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Vehicle as a Mobile Computing Platform: Opportunities and Challenges

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Abstract**—Over the past century, vehicles have predominantly functioned as a means of transportation. However, as vehicular computation and communication capacities continue to expand, it is anticipated that upcoming connected vehicles (CVs) will not only serve their conventional transport functions, but also act as versatile mobile computing platforms. In this article, we present the concept of Vehicle Computing, encompassing five primary functionalities of CVs: computation, communication, energy consumption and storage, sensing, and data storage. We also propose a potential business model and explore the challenges and opportunities associated with these domains.**

Connected Vehicles: Transitioning into the Future

The rapid progression in computing technologies and the pervasive implementation of communication mechanisms have catalyzed the evolution of connected vehicles (CVs), which are rapidly revolutionizing the automotive landscape. In 2021, the global market for CVs was valued at $65 billion and is forecasted to soar to $225 billion by 2027, exhibiting a robust compound annual growth rate (CAGR) of 17% [1]. Moreover, the Automotive Edge Computing Consortium (AECC) foresees that by 2025, every new vehicle on the road - estimated to be 400 million in total - will be equipped with connectivity features, implying that half of the national vehicle population will have integrated connected capabilities [2].

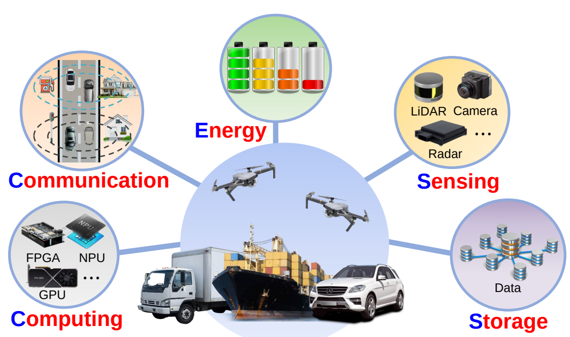

Figure 1. Vehicle computing: Vehicle as a mobile computation, communication, energy consumption and storage, sensing, as well as data storage (ACCESS) platform.

This article postulates that in the coming century, CVs will serve as a mobile computing platform with the capabilities of computation, communication, energy consumption and storage, sensing, and data storage, in addition to their conventional transportation role, as depicted in Figure 1. Subsequently, we describe the five functions of CVs in detail, introduce a potential business model, followed by a discussion of the challenges and opportunities. We hope that this article will generate interest among automotive communities and inspire further research in the field of CVs.

Vehicle as a Mobile Computation Platform

In addition to their traditional transportation roles, CVs will also function as mobile computing platforms. In the current technological landscape, a wide array of computing hardware, varying in design, has become prominent in both the automotive and broader technology sectors. Noteworthy examples of these designs utilize Graphic Processor Units (GPUs), Digital Signal Processors (DSPs), Field Programmable Gate Arrays (FPGAs), and Application-Specific Integrated Circuits (ASICs), enabling vehicles to finish complex computation tasks. In this article, we introduce our vision of Vehicle Computing, followed by a case study of this concept.

Definition of Vehicle Computing

Vehicle Computing pertains to the technologies that enable computing to be performed on CVs, allowing them to serve as a mobile computation, communication, energy consumption and storage, sensing, as well as the data storage platform for a variety of edge-enabled services. It emphasizes that CVs are promising mobile computing platforms that can assist in analyzing data flow from onboard sensors and surrounding connected devices/things, even when the vehicle is parked or being charged.

In accordance with the concept of Vehicle Computing, the forthcoming Vehicle Computing paradigm is depicted in Figure 2 [3], driven by Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V), and potentially Vehicle-to-Everything (V2X) communication. The term ”V2I” refers to the communication framework that enables vehicles to interact directly with the fixed components of the transportation system, such as traffic signals, roadside sensors, weather stations, and other infrastructure elements. V2X allows connected vehicles to not only establish communication with a variety of transportation systems, such as cellular towers, traffic monitoring cameras, and roadside units (RSUs), as well as other roadway users like scooter riders, cyclists, and pedestrians, but also to engage with components of the adjacent environment, including industrial IoT devices, health monitoring sensors, smart home detectors, and edge servers.

