On leveraging Named Data Networking for vehicular and edge computing applications

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Abstract. *Vehicular and edge computing environments exhibit high mobility, intermittent connectivity, and rapidly changing network topologies, challenging traditional host-centric networking models. This thesis investigates Named Data Networking (NDN) as an enabling architectural approach to communication for realistic vehicular and edge computing applications in smart city scenarios. The work proposes NDN4IVC, a comprehensive experimental framework for NDN-based vehicular experimentation; NDN-Waze, a data-centric intelligent transportation system; and an NDN-based data offloading model for vehicular edge computing, including the Intelligent Edge Traffic Routing (iETR) architecture and the Data Mule Service Provider (DMSP) design. Simulation-based experiments under realistic mobility conditions show that NDN-based solutions improve robustness and data availability while reducing application-layer complexity. These results support the suitability of NDN as an architectural foundation for vehicular and edge computing systems.*

1. Introduction and Context

Over the last years, vehicles have evolved into integral components of distributed computing environments by incorporating onboard processing, storage, sensing, and wireless communication capabilities. This evolution has enabled a wide range of data-driven applications in Intelligent Transportation Systems, smart cities, and vehicular edge computing. Nevertheless, the highly dynamic nature of vehicular environments–characterized by high mobility, rapidly changing network topologies, and intermittent connectivity—limits the effectiveness of traditional networked system designs [Yan et al. 2024, Gong et al. 2023].

From a networking perspective, traditional TCP/IP-based architectures are designed under the assumption of relatively stable end-to-end connectivity and address-oriented communication. In vehicular environments, however, highly transient links and frequent topology changes violate these assumptions, making end-to-end communication paths difficult to maintain. As a consequence, applications are often required to explicitly handle mobility and intermittent connectivity at the application layer, embedding network-dependent logic into their design. This approach increases application complexity and introduces strong dependencies between system functionality and underlying network models, ultimately limiting scalability and maintainability.

In contrast, Named Data Networking (NDN) adopts a data-centric communication model in which information is retrieved by name rather than by location. By decoupling data from network endpoints, NDN inherently supports in-network caching, flexible data forwarding, consumer-driven communication, and data-centric security [Zhang et al. 2014, Khelifi et al. 2020]. These properties make NDN particularly suitable for vehicular and edge computing environments and motivate its investigation as an enabling architecture for the systems developed in this thesis.

2. Problem Statement and Research Challenges

The design of vehicular and edge computing systems is inherently constrained by the dynamic nature of the environments in which these systems operate. Vehicular nodes continuously join and leave the network, communication opportunities are short-lived, and connectivity conditions vary significantly over time and space. In this context, distributed applications must operate securely without assumptions of persistent connectivity, stable communication paths, or fixed roles among participating nodes.

Despite these characteristics, most existing vehicular applications are still built upon host-centric networking abstractions. Communication mechanisms based on the TCP/IP architecture assume that data exchange occurs between identifiable endpoints and that communication sessions can be maintained for the duration of an interaction. When applied to vehicular environments, these assumptions introduce fundamental inconsistencies between the network model and the operational conditions, often resulting in complex communication behavior.

As a consequence, application designs are required to explicitly address network dynamics. Tasks such as mobility management, failure recovery, and data availability are commonly embedded into application logic or delegated to additional components. While these approaches may partially mitigate connectivity issues, they increase system complexity.

3. Research Objectives and Contributions

The central objective of this Ph.D. thesis is to investigate how the intrinsic properties of the Named Data Networking (NDN) architecture can be leveraged to facilitate the design, deployment, and evaluation of emerging vehicular and edge computing applications in highly dynamic smart city environments. Rather than positioning NDN as a drop-in replacement for the TCP/IP protocol stack, this work explores NDN as an architectural paradigm that supports application development and addresses robustness, data availability, and security aspects, including data-centric security mechanisms and application-level trust schemas, under vehicular mobility. To achieve this main objective, the thesis is guided by the following research question:

> *How can the data-centric communication model and architectural properties of NDN be exploited to support distributed vehicular and edge computing services more effectively than traditional host-centric approaches?*

To investigate this research question, the thesis defines the following specific objectives:

- To characterize the limitations of host-centric networking abstractions when applied to vehicular and edge computing scenarios, with emphasis on mobility, intermittent connectivity, security requirements, and data dissemination patterns.

