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TOWARDS CONCEPTUALIZING SOFTWARE-DEFINED VEHICLES: A SYSTEMATIC REVIEW AND FUTURE RESEARCH AVENUES

Short Paper

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Abstract

Software has become increasingly pivotal in transforming products, processes, and business models across industries. This shift is especially evident in the European automotive industry, as vehicles become progressively defined by software. However, this transformation induces substantial challenges, exemplified by Volkswagen's struggles establishing an effective information systems (IS) organization, pioneering vehicle software. These challenges present a unique research opportunity for the IS community, with its interdisciplinary nature and capability to bridge the realms of engineering and management. To establish a common understanding, we conducted a scoping review of 425 scientific articles and 62 industry reports, providing a preliminary overview of software-defined vehicle (SDV) research. We identify 13 key topics, highlighting a significant gap between academic and practitioner perspectives, thereby contributing to an initial conceptualization of the term 'SDV'. Our findings aim to guide future IS research in understanding and navigating the complexities of software-defined products and their transformative impact on organizations.

Keywords: Software-Defined Vehicles, Software-Defined Business, Digital Transformation, Automotive Industry.

1 Introduction

The ongoing digital transformation reshapes established industry structures, with software increasingly becoming the pivotal factor influencing products, processes, and business models (Alt et al., 2020; Baiyere et al., 2023; Zhu et al., 2016). Mastering this transformation is particularly critical for the European automotive industry, which is fundamental to prosperity and employment in Europe, contributing nearly 7% of the region's GDP and securing more than 14 million jobs in Europe (Cornet et al., 2023). Today, however, the European automotive industry is in the midst of its deepest crisis with software being at the heart of its struggle. Volkswagen's software unit CARIAD, for example, experienced severe delays in developing a unified software platform across multiple vehicle models, leading to postponed launches, significant cost overruns, and organizational conflicts due to misaligned software and hardware development processes (Freitag, 2024). Such examples underscore the critical need to better understand how shifting from traditionally hardware-focused products to software-defined products affects organizational structures, management processes, and strategic decisions.

A decade ago, both science and practice focused on the concept of the '*connected car*'. Specifically, connected cars primarily enable (1) the intelligent linking of in-vehicle sensors and electronic control units (ECUs) and (2) wireless connectivity between the vehicle and its environment. These capabilities allow for features like vehicle-to-vehicle communication and over-the-air (OTA) updates (Lu et al., 2014; Svahn et al., 2017; Teece, 2018). However, the automotive industry has evolved: vehicles are not only connected but have also become inherently digital. Driven by global competitive pressure, rapid

technological advancements, and shifting political landscapes, original equipment manufacturers (OEMs), such as Mercedes, are reimagining vehicle design from the ground up. Increasingly, core mechanical components are now software-defined. For instance, modern vehicles use ‘steer-by-wire’ systems, which translate steering inputs via sensors rather than mechanical linkages (Cassar & Sahn, 2023). Those vehicles encompass roughly 640 million lines of software code, which strikingly contrast 14 million lines found in a Boeing 787 Dreamliner (Goldman Sachs, 2022; Mihailovici, 2021).

Ultimately, the term ‘*software-defined vehicle*’ (SDV) has emerged in response to the shift disrupting the mechanical backbone of automotive vehicles (Weber, 2024). SDVs introduce new possibilities in functionality (e.g., autonomous driving), modularity (e.g., software platforms), and scalability (e.g., software re-use), fundamentally transforming how vehicles are designed, produced, and maintained (Felser & Wynn, 2023; Llopis-Albert et al., 2021). Since the current academic discourse lacks a definition, we preliminarily define an SDV as an automotive vehicle whose core value proposition (e.g., autonomous driving) is predominantly enabled, controlled, and continually enhanced by software rather than mechanical components. Distinctively, SDVs enable continuous value creation throughout their lifecycles by allowing dynamic software-based enhancements via software updates, shifting vehicle design and innovation from hardware-centric paradigms towards flexible software architectures, thereby going beyond mere connectivity. Although SDVs present numerous opportunities for both customer and OEMs, realizing these benefits requires substantial changes to organizational structures and processes, underscoring the need for an in-depth examination of SDVs and their impact on IS organizations.