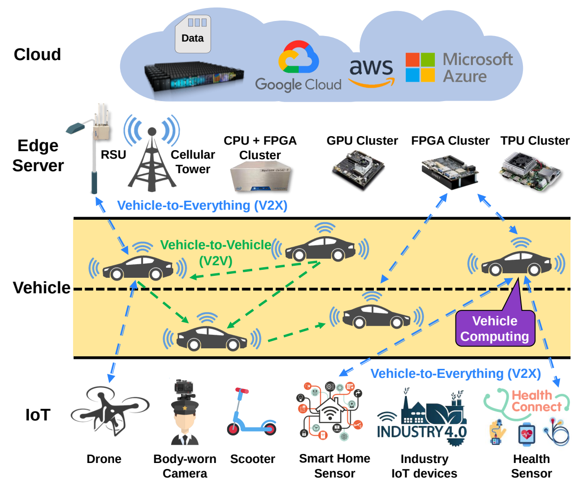

Figure 2. The paradigm of Vehicle Computing [4].

Vehicle as a Mobile Communication Platform

In addition to their computing roles, CVs will also function as mobile communication platforms, providing communication support for surrounding devices such as smart home IoT devices, personal or work equipment of road users, and roadside units. Wireless communication advancements enable real-time information sharing between vehicles and infrastructure. With vehicular communication technologies, a vehicle's sensors or cameras can detect a pothole in the roadway and notify other drivers, providing them with sufficient time to take evasive action. Road maintenance personnel can receive notifications about an approaching vehicle that is maintaining insufficient distance from them. Similarly, school bus operators can be cautioned against allowing children to disembark if an adjacent vehicle does not come to a halt. Furthermore, bicyclists and drivers can be made aware of each other's presence to prevent possible collisions.

The pervasive adoption of advanced communication mechanisms in CVs has paved the way for information exchange with other vehicles, roadside infrastructures, and even pedestrians. This interconnected environment enhances situational awareness and enables more intelligent decision-making. Recent case studies have demonstrated the effectiveness of this approach in real-world applications, providing tangible evidence of its value in modern transportation systems [5], [6], [7], [8].

LTE/4G/5G/6G Long-Term Evolution (LTE) serves as an intermediate solution in the transition from 3G to 4G communication technologies [9], delivering uplink rates of 75 Mbit/s and peak downlink rates of 300 Mbit/s. Normally, 4G provides maximum speeds of 1 Gbit/s for fixed reception and 100 Mbit/s for mobile connectivity. As the succeeding mobile communication technology, the swiftest average 5G download speed encountered by U.S. users reached 494.7 Mbps on Verizon's network, which is 17.7 times quicker than 4G. Early data from Verizon indicate that 5G latency is under 30 ms, offering a 23 ms improvement over the average 4G measurement. Nevertheless, it is important to recognize that 5G still encounters a number of obstacles, such as intricate systems, elevated costs, and restricted capacity to circumvent hindrances. With 6G promising to revolutionize the way we communicate and interact, the convergence of vehicle computing with 6G indeed holds the potential to transform transportation systems, enhance vehicular communications, and offer unprecedented services.

Dedicated short-range communication Dedicated short-range communication (DSRC) is a V2X communication protocol that is specifically designed for connected vehicles. It is based on the IEEE 802.11p standard and operates at a frequency of 5.9 GHz [10]. The SAE J2735 standard defines fifteen message types that cover information such as the vehicle's position, map information, and emergency warnings. Due to limited bandwidth, DSRC messages have a small size and low frequency. Nevertheless, DSRC offers reliable communication, even when the vehicle is traveling at a speed of 120 miles per hour.

Cellular Vehicle-to-Everything Cellular Vehicle-to-Everything (C-V2X) is a combination of the traditional V2X network and the cellular network, bringing the mature network support and commercial services of 4G/5G into the realm of connected mobility. Similar to DSRC, C-V2X primarily operates in the shared spectrum at 5.9 GHz. However, in contrast to CSMA-CA utilized in DSRC, C-V2X employs semi-persistent transmission with relative energy-based selection, which eradicates contention overhead. Additionally, C-V2X performance can be effortlessly improved through cellular network upgrades. In general, C-V2X is better suited for V2X situations where cellular networks are extensively implemented.

Vehicles as a Mobile Energy Consumption, Storage, and Delivery Platform

Electric-drive vehicles (EVs), encompassing both purely electric plug-in vehicles and plug-in hybrid electric vehicles (PHEVs) with combined energy sources and power electronics, are steadily gaining popularity. These vehicles typically charge at night and on weekends when electricity value and prices are relatively low and passenger vehicles are not in use.