- To identify and analyze how core NDN properties—such as name-based communication, in-network caching, consumer-driven data retrieval, and data-centric security—map to the communication and service requirements of vehicular environments.
- To design and implement NDN-based architectures and services for vehicular and edge computing in which mobility handling, data availability, and trust management are addressed by the network architecture rather than embedded in application logic.
- To assess the behavior of the proposed architectures through simulation-based experiments under realistic urban mobility scenarios, considering heterogeneous communication technologies and representative vehicular application workloads.

Based on these objectives, this thesis makes the following main contributions:

1. **NDN4IVC: An Experimental Framework for Vehicular NDN Applications.** This work introduces NDN4IVC, a simulation framework that integrates ndnSIM with vehicular mobility and wireless communication models to support the design and evaluation of NDN-based vehicular applications. NDN4IVC enables the realistic assessment of data-centric communication strategies under vehicular mobility, providing a reproducible environment for experimenting with different application designs, dissemination strategies, and network configurations.
2. **NDN-Waze: A Data-Centric Intelligent Transportation System.** The thesis proposes NDN-Waze, an NDN-based intelligent transportation system designed to disseminate traffic and navigation information in urban environments. By leveraging name-based data retrieval and in-network caching, NDN-Waze decouples data consumers from producers, enabling efficient and resilient information dissemination despite frequent topology changes. The system demonstrates how NDN simplifies the development of distributed vehicular services while improving scalability and robustness when compared to IP-based approaches.
3. **NDN-Based Data Offloading for Vehicular Edge Computing.** This work presents an NDN-based architecture for vehicular data offloading in edge computing scenarios, including the Intelligent Edge Traffic Routing (iETR) mechanism and the Data Mule Service Provider (DMSP) model. These solutions exploit NDN's data-centric communication to support opportunistic data transfer, service decoupling, and efficient utilization of mobile and fixed edge resources, even in the presence of intermittent connectivity.
4. **Comprehensive Experimental Evaluation in Realistic Scenarios.** The proposed architectures and systems are evaluated through extensive simulations that consider realistic urban mobility patterns, heterogeneous wireless technologies, and representative vehicular workloads. The evaluation demonstrates that NDN-based solutions provide improved resilience, data availability, and communication efficiency while reducing the complexity required at the application layer.

Collectively, these contributions demonstrate that NDN is not merely an alternative networking protocol, but a suitable architectural foundation for vehicular and edge computing systems. By shifting complexity from applications to the network architecture, NDN enables the development of scalable and robust vehicular services that better cope with the inherent dynamics of smart city environments.

4. NDN4IVC: An Experimental Framework for Vehicular NDN Applications

This section builds upon results previously published in Conference Papers C1 and C2 and in Journal Paper J1. One of the challenges in evaluating vehicular networking solutions lies in the limited availability of experimental frameworks that capture vehicular dynamics while supporting emerging network architectures. Vehicular scenarios involve high mobility, rapidly changing topologies, heterogeneous wireless technologies, and intermittent connectivity, which affect communication behavior and application performance. These characteristics are relevant when investigating data-centric networking models such as Named Data Networking (NDN), whose communication semantics differ from those of traditional TCP/IP-based, host-centric approaches.

To address this limitation, this thesis introduces *NDN4IVC*, an experimental framework designed to support the development and evaluation of NDN-based vehicular and edge computing applications. NDN4IVC integrates the *ndnSIM* simulator with vehicular mobility traces generated by *SUMO*, modeling vehicles as mobile NDN nodes equipped with wireless communication interfaces. This integration enables the evaluation of NDN mechanisms—such as name-based forwarding, in-network caching, and consumer-driven communication—under urban mobility patterns and traffic conditions.

NDN4IVC supports the evaluation of different caching strategies, forwarding policies, and naming schemes, as well as analyses of their impact on data availability, communication overhead, and application performance. The framework was employed throughout this thesis as the experimental platform for developing and evaluating NDN-based safety, navigation, and data dissemination applications, providing consistent and reproducible experimental conditions across multiple case studies. Figure 1 shows the main components of NDN4IVC and logical view for VNDN architecture.

