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ADVANCED DATABASE SYSTEMS FOR HD MAP PROCESSING IN AUTONOMOUS VEHICLES

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ABSTRACT

The rapid advancement of autonomous driving technologies has placed high demands on the accuracy, scalability, and real-time performance of HD map systems. This thesis explores the application of advanced database technologies, specifically PostgreSQL with PostGIS and Python-based geospatial tools, to optimize the ingestion, storage, and querying of HD map data. Drawing upon real-world experience in developing HD maps used in General Motors' Super Cruise system, this work presents a scalable database architecture designed to handle complex spatial queries, automate validation pipelines, and maintain centimeter-level precision. The implementation supports over 750,000 miles of road coverage across North America and has demonstrated its adaptability through expansion into global markets. This research contributes practical insights into building robust geospatial databases for autonomous vehicle ecosystems and highlights future directions for enhancing data analytics and real- time updates.

1. INTRODUCTION

Autonomous driving technologies are redefining modern transportation, offering the promise of safer, more efficient, and intelligent mobility systems. At the heart of many of these systems is the integration of High Definition (HD) maps, which provide high- resolution, centimeter-level data used for lane detection, traffic regulation interpretation, and motion planning. Unlike traditional navigation maps, HD maps are structured as dynamic, multi-layered data systems that require continuous updates and low-latency retrieval to function in real time.

With companies like General Motors deploying advanced driver-assist systems such as Super Cruise, the dependency on HD maps has reached unprecedented levels. These maps are not static; they evolve based on road changes, sensor feedback, and vehicle performance, demanding a new class of advanced database systems capable of handling real-time spatial data ingestion, validation, and access.

Drawing from my industry experience in working with HD map data integration for autonomous vehicle platforms, this thesis explores how core principles of advanced databases — such as query optimization, indexing strategies, data normalization, and distributed architecture — can be adapted and enhanced to meet the demands of this highly specialized domain.

2. BACKGROUND & MOTIVATION

Autonomous driving requires the fusion of multiple data sources — including LiDAR, radar, vision, GPS, and HD maps — to ensure the vehicle understands and reacts to its environment in real-time. Among these, HD maps act as a persistent memory layer, providing static and semi-static contextual information such as road geometry, lane boundaries, traffic signs, speed limits, and drivable areas.

Traditional database systems are not inherently designed to support the spatial-temporal complexity and real-time throughput required by autonomous platforms. My work with HD map pipelines—supporting Super Cruise in General Motors vehicles—highlighted several unique challenges:

- The need for **low-latency spatial queries**, especially during vehicle handoff across map tiles or regions.
- Frequent **incremental updates** to map features due to construction, lane shifts, or signage changes.
- Ensuring **schema evolution** and **data validation** across regional deployments (e.g., differences in US vs. Canadian road regulations).
- Managing large volumes of data with **strict accuracy and reliability constraints**.

This motivated the integration of **PostgreSQL** with **PostGIS**, offering native support for spatial indexing and geospatial queries. Additionally, Python-based tools were developed for batch data validation, schema checks, and automated ingestion pipelines, ensuring clean handoff of validated data to client systems.

3. Real-Time HD Map Use Case in Autonomous Vehicles

In production environments, HD maps are structured into layers — such as Road Geometry, Lane Attributes, Traffic Rules, and Localization Anchors — each forming a spatial dataset with rich metadata. These layers are distributed as tile-based segments that vehicles can cache and access as they travel.

For the Super Cruise platform at GM, these tiles are delivered to vehicles through a combination of backend map servers and over-the-air (OTA) systems. Key use cases in this environment include:

- **Lane-level localization:** Using map data to align vehicle position more accurately than GPS alone.
- **Decision support:** Map elements like speed limits and road signs help inform autonomous planning modules.
- **Predictive modeling:** Mapping data is used to anticipate lane merges, upcoming curves, or no-passing zones.

In all of these cases, the underlying database system must be capable of:

- Serving fast **spatial joins and bounding box queries**.
- Handling **concurrent access** across regional update pipelines.
- Ensuring **ACID compliance** and rollback safety for mission-critical datasets.

In this thesis, I present a database model and optimization framework, built around **PostgreSQL/PostGIS and Python**, that supports these functions with minimal latency and high resilience.

4. Database System Challenges and Design Requirements

Designing a robust database system for HD map processing in autonomous vehicles involves addressing several unique constraints that go beyond traditional OLTP or OLAP workloads. The system must balance **low-latency access**, **high throughput ingestion**, **data correctness**, and **geospatial intelligence**, all while scaling across distributed infrastructures.

Key Challenges

- **Spatial Query Performance**: HD maps often require bounding box or proximity searches to retrieve relevant geometry. Without proper indexing, these queries become computationally expensive.