Energy Consumption EVs consume significant amounts of energy. For instance, in the United States, an EV's total mileage comprises 55% city mileage and 45% highway mileage, with an average speed of 31 mph and 56 mph, respectively. As a result, the annual energy consumption of EVs nationwide for computation is estimated at approximately 180 terawatt-hours [11]. According to reports, Google's data centers currently consume around 12 terawatt-hours of electricity annually [12]. We can infer from this data that the national energy consumption of EVs is equivalent to the combined energy consumption of 15 representative technology companies' data centers each year.

Energy Storage On the other hand, EVs themselves can serve as a source of electricity and energy storage platforms. A well-designed EV can generate 60 Hz of alternating current and produce over 10 kW of electricity, equivalent to the average electricity consumption of 10 households. When connected to the grid, the batteries in EVs can provide many of the same grid services as stationary storage systems and can be actively managed to minimize their impact on the grid while charging, which is increasingly critical as more EVs are connected to the grid. As EV charging during on-peak hours becomes more prevalent, energy storage will play a crucial role in addressing the resulting challenges. Moreover, as more homes and businesses install EV chargers, it is conceivable that EVs could become a significant source of electricity during emergencies or other periods of grid stress.

Vehicle-to-Grid (V2G) It is noteworthy that Vehicle-to-Grid (V2G) technology enables electric vehicles (EVs) to be utilized as a source of power during emergencies, such as disaster rescue operations, or when there are extreme shortages in the electrical supply. These V2G-enabled EVs can either be used independently or in conjunction with electricity storage systems to provide power to the grid, helping to mitigate the effects of supply disruptions and ensure the stability of the grid. Besides, they have controls that allow them to charge and discharge economically by charging when electricity is cheap and discharging when it is expensive. The grid utilizes reserve power to even out fluctuations in power generation and to respond to unexpected power outages. According to Precedence Research, the global V2G technology market is projected to reach $17.43 billion by 2027, growing at a CAGR of 48% from 2020 to 2027.

Equipping electric vehicles (EVs) with Vehicle-to-Grid (V2G) functionality holds three principal advantages. Firstly, this design enables EV owners to gain supplemental income by utilizing the stored power in their vehicles, consequently reducing the overall ownership expenses. Despite the prevalent higher costs compared to traditional gasoline vehicles (GVs), such utilization can make EVs financially more appealing. For instance, an analysis has shown that a Toyota RAV4 EV might generate as much as $2554 each year by offering reserve services to the power grid [13]. Furthermore, V2G vehicles have the potential to complement renewable energy sources like wind and solar. Since these energy forms tend to have more pronounced fluctuations in their output, driven by environmental factors, V2G vehicles can act as storage during peak production times and provide reserve power during dips, thereby stabilizing the energy supply. Besides, V2G-equipped vehicles can function as cost-effective energy storage solutions and backups for renewable electricity, managing continual variations in demand and responding to unforeseen equipment breakdowns. These disruptions contribute to 5–10% of the electricity costs, or about $12 billion annually in the US [14]. Thus, V2G vehicles can significantly enhance the stability and dependability of the electric grid. This concept has already begun to capture the attention of decision-makers and energy providers, signifying a promising avenue for future innovation.

Vehicle as a Mobile Sensing Platform

CVs, particularly those that are autonomous, rely on sophisticated sensors like cameras, LiDARs, radars, IMUs, and GPS to observe and adapt to their environment. Consequently, CVs are envisioned to function as mobile sensing platforms. Autonomous vehicles typically employ an assortment of sensors, including:

Cameras: Widely used in autonomous vehicles for their cost-effectiveness, cameras provide valuable 2D information for tasks such as object identification and lane monitoring. However, their reliance on light limits their effectiveness in poor weather and low light conditions. Additionally, cameras generate substantial data, averaging 20-40MB per second. Cameras offer an affordable means of machine vision, producing high-resolution images at a high frame rate. Despite extensive research on image processing, cameras face challenges in occlusion, shadows, or low light situations.

Radar: Utilizing radio waves, radar measures both the distance and speed of objects. Normally, operating at frequencies of either 24GHz or 77GHz, 77GHz radar offers increased precision and reduced interference. While more expensive than cameras, radar is less affected by adverse weather and low-light environments and generates smaller data sizes, typically ranging from 10-100KB per second.