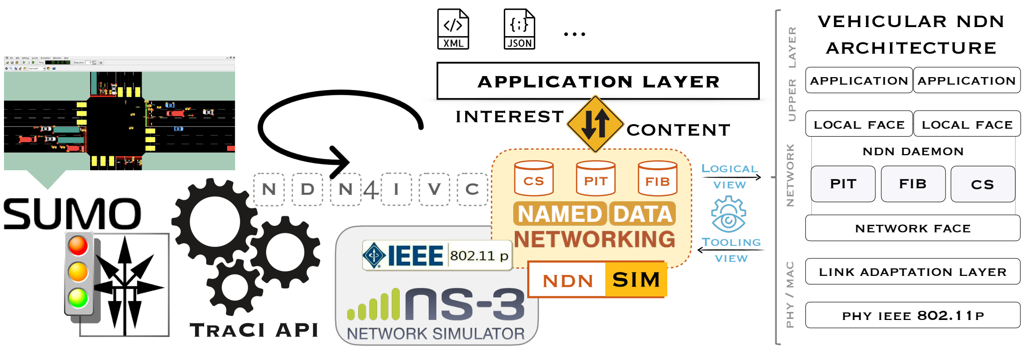

Figura 1. NDN4IVC main components: overview [Araujo et al. 2023].

5. NDN-Waze: A Data-Centric Intelligent Transportation System

This section is based on results previously presented in Conference Paper C3 and Journal Paper J2. Urban traffic management and navigation services rely on the dissemination of information among a large number of mobile participants, including vehicles and roadside infrastructure, to support applications such as route planning, traffic monitoring, and incident notification. In vehicular environments, frequent topology changes, intermittent connectivity, and heterogeneous communication technologies make it difficult to maintain stable communication paths, posing challenges for traditional IP-based approaches that assume persistent end-to-end interactions.

To address these limitations, this thesis proposes *NDN-Waze*, a data-centric intelligent transportation system based on the Named Data Networking architecture. NDN-Waze decouples data production from data consumption, enabling information to be retrieved opportunistically from any node holding a valid copy, without relying on persistent communication sessions.

The system architecture is based on distributed services that interact through named data exchanges. Vehicles operate as both data producers and consumers, generating traffic-related information and requesting navigation data, while roadside units aggregate and disseminate content without centralized coordination. This organization supports incremental deployment and avoids single points of failure.

NDN-Waze leverages in-network caching and consumer-driven communication to support data availability under dynamic network conditions. Traffic information may be cached at intermediate nodes and retrieved on demand through Interest packets, reducing dependence on stable connectivity and limiting unnecessary transmissions. Security relies on data-centric mechanisms in which each data packet is cryptographically signed by its producer, allowing integrity and authenticity verification independently of the data source. Figure 2 presents an overview of the NDN-Waze system design proposed in this thesis.

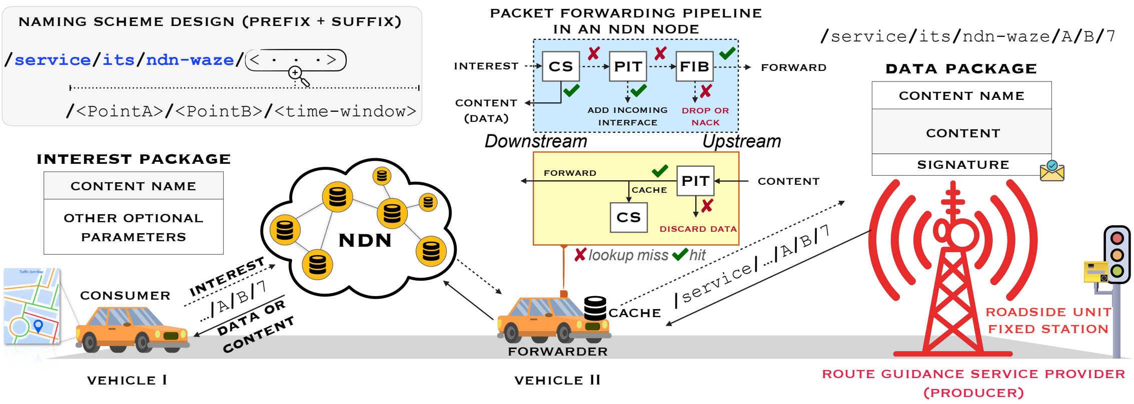

Figura 2. NDN-Waze: A Data-Centric System for Vehicular Application.