The shift towards SDVs also presents significant opportunities for IS research, offering a novel empirical context for exploring digital transformation in a formerly hardware-centric industry. SDVs exemplify a fundamental strategic shift, where value creation transitions from physical components towards modular software platforms, a well-established research area within IS. Given the similarities between SDVs and digital product platforms, IS researchers can leverage and further develop existing platform research (e.g., Tiwana, 2015), particularly addressing tensions related to modularity, openness, and governance in historically proprietary industries. Moreover, the transition to SDVs challenges traditional enterprise architecture (EA) frameworks, requiring more flexible architectures capable of aligning complex business processes with rapid software development practices (e.g., Sedera et al., 2016). Consequently, SDVs offer a unique opportunity to enhance theoretical understanding of organizational design, process automation, and architectural agility within complex product contexts. Taken together, these theoretical opportunities underscore the relevance of SDVs as a critical area for IS research, motivating our study’s objectives to (1) conceptualize SDVs and (2) outline future IS research opportunities. Specifically, our study investigates: *What thematic concepts constitute the current research landscape on SDVs?* (RQ1), as well as outlining future research avenues, thus: *What promising directions for future information systems research emerge from the transformation towards SDVs?* (RQ2).

Bridging the realm of scientific research and industry expertise, we conducted a scoping review (Arksey & O’Malley, 2005; Munn et al., 2018; Snyder, 2019), analyzing 425 academic articles and 62 industry reports. Through this approach, we identify and conceptualize the thematic fields surrounding SDVs, comparing the focus of scientific research with current industry discussions. Finally, we outline preliminary key topics for defining SDVs and suggest avenues for future IS research. In subsequent research, we intend to validate and extend these findings and refine a formal SDV definition.

2 Background

2.1 Software-Defined Business

Over the past decades, the terms ‘digital’, ‘digitization’, and ‘digitalization’ have been extensively discussed within the IS community, describing the transformation of physical objects into the digital realm of bits and bytes (Baiyere et al., 2023; Bharadwaj et al., 2013). A key aspect of this evolution is the increasing dominance of software over hardware, shifting how organizations create and capture value. Initially, software was tightly integrated with hardware, which limited its flexibility (Lyytinen et al., 2004; Peppard, 2020). However, over time, digital technologies such as enterprise systems and cloud

computing enabled organizations to increasingly decouple software from physical infrastructure, making it more adaptable and scalable (Malhotra et al., 2021; Tilson et al., 2010).

Contemporary IS research highlights an inverted dynamic, where software dictates hardware design rather than being constrained by it (Alt et al., 2020; Beverungen et al., 2019; Bharadwaj et al., 2013; Zhu et al., 2016). The term ‘*software-defined anything*’ emerged from this shift, describing software’s ubiquity within various applications (e.g., software-defined data centers) (Zhu et al., 2016). This concept further evolved into ‘*software-defined business*’, which describes organizations whose value creation depends primarily on software and digital services (Alt et al., 2020). This broader shift towards software-defined business is particularly evident in the automotive industry, where manufacturers increasingly rely on software-centric strategies to differentiate products and services (Jacobides et al., 2016; Murmann & Schuler, 2023). Consequently, the industry’s transition to SDVs represents a manifestation of software-defined business. However, the academic discourse remains fragmented, primarily addressing isolated technical and managerial aspects rather than developing a holistic understanding.