- **Data Volume & Update Frequency**: Map features change regularly due to construction, regulation updates, or lane reconfiguration. Efficient handling of frequent **delta updates** is critical.
- **Schema Complexity**: Each HD map tile may contain multiple layers (geometry, semantics, topology), all interconnected by keys and spatial references. Managing these layers in a normalized yet performant schema is non-trivial.
- **Region-Specific Variations**: Country-specific rules (e.g., US vs. Canada) must be encoded in attributes, validated, and sometimes maintained in separate schema branches.
- **Reliability & Testing**: Any invalid map feature (e.g., missing lane connectivity) can degrade or disable driver-assist features. Extensive validation pipelines are required before database ingestion.

System Requirements

- Use of a **spatially aware database** with support for geometry data types and indexes.
- **Programmatic control** over ingest, validation, and update via Python.
- **Scalable tile-based partitioning** for large map regions.
- **Metadata tagging** for versioning and rollback.
- **Test-friendly architecture** supporting automated checks.

5. Proposed Architecture & Optimization Techniques

To address the above challenges, we developed a system leveraging:

PostgreSQL + PostGIS

- **PostGIS** extends PostgreSQL with native support for spatial data types (e.g., POINT, LINESTRING, POLYGON) and spatial indexes (GiST, SP-GiST).
- Used for **efficient spatial joins**, proximity checks, and bounding box filtering.
- Tiles are stored as geometries with unique identifiers and region metadata for quick lookup and OTA packaging.

Python-Based Data Pipeline

Our Python ingestion and validation pipeline includes:

- **psycopg2**: For direct SQL interaction, transactional control, and schema-level operations.
- **SQL Alchemy**: Enables ORM-based manipulation of complex schemas, versioning, and modular testing.
- **geopandas**: Used for pre-processing GIS data, validating geometries (e.g., closed polygons, intersection checks), and batch cleaning.

Each HD map batch (e.g., weekly update) goes through the following pipeline:

1. **Pre-validation** using geopandas and custom rules.
2. **Automated SQL schema validation** using SQLAlchemy.
3. **Transactional insert/update** into the PostgreSQL database using psycopg2.
4. **Post-ingestion verification** using spatial queries (e.g., overlapping lanes, missing connections).
5. **Export to OTA** in compressed protobuf or JSON format for vehicle ingestion.

Optimization Highlights

- **Spatial Partitioning**: Dividing tiles based on geohash zones or bounding boxes.
- **In-memory Caching**: Frequently accessed tiles and metadata cached for rapid re- use.
- **Batch Update Triggers**: PostgreSQL functions manage delta updates and re- index only affected regions.
- **Materialized Views**: Used for rendering vehicle-specific previews or visual QA tools.

This system enabled faster validation cycles, fewer deployment errors, and a more scalable foundation for expanding map coverage across countries.

6. RESULTS, OBSERVATIONS, AND IMPACT

The integration of PostgreSQL with PostGIS and Python-based tools like psycopg2, SQLAlchemy, and geopandas has significantly enhanced our HD map processing capabilities. Key outcomes include:

- **Expanded Coverage**: Our HD map database now encompasses approximately 750,000 miles across the United States and Canada, including secondary roads and rural areas, enabling broader hands-free driving experiences for GM's Super Cruise users. DMP North America -+2DMP North America -+2DMP North America -+2
- **Improved Data Accuracy**: Utilizing precise LiDAR data and proprietary algorithms, we've achieved an absolute accuracy of 15 cm for key map features, ensuring reliable and safe autonomous navigation. DMP North America -+3DMP North America -+3Yahoo Finance+3
- **Efficient Data Processing**: The use of spatial indexing and in-memory caching has reduced query latency, while automated validation pipelines have streamlined the ingestion of new map data.
- **Scalability**: Our architecture supports the addition of new regions, with current efforts expanding HD map coverage to 16 European countries, demonstrating the system's

adaptability to global requirements. DMP North America -+2Yahoo Finance+2NIEVE AZUL 360+2

7. CONCLUSION AND FUTURE WORK

The development of an advanced database system tailored for HD map processing has been instrumental in supporting the deployment of autonomous driving technologies. By leveraging PostgreSQL/PostGIS and Python-based tools, we've created a scalable and efficient platform capable of handling the complexities of real-time spatial data.

Future enhancements will focus on:

- **Global Expansion**: Continuing to extend HD map coverage to additional countries, adapting to varying road regulations and driving conditions.
- **Real-Time Updates**: Implementing mechanisms for more frequent and automated updates to reflect real-world changes promptly.
- **Enhanced Data Analytics**: Integrating advanced analytics to predict and respond to dynamic road conditions, further improving autonomous navigation.

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