The system was evaluated using the NDN4IVC framework under urban mobility scenarios, considering metrics such as communication overhead, data retrieval latency, and route efficiency. The evaluation shows that NDN-Waze maintains service availability under mobility and intermittent connectivity, while reducing application-layer dependence on stable communication paths when compared to IP-based approaches.

6. NDN-Based Data Offloading for Vehicular Edge Computing

This section brings discussion reported in part in Journal Papers J3 and J4 and fully consolidated in Journal Paper J5. Vehicular edge computing environments aim to exploit computational and storage resources available at the network edge to support data-intensive and latency-sensitive applications. In such scenarios, vehicles generate volumes of data that may exceed their local processing and storage capabilities, making data offloading an important operation. The design of data offloading mechanisms in vehicular environments is challenged by intermittent connectivity, dynamic network topologies, and the lack of stable communication paths between vehicles and edge infrastructure.

Traditional IP-based offloading approaches typically rely on fixed associations between vehicles and edge servers, assuming stable end-to-end connections and explicit session management. In vehicular scenarios, these assumptions can lead to unsuccessful offloading attempts, inefficient resource utilization, and increased application complexity. In addition, IP-based solutions commonly bind data transfer to specific endpoints, which limits flexibility when alternative communication opportunities arise.

To address these challenges, this thesis proposes an NDN-based data offloading architecture for vehicular edge computing environments. By leveraging the data-centric communication model of Named Data Networking, the proposed approach decouples data from specific producers and consumers, enabling opportunistic data transfer across mobile and fixed nodes. Data offloading is driven by named data exchanges, allowing vehicles to disseminate data when communication opportunities become available, without requiring persistent connectivity to a specific edge entity.

The proposed architecture introduces the *Intelligent Edge Traffic Routing (iETR)* mechanism, which uses NDN's name-based forwarding and in-network caching to guide data offloading decisions. Rather than relying on static network addresses, iETR routes data toward edge resources based on data names and contextual information, allowing offloading processes to adapt to changes in network topology and node availability.

The architecture also incorporates the *Data Mule Service Provider (DMSP)* model to support scenarios in which direct connectivity between vehicles and edge infrastructure is limited or unavailable. In this model, mobile nodes store and carry data while moving through the network and forward it to edge resources when connectivity becomes available. This approach enables the use of transient communication opportunities without requiring explicit coordination among nodes.

Applications interact through named data without maintaining state about communication endpoints or explicitly managing mobility-related events. Data retrieval may occur from multiple sources, including intermediate caches and mobile carriers, allowing offloading operations to proceed under intermittent connectivity and changing network conditions. Figure 3 provides an overview of the DMSP service model.

The proposed solutions were evaluated using the NDN4IVC framework under vehicular mobility scenarios, considering metrics such as offloading success rate, data delivery delay, and communication overhead. The evaluation indicates that the NDN-based offloading approach supports data delivery under intermittent connectivity and enables opportunistic communication when compared to host-centric solutions.

7. Experimental Evaluation and Discussion

This section summarizes and discusses the experimental evaluation conducted throughout the thesis to assess how the architectural properties of Named Data Networking impact the behavior of vehicular and edge computing applications. All experiments were carried out using the NDN4IVC framework, which enables controlled and reproducible evaluations under realistic urban mobility conditions. The evaluation focuses on understanding system behavior rather than isolated performance gains, emphasizing robustness, data availability, and application-layer simplicity under highly dynamic scenarios.