2.2 Automotive Software

In recent years, software-driven functionality became pivotal for automotive OEMs in securing competitive advantage. In fact, software-driven functionality significantly matured from electronic fuel injections towards highly sophisticated autonomous driving (e.g., Tesla’s Autopilot) (Alt et al., 2020; Jacobides et al., 2016; Murmann & Schuler, 2023; Teece, 2018). Today’s vehicles integrate increasingly complex and interconnected software capabilities, including cloud-based services like Amazon’s Alexa and ChatGPT, which articulate software’s leading role for product design and development (Lichtenstein et al., 2019; Reischauer et al., 2024). Beyond enhancing vehicle functionality, the increasing software integration fosters new forms of data monetization and business models, where vehicle data becomes a strategic asset (Bellin et al., 2024; Sterk et al., 2022; Stocker et al., 2017).

To navigate this complexity, OEMs organize software functionality into distinct vehicle domains, analogous to the building blocks of enterprise systems in IT architecture (Strong & Volkoff, 2010). Typically, five vehicle domains can be differentiated: advanced driver assistance systems (ADAS), infotainment, chassis, powertrain, and body functions (Becker, 2022; McKinsey, 2020). The ADAS domain encompasses autonomous driving and sensor data processing. Infotainment, a mix of information and entertainment, provides digital interfaces for passengers, including platforms like ‘Android Auto’ and ‘Apple CarPlay’. Chassis and powertrain entail vehicle performance, engine handling, battery management, steering, and stability functions. The body domain manages functions related to comfort features (e.g., climate control and lighting) (Vdovic et al., 2019). Given the increasing software complexity, OEMs are shifting from multiple isolated ECUs within each vehicle domain (often more than 100 units) to more centralized architectures controlled by few interconnected high-performance computers (Bandur et al., 2021). The vehicle software stack supporting these architectures is generally organized into three layers: the hardware base layer (i.e., drivers and firmware for physical control), the software base layer (i.e., operating systems and middleware), and the application layer (i.e., actual vehicle functions, such as pedestrian detection) (Becker, 2022; Darko, 2021; Liu et al., 2022).

3 Research Methodology

To systematically map the emerging body of knowledge on SDVs, we chose a scoping review approach (Arksey & O’Malley, 2005). A scoping review is appropriate given the novelty of the topic, allowing us to broadly capture existing research and industry perspectives, identify key themes, and highlight knowledge gaps for future IS research (Munn et al., 2018). Within seminal IS research (see Smith et al., 2011), scoping reviews already yielded unprecedented results, analyzing emergent topics, similarly to SDVs. Thereby, we gain a comprehensive overview on SDV-related research being able to contrast this accumulated body of knowledge with real-world industry perspectives (Snyder, 2019). We follow established IS research guidelines (vom Brocke et al., 2009; Webster & Watson, 2002; Wolfswinkel et al., 2013) ensuring rigor and relevance in capturing key constructs and research gaps in this emerging field. The applied literature search process is displayed in Figure 1 below.