LiDAR: LiDAR uses lasers to determine distances based on Time of Flight (TOF), creating 3D images of objects. While offering broader sensing ranges and resistance to adverse condi-

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tions, LiDAR's high cost limits its adoption in autonomous vehicles. LiDAR generates significant data, between 10 and 70MB per second, which can be challenging to process in real-time.

GPS/GNSS/IMU: Localization, crucial in autonomous driving systems, relies on the Global Positioning System (GPS), Global Navigation Satellite System (GNSS), and the Inertial Measurement Unit (IMU). GPS accuracy varies depending on observation values and processing algorithms. GPS offers low cost and minimal error accumulation over time but has limitations, such as one-meter accuracy and the need for an unobstructed sky view. GPS updates every 100ms, which may be insufficient for real-time localization.

IMU consists of gyroscopes and accelerometers that measure angular speed and linear acceleration, respectively. IMU does not require an unobstructed sky view but has low accuracy and accumulating error over time. IMU complements GPS with 5ms updates and functionality in environments like tunnels. Typically, a Kalman filter is used to merge GPS and IMU data for fast and precise localization results.

Vehicle as a Mobile Data Generation and Storage Platform

CVs, especially connected and autonomous vehicles (CAVs), generate a massive amount of data, typically ranging from 20 TB to 40 TB daily per vehicle, as stated by AutoTech [15]. This data includes camera data (20 to 40MB), sonar (10 to 100KB), radar (10 to 100KB), and LiDAR (10 to 70MB). Efficient and secure storage of this data can significantly enhance overall system performance. For instance, object detection can benefit from historical data, which can be used to improve the precision of machine learning algorithms. Similarly, map generation can be enhanced through the use of stored data in updating traffic and road conditions. Furthermore, sensor data can be used for public safety and predicting and preventing crime. The foremost challenge entails guaranteeing that sensors accurately gather data, process it immediately, securely store it, and transmit it to other elements in the system, such as RSUs, cloud data centers, and third-party users. Developing a hierarchical storage and workflow structure that facilitates smooth data access and computation continues to be a crucial unresolved issue for the future advancement of CVs.

In the previous work [16], researchers propose a computational storage system, named HydraSpace, to address the storage challenges of autonomous driving vehicles. HydraSpace incorporates a multi-layered storage framework and efficient compression algorithms to oversee the sensor data pipeline. OpenVDAP is a comprehensive edge-based data analytics platform for CAVs [17]. OpenVDAP introduces a hierarchical storage system design known as the driving data integrator (DDI), which offers sensor-aware and application-aware data storage and processing.

Vehicle Computing Business Model

While Vehicle Computing technology offers a plethora of advantages, it also introduces supplementary expenses, such as those associated with hardware for computing and communication, as well as software-related costs for service and maintenance. We posit that an innovative and transformative business model is crucial, diverging from the conventional relationships among automotive Original Equipment Manufacturers (OEMs), vehicle dealerships, and end users. Here, we present a prospective business model for CV technology that fosters the emergence of fresh revenue sources and counterbalances the elevated expenses associated with constructing and supporting intelligent CVs.

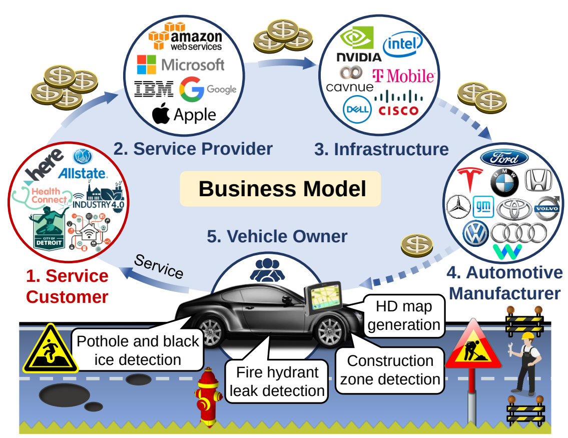

Figure 3. A potential business model to support Vehicle Computing [18].