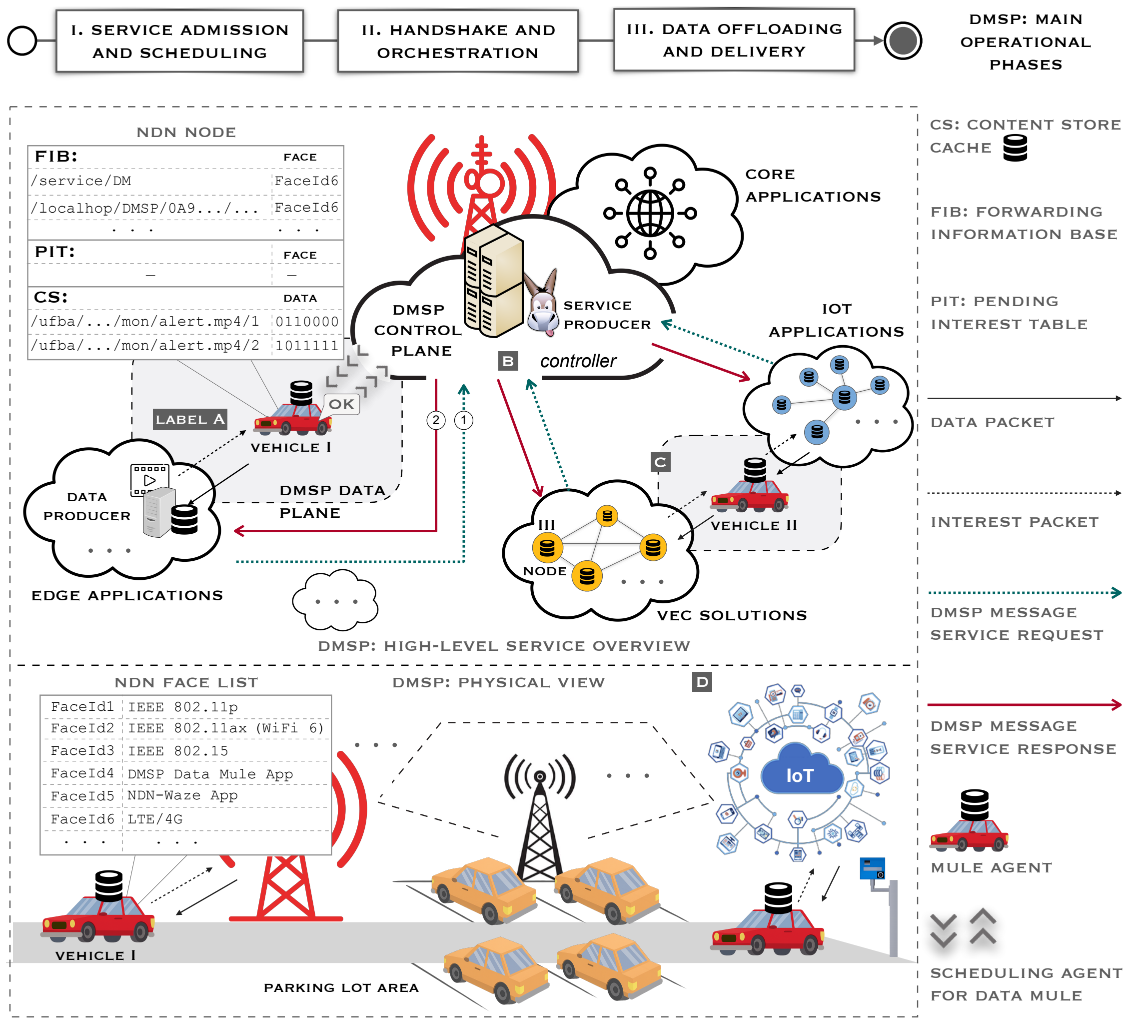

Figura 3. iETR service architecture for Data Mule Service Providers (DMSP): Service Model Using Data Mule Agents. The service operation involves three main parts: (i) Service Admission and Scheduling; (ii) Handshake and Orchestration; and (iii) Data Offloading and Delivery. DMSP redefines service design by separating control and data planes to support on-demand bulk data transfer applications.

7.1. Experimental Methodology

The experimental setup considers realistic urban mobility patterns, heterogeneous wireless communication technologies, and representative vehicular workloads. Vehicles are modeled as mobile NDN nodes capable of producing, forwarding, caching, and consuming named data, while roadside infrastructure operates as distributed service providers without assuming centralized coordination. The evaluated scenarios include vehicle-to-vehicle and vehicle-to-infrastructure interactions, intermittent connectivity, and frequent topology changes, reflecting typical smart city environments.