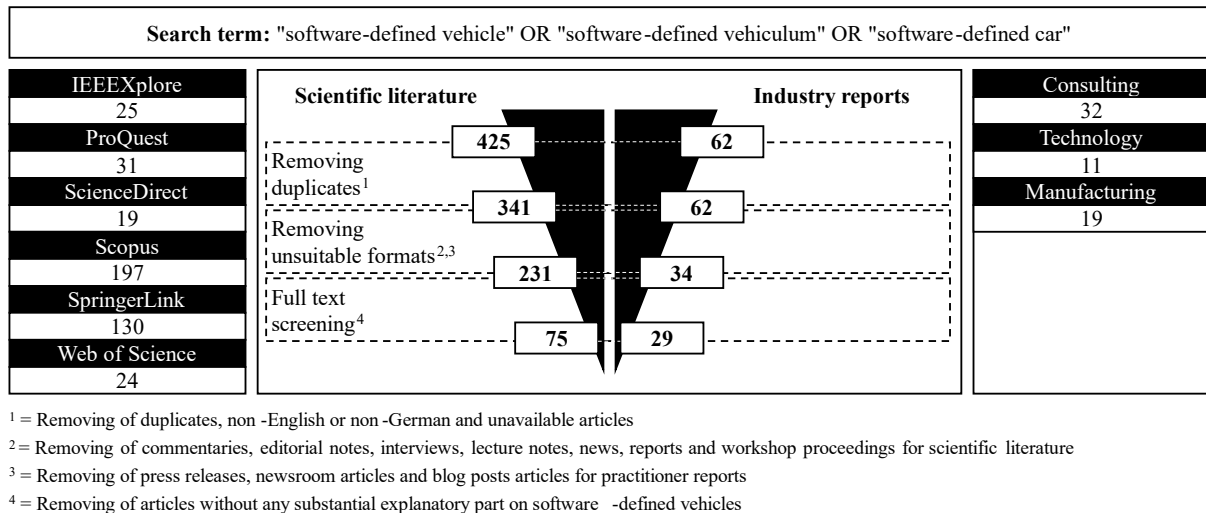


Figure 1. Literature search process for scientific literature and industry reports.

Initially, we conducted a pilot search, using various terms associated with SDVs, such as ‘connected car’. However, this yielded results that were either misleading (e.g., focused on macro-level mobility) or out of scope (e.g., communication technology). To refine our search, we examined press archives from OEMs and identified terms commonly used in practice: ‘software-defined vehicle’, ‘software-defined vehiculum’, and ‘software-defined car’. Using these terms, we conducted a targeted search in multiple scholarly databases across various research disciplines, selecting peer-reviewed journal and conference articles in English or German from databases such as IEEEExplore, ProQuest, ScienceDirect, Scopus, SpringerLink, and Web of Science. We limited our search to articles published from 2016 onwards, as our initial searches indicated that the investigated terms emerged explicitly in academic literature around this time (e.g., Hoffmeister, 2016). This aligns with practitioner-oriented articles, which first explicitly introduced the term in the mid-2010s (e.g., Weber, 2024). Finally, we included articles that explicitly discuss or conceptualize SDVs beyond mere connectivity or digital features.

Second, we narrowed down the number of articles by removing duplicates, yielding 341 unique articles. After excluding unsuitable formats (e.g., commentaries, editorials, news, and workshop proceedings) that typically lack rigorous empirical or theoretical contributions, 231 articles remained. While editorials and workshop proceedings may offer initial perspectives, they often do not provide systematic analyses or in-depth conceptual development, making them less suitable for inclusion in our review. While established guidelines for literature reviews in IS research (e.g., vom Brocke et al., 2009; Webster & Watson, 2002) emphasize screening articles at this point based on title, abstract, and keywords, the inflationary use of the term SDV led us to analyze all remaining articles in full text. Before screening, we established minimal inclusion and exclusion criteria to guide the process among the three researchers involved (Webster & Watson, 2002). Due to the novelty of the topic, we excluded articles focusing solely on digital features (e.g., infotainment or connectivity), as these studies typically analyze isolated software applications rather than addressing the broader transformation towards SDVs. Conversely, we included remaining articles that contributed explanatory insights on SDVs to ensure comprehensive coverage. This process further refined our selection to 75 articles.

Lastly, to triangulate our findings, we selected industry reports as a complementary data source due to their practice-oriented insights. Conducting our search via the search engine ‘Google’, we initially identified 62 reports, with contributions from consulting firms (e.g., McKinsey), technology providers (e.g., NVIDIA), and manufacturing firms (e.g., Bosch). Following an initial review, we excluded formats like press releases, newsroom articles, and blog posts due to their typically shallow and biased information basis. While we acknowledge that all sources with commercial interest, may carry inherent biases, we prioritized practitioner-oriented studies that provide structured, data-driven insights rather than marketing-oriented content. After applying these criteria, we selected 29 reports for in-depth analysis. For both scientific literature and industry reports, we performed thematic analysis and

qualitative, inductive coding (Wolfswinkel et al., 2013). Two researchers independently coded each document, aligning on key topics through iterative discussions and validation, with a third researcher resolving discrepancies. This systematic coding helped structure the current understanding of SDVs in both academic and industry contexts.