Figure 3 illustrates the proposed vehicle computing technology business model, encompassing

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five primary elements:

i) **Service customers** consist of, but are not limited to, insurance companies, government agencies, technology firms, and smart home systems. These customers receive and pay for services delivered through CV technology, such as pothole and black ice detection, fire hydrant leak identification, construction zone recognition, and high-definition (HD) map creation.

ii) **Service providers** are companies that drive a range of emerging mobility services through CV advancements. For instance, AWS has developed a comprehensive suite of automotive-focused services and solutions to enable digital transformation within the automotive sector.

iii) **Infrastructure providers** deliver the essential building blocks required for developing, validating, and scaling CV technologies or offer communication support. For example, Cavnue is currently working on the physical, digital, coordination, and operational infrastructure for CVs to enhance road safety and reduce congestion.

iv) **Automotive manufacturers** collect and supply vehicular data through open data analytics platforms or software/system architectures, such as Arm's SOAFEE, AUTOSAR (AUTomotive Open System ARchitecture), and OpenVDAP (Open Vehicle Data Analysis Platform).

v) **Vehicle owners** leverage their vehicles' computational resources and acquired/generated data to offer services to customers, thereby earning additional revenue.

As a specific example, consider an electric vehicle (EV) that drives along several downtown roads before slow charging. Most slow charging stations have a 3kW rating and recharge an EV in 8 to 12 hours, making them ideal for overnight or office hours charging. This creates a perfect opportunity for CV technology implementation. During slow charging, the EV can perform energy-intensive computations based on data from various sensors, such as identifying roadwork that impacts lane or road boundaries and generating reliable HD maps in a slow charging state. This updated HD map can then be provided to service customers (e.g., HERE Technologies). Consequently, CV technology during slow charging offers a cost-effective method for maintaining up-to-date HD maps. Moreover, if the EV detects a leaking or damaged hydrant, it can report this information to the relevant government department. In this scenario, service customers (i.e., HERE Technologies and the local government agency) will pay for the requested services. As the service provider, infrastructure, automotive manufacturer, and vehicle owner all contribute to these services, they will all receive compensation (as demonstrated in Figure 3). This business model fosters a mutually beneficial relationship among the five key components, as they support each other by opening revenue streams or providing desired services efficiently.

Teachinal Challenges and Opportunities

In this section, we will discuss the remaining challenges for future CVs in terms of computing, communication, energy, sensing, and data storage.

Challenges in Vehicle Computing

Heterogeneity of vehicle system components: The second challenge in the development of future CVs lies in the heterogeneity of vehicle system components from various vendors, which comprise a combination of micro-controllers, real-time processors, microprocessors, and an assortment of general-purpose accelerators like GPUs and FPGAs. Some of these micro-controllers cannot be re-programmed or configured as a general-purpose computing device. For example, the capabilities of numerous Electronic Control Units (ECUs) cannot be modified without explicit authorization, and some are equipped with digital rights management in the shape of protective locks. This is reasonable as the software and hardware of ECUs are usually developed by tier-one suppliers with FuSA (Functional Safety) in mind. They must undergo a rigorous testing and validation process, such as the failure mode and effect analysis, to detect various failures that could lead to catastrophic injuries to customers.

Furthermore, due to the varying nature of devices from different vendors, there is no established standard approach for profiling that can link metrics gathered from these diverse devices. Consequently, it becomes nearly impossible to

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conduct architectural-level evaluations and benchmarking.

Real-time constraints of automotive services: Another primary challenge faced in automotive services is meeting real-time constraints, which involves identifying the most critical tasks from a variety of dynamically changing tasks. Real-time constraints can be categorized into three types: hard real-time, soft real-time, and non-time-critical. A missed hard real-time deadline can lead to catastrophic consequences while missing a soft real-time deadline may render computation results useless. Missing a non-time-critical deadline may reduce the effectiveness and degrade the utility of the results. For instance, during normal driving scenarios, video stream processing may be soft real-time or even non-time-critical. However, in the event of a vehicle collision, the analysis of camera video streams becomes critically important and a hard real-time task. The system must quickly identify critical services and allocate guaranteed system resources to process those tasks and ensure real-time constraints on vehicle collision avoidance tasks.

Security and Privacy Sanctuary Technologies:

Driven by megatrends such as new vehicle applications and vehicle-edge-cloud collaboration, the demand for security and privacy sanctuary solutions across computing platforms and vehicular services is ever-increasing.

For example, contemporary vehicles are equipped with over 100 electronic control units (ECUs) that deliver safety and comfort features by interconnecting with one another and the cloud. A large number of independent systems leads to increasing hardware, development, and maintenance costs due to their complex dependencies and interactions.

To securely consolidate multiple systems, it is crucial that the underlying software architecture provides strong hardware-assisted isolation mechanisms and adheres to safety and privacy requirements dominant in many embedded industries. Besides, it is necessary to unify the security properties of all computation devices and services, thus simplifying their development and maintenance, and allow security and privacy sanctuary operations in distributed scenarios.