Across all case studies, the evaluation considers common metrics such as communication overhead, data retrieval latency, delivery success ratio, and application-level effectiveness. Rather than optimizing individual protocol parameters, the experiments aim to highlight how NDN's data-centric communication model influences system behavior when compared to traditional host-centric approaches.

7.2. Results and Analysis

The results indicate that NDN-based solutions provide higher data availability under mobility and network disruptions when compared to IP-based approaches. In the NDN-Waze case study, traffic and navigation information remains accessible even when original data producers become unreachable, due to the use of in-network caching and the availability of multiple data sources. In contrast, IP-based designs tend to experience service interruptions when communication with specific endpoints fails.

In vehicular edge computing scenarios, the iETR and DMSP mechanisms illustrate the effectiveness of opportunistic data transfer supported by NDN. Data offloading operations leverage transient contacts among vehicles and infrastructure without relying on stable end-to-end connections. Retrieving data from intermediate caches or mobile carriers mitigates offloading failures and enhances data delivery reliability, particularly in sparse or highly dynamic environments.

With respect to communication efficiency, the experimental results suggest that NDN's consumer-driven communication model helps reduce unnecessary transmissions by delivering data only in response to explicit requests. When combined with in-network caching, this model limits redundant data dissemination and reduces network load, especially in scenarios where multiple consumers request similar content. Although name-based forwarding and security mechanisms introduce additional overhead, this cost is offset by increased resilience and a reduction in application-layer complexity.

7.3. Discussion

The experimental evaluation suggests that the observed effects are largely related to NDN's architectural characteristics rather than to application-specific logic. By decoupling data from network endpoints, NDN shifts part of the system complexity from applications to the network layer, enabling more modular application designs and reducing the need for explicit mechanisms to handle mobility, session continuity, and failure recovery.

Overall, the findings suggest that Named Data Networking represents a viable architectural option for vehicular and edge computing systems. Rather than emphasizing isolated performance improvements, NDN enables a design approach in which robustness, data availability, and scalability stem from architectural properties, supporting the thesis hypothesis that NDN can facilitate the development of distributed vehicular applications in highly dynamic environments.

8. Scientific Impact and Publications

The research developed in this Ph.D. thesis resulted in a set of scientific contributions in the areas of vehicular networking and edge computing based on the Named Data Networking architecture. These contributions were systematically investigated, implemented, and evaluated, and their main results were disseminated through peer-reviewed publications in conferences and journals related to computer networks and distributed systems.

Taken together, the publications associated with this thesis consolidate its main findings and link network architectural concepts to system-level design, contributing to discussions on the applicability of Named Data Networking to vehicular and edge computing in smart city contexts. The publications are listed below.

Tabela 1. Publications related to this thesis and associated research questions.