4 Preliminary Results

4.1 Current Status of Literature on SDV

We retrieved 75 peer-reviewed articles including explanatory parts on SDVs from six scholarly databases across multiple scientific research fields (Figure 1). These include 24 conference proceedings and 51 journal articles. Notably, 80% (59 of 75) of these publications appeared between 2021 and 2023, reflecting a rapid increase in SDV research. Prior to 2021, publication rates were significantly lower, with fewer than two articles per year. During the recent surge, journal articles consistently outnumbered conference proceedings. Additionally, SDV research is primarily concentrated in engineering (47) and computer science (21), accounting for 91% of the sample. The remaining seven contributions originate in the fields of mathematics, energy, physics, social sciences, and business and management. Building upon the initial review of scientific literature on SDVs, we conducted qualitative, inductive coding to discern primary topics prevalent within the ongoing scientific discussion on SDVs. Ultimately, we identified 13 key topics (i.e., first-order constructs), emerging into three overarching categories (i.e., second-order constructs), as depicted in Figure 2 below, organized by the number of relevant articles: *technological foundation*, *software development*, and *future mobility*.

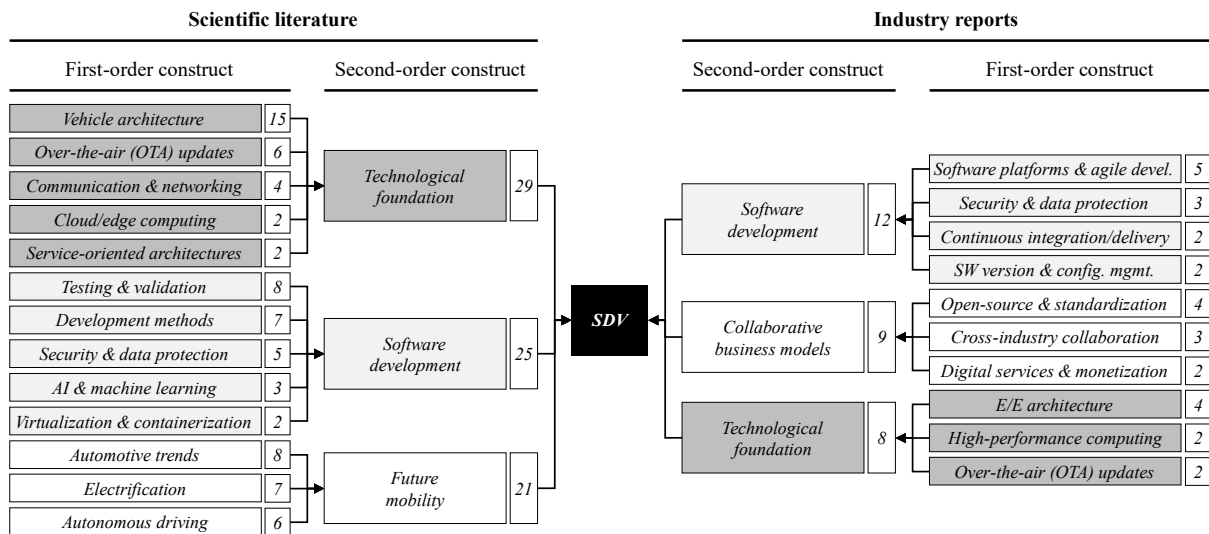


Figure 2. Decomposition of the SDV concept into first-order and second-order constructs.

