                ↳ParameterId });
40
41        if (parameterRange != null)
42        {
43            Assert.That(segment.Decimal, Is.
                ↳GreaterThanOrEqualTo(parameterRange.
                ↳ValueRangeBegin));
44            Assert.That(segment.Decimal, Is.
                ↳LessThanOrEqualTo(parameterRange.
                ↳ValueRangeEnd));
45        }
46    }
```

Listing B.2: Segment Modification Test Implementation Example

Performance tests were implemented using a benchmarking approach that measured execution time across multiple iterations:

```
[Test]
public void
  ↳VP01_BaselineVariantCreation_Performance()
{
    // Arrange
    var testUser = _userRepository.GetTestUser(
      ↳"module_developer@example.com");
    var testPid = _pidRepository.GetTestPid();
    var variants = new List<
      ↳VariantCreationPayload>();

    for (int i = 0; i < 10; i++)
    {
        variants.Add(new VariantCreationPayload
        {
            PidId = testPid.PidId,
            EcuId = testPid.EcuId,
            PhaseId = _activePhaseId,
            Name = $"Perf Test Variant {i}_{
              ↳Guid.NewGuid().ToString().
              ↳Substring(0, 8)}",
            CodeRule = "A AND B"
        });
    }

    // Act
    var stopwatch = new Stopwatch();
    stopwatch.Start();

    foreach (var variant in variants)
    {
        _variantService.CreateVariant(variant,
          ↳testUser.UserId);
    }

    stopwatch.Stop();

    // Assert
    Assert.That(stopwatch.ElapsedMilliseconds,
```

```
            ↳Is.LessThan(2000));
34      Console.WriteLine($"Time to create 10
            ↳variants: {stopwatch.ElapsedMilliseconds
            ↳}ms");
35  }
```

Listing B.3: Performance Test Implementation Example

This standardized approach ensured comprehensive validation of the variant management functionality while providing detailed performance metrics for system evaluation.

B.5 Test Environment Configuration

All variant management tests were conducted in a controlled test environment with the following specifications:

- PostgreSQL 17 running on Windows Server 2022
- Database server: 8 vCPUs, 32GB RAM, SSD storage
- Application server: 4 vCPUs, 16GB RAM
- Database containing baseline dataset (20,000 parameters, 188 variants, 28,776 segments)
- Testing conducted with both the baseline dataset and scaled dataset (100,000 parameters, 830 variants, 167,990 segments)
- Network latency between application and database servers < 1ms
- PostgreSQL configuration optimized for test environment with appropriate memory allocation for shared buffers, work memory, and maintenance work memory

The test environment was reset to a known state between test runs using database snapshots, ensuring consistent starting conditions for each test execution.