Conference Paper (C1) Qualis A1	**Guilherme B. Araujo**, Maycon L. M. Peixoto, Leobino N. Sampaio. *NDN4IVC: Um Arcabouço para Simulação e Experimentação de Aplicações em Redes Veiculares de Dados Nomeados*. SBRC Simpósio, 2021. **Note:** Addresses Research Question 1 of this thesis and introduces the first version of the NDN4IVC simulator.
Conference Paper (C2)	**Guilherme B. Araujo**, Maycon L. M. Peixoto, Leobino N. Sampaio. *NDN4IVC: A framework for simulations of realistic vehicular applications through NDN*. Proceedings of the 9th ACM Conference on Information-Centric Networking (ICN '22), 2022. **Note:** Addresses Research Question 1 by extending the NDN4IVC simulator.
Journal Paper (J1) Qualis A1 IF. 4.6	**Guilherme B. Araujo**, Maycon L. M. Peixoto, Leobino N. Sampaio. *A comprehensive and configurable simulation environment for supporting vehicular named-data networking applications*. Computer Networks, 2023. **Note:** Addresses Research Question 1 of this thesis and provides a complete description of the NDN4IVC experimentation environment.
Conference Paper (C3) Qualis A1	**Guilherme B. Araujo**, Leobino N. Sampaio. *NDN-Waze: Um Sistema Distribuído para Gerenciamento de Tráfego Veicular via Redes de Dados Nomeados*. SBRC Simpósio, 2023. **Note:** Addresses Research Questions 2 and 3 of this thesis by comparing NDN and IP from a real-application perspective.
Journal Paper (J2) Qualis A1 IF. 4.8	**Guilherme B. Araujo**, Leobino N. Sampaio. *A scalable, dynamic, and secure traffic management system for vehicular named data networking applications*.Ad Hoc Networks, 2024. **Note:** Addresses Research Questions 2 and 3 of this thesis and further details the RSU-as-a-Service model adopted in NDN-Waze.
Journal Paper (J3) Qualis A4 IF. 1.3	**Guilherme B. Araujo**, Leobino N. Sampaio. *An Intelligent Edge-Traffic Routing Architecture for Vehicular Data-Mule Services*. IEEE Latin America Transactions, 2021. **Note:** Partially addresses Research Question 4 of this thesis, with insights on data offloading strategies in edge computing scenarios.
Journal Paper (J4) Qualis A1 IF. 5.4	André L. R. Madureira, Francisco R. C. Araújo, **Guilherme B. Araújo**, Leobino N. Sampaio. *NDN Fabric: Where the Software-Defined Networking Meets the Content-Centric Model*. IEEE Transactions on Network and Service Management, 2021. **Note:** Investigates NDN-based forwarding integration for future DMSP deployments.
Journal Paper (J5) Under Submission	**Guilherme B. Araujo**, Leobino N. Sampaio. *DMSP: A Novel NDN-Based Data Offloading Architecture for Edge Computing Applications*. **Note:** Addresses Research Question 4 of this thesis by presenting the design of the DMSP architecture for data offloading in vehicular edge computing.

Finally, Table 2 summarizes the total number of citations of the proposals developed in this thesis according to Google Scholar (February 1, 2026).

Tabela 2. Number of citations per proposal according to Google Scholar

Proposal developed in this thesis	Number of citations (aggregated)
NDN4IVC (C1, C2, J1)	27
NDN-Waze (C3, J2)	9
DMSP (J3)	5
NDN-Fabric (J4)	20
Total	**61**

9. Conclusions and Final Remarks

This thesis investigates how the architectural properties of Named Data Networking can be leveraged to support vehicular and edge computing applications in smart city environments. By adopting a data-centric communication model, the proposed solutions address challenges related to vehicular mobility, intermittent connectivity, and heterogeneous infrastructure that are difficult to handle under traditional host-centric networking paradigms. The results indicate that NDN simplifies the design of distributed vehicular applications by decoupling data from network endpoints and incorporating key functionalities into the network architecture. Features such as name-based communication, in-network caching, consumer-driven data retrieval, and data-centric security enable application operation under frequent topology changes while reducing reliance on application-level mechanisms for mobility management, fault tolerance, security and session continuity.

In conclusion, this thesis provides methodological and practical insights into the use of Named Data Networking in vehicular environments. By examining how NDN enables alternative design approaches for distributed vehicular services, this work contributes to the ongoing discussion on data-centric networking as an architectural option for smart city and edge computing applications.

Referências

Araujo, G., Peixoto, M., and Sampaio, L. (2023). A comprehensive and configurable simulation environment for supporting vehicular named-data networking applications. *Computer Networks*, 235:109949.

Gong, T., Zhu, L., Yu, F. R., and Tang, T. (2023). Edge intelligence in intelligent transportation systems: A survey. *IEEE Transactions on Intelligent Transportation Systems*, 24(9):8919–8944.

Khelifi, H., Luo, S., Nour, B., Moungla, H., Faheem, Y., Hussain, R., and Ksentini, A. (2020). Named data networking in vehicular ad hoc networks: State-of-the-art and challenges. *IEEE Communications Surveys & Tutorials*, 22(1):320–351.

Yan, G., Liu, K., Liu, C., and Zhang, J. (2024). Edge intelligence for internet of vehicles: A survey. *IEEE Transactions on Consumer Electronics*, 70(2):4858–4877.

Zhang, L., Afanasyev, A., Burke, J., Jacobson, V., claffy, k., Crowley, P., Papadopoulos, C., Wang, L., and Zhang, B. (2014). Named data networking. *SIGCOMM Comput. Commun. Rev.*, 44(3):66–73.