The first category – technological foundation – encompasses five key topics: *vehicle architecture*, *over-the-air (OTA) updates*, *communication and networking*, *cloud/edge computing*, and *service-oriented architecture*. This category addresses the core technological elements essential for enabling SDVs, focusing on the structural, communicative, and processing capabilities that underpin software-defined functionalities. The second category – software development – includes five key topics: *testing & validation*, *development methods*, *security & data protection*, *AI & machine learning*, and *virtualization & containerization*. This category captures the processes, methods and tools necessary for developing, safeguarding, and optimizing SDV software. The third category – future mobility – aggregates three key topics: *automotive trends*, *electrification*, and *autonomous driving*. This category highlights significant industry-wide shifts, illustrating how SDVs are influenced by emerging technologies and broader trends. When triangulating our findings, both scientific literature and industry reports address the technological foundation of SDVs and software development. Thereby, industry reports place a slightly stronger focus on software development (41% of publications) compared to scientific literature (33% of publications).

A notable divergence lies in the industry reports' emphasis on collaborative business models, a category being underrepresented in the academic publications. The industry reports particularly highlight the importance of scalable software platforms that enable OEMs to deploy vehicle software across multiple models efficiently. Additionally, they underscore open-source software as a competitive advantage, enhancing efficiency and reducing development costs. Cross-industry collaboration emerges as a central theme in industry reports, reflecting a shift in the automotive sector from traditional OEM-supplier relationships towards co-development models within a broader ecosystem. This shift underscores the industry's adaptation to a more interconnected, collaborative approach in software development.

4.2 Avenues for Future SDV Research

Our study highlights significant differences between the topics prioritized in scientific research and those emphasized in industry, suggesting that an expanded research focus on SDVs could generate both theoretical insights and practical impact on software-defined products. The IS community is uniquely positioned to bridge technical and managerial dimensions, drawing from fields such as software platforms, EA, and software development. Although numerous topics merit further exploration, we identify two primary avenues for impactful IS research on SDVs, based on gaps observed in our analysis: *automotive software development* and *collaborative business models*. These areas offer particularly promising opportunities for advancing IS contributions in the evolving SDV landscape, particularly in supporting the effective design of IS organizations, as illustrated by the case of CARIAD.

The first avenue – automotive software development – focuses on emerging software development approaches that are disrupting traditionally rigid industry structures and processes. As software takes on a pivotal role in vehicle development, OEMs are adopting agile methods for a greater flexibility, but this shift introduces substantial challenges for agile project management in IS development. The IS community's extensive research on DevOps practices that enable continuous integration and delivery, can inform strategies for rapid, reliable deployment of automotive software updates and features. As OEMs aim for shorter development cycles and embrace agile workflows, we invite IS researchers to investigate: *How can the automotive industry adapt agile and DevOps practices to support the structural and operational needs of its IS organizations?* The second avenue – collaborative business models – centers on rethinking traditional, dyadic supply chain relationships in favor of more collaborative, open ecosystems. Seminal research on IS sourcing and open-source software development offers valuable insights, yet a holistic exploration of open-source development ecosystems across specific SDV technology stack layers (i.e., middleware and operating system) is needed to fully grasp its full potential. This research can support IS organizations in navigating the transition to more collaborative frameworks. Thus, we propose further investigation into: *How can an open-source ecosystem be fostered in the automotive industry, which is traditionally oriented towards proprietary systems?*

5 Conclusion and Next Steps

This study provides early insights on current SDV research through a scoping review including 425 scientific articles and 62 industry reports. Using established IS research methodologies, we synthesized findings to identify 13 key topics central to SDV research in academia. We also highlighted 10 additional topics prominent in industry reports, underscoring significant differences between scientific and practitioner perspectives. Our initial contributions are twofold: first, we provide a foundational overview of SDV-related scientific and industry literature, identifying key topics that inform conceptualizing the term 'SDV'. Second, we propose future research avenues (i.e., automotive software development and collaborative business models), revealing significant research potential in areas like DevOps practices in automotive software development and open-source ecosystems in the automotive industry, thereby supporting the future design of IS organizations. Together, these insights highlight the essential role of the IS community in understanding and addressing the impact of software-defined products.

Moving forward, we aim to (1) validate and further elaborate on the proposed research avenues and to (2) develop a foundational definition of SDVs that serves as a reference point for both academic and industry discussions, contributing to a unified understanding of SDVs in research and practice.

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