Challenges in Vehicular Communication

Communication mechanisms: A significant challenge in the development of CVs is the unreliability of networking connectivity for a vehicle that is constantly on the move. This poses significant challenges for vehicle service continuity in the event of service migration across different wireless networks and cloud providers. Mainstream communication mechanisms, such as DSRC, LTE, C-V2X, and WiFi, have enabled CVs to communicate with nearby vehicles, connected devices/things, and the cloud. However, DSRC has some drawbacks, such as low throughput and limited coverage. Although LTE and WiFi offer more bandwidth, they perform poorly in mobile scenarios. C-V2X is a promising new technology that performs well in environments with high vehicle density mobility. However, C-V2X is relatively new, expensive, and not widely deployed. Therefore, achieving ultra-reliable, low-latency, and energy-efficient communication for distributed and moving CVs with massive connectivity density may be one of the most challenging tasks. Several established automotive manufacturers, such as BMW and Ford, and well-known chip manufacturers, such as Ericsson and Qualcomm, have recently shifted their focus to C-V2X.

Communication Cost: As vehicle numbers grow, transmission costs for uplink (data updates) and downlink (software/firmware updates) become crucial factors for automakers to consider in their planning and cost allocation. A recent Guidehouse Insights report [19] estimates that 10 million vehicles can transmit over 20 PB of data, leading to more than $1 billion in yearly costs.

Regarding uplink, research indicates that by 2023, a single Connected Vehicle (CV) will generate 40TB of data, with an average daily transmission of 8GB [20]. For downlink, in-vehicle infotainment system (IVI) updates average 500MB per vehicle [21].

Mobile network operators (MNOs) such as AT&T and Verizon provide two vehicle-centric pricing plans: ”Cost per Usage” and ”Unlimited Prepaid Data Plan.” The former is based on a Spendemont report [21], which places the average worldwide price of 1GB of mobile data at $8.53, with costs varying by country. The latter, starting

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at around $20 per month, includes Wi-Fi/LTE services for vehicles.

Considering one software/firmware update per quarter [21] and the most affordable plans, a single CV incurs annual costs of $240 for uplink and $25 for downlink. For millions of vehicles, transmission costs become substantial, necessitating Edge Computing in connected mobility. Edge Computing processes vehicle data closer to the source, reducing transmission needs. Analysys Mason [22] suggests a 10-30% cost reduction and 10-20% operational savings using Edge Computing across industries. However, overcoming barriers to automotive edge adoption remains an open issue.

Challenges in Vehicular Energy and V2G

Energy Efficiency: Owing to the extensive use of sensors and the implementation of intricate algorithms in Connected Vehicles (CVs), significant energy consumption has emerged as a critical challenge. For instance, the NVIDIA Drive PX Pegasus, operating at an AI computing capability of 320 INT8 TOPS, may demand power up to 500 watts. The situation is further intensified if a redundancy system is introduced to guarantee the reliability of vehicular applications, potentially pushing the total power consumption to as high as 2000W. Consequently, addressing this substantial energy consumption is of vital importance. Additionally, as the majority of energy is expended by the vehicle's motor, it necessitates an integrated design approach encompassing the energy management system, computing system, and battery. This integration aims to foster energy-efficient driving, aligning with the increasing emphasis on sustainability and efficiency in modern automotive technology.

V2G: V2G technology adoption is in its early stages, facing challenges like battery technology, business models, commercial viability, and regulatory issues. Battery durability is critical, as V2G accelerates battery wear through increased cycling. Manufacturers must design and commercialize batteries that can endure V2G demands.

Developing business models is essential for V2G adoption. One-direction EV charging models are well-established, but two-way models, like V2G, require driver compensation, energy discounts, and replacement batteries, ensuring fair benefit and risk distribution. Consumer interest in selling power to the energy sector and its impact on EV market growth are significant factors.

Moreover, the commercial feasibility of V2G systems must be evaluated. Is it economically viable for energy companies or e-mobility service providers to invest in V2G infrastructure? Assessing the investment needed for two-way charging software and hardware, tracking, billing, and refund systems is crucial.

Challenges in Vehicular Sensing

CVs face technical challenges in sensing that need to be addressed. A significant challenge is the joint usage of cameras and LiDAR sensors. These sensors can compensate for each other's limitations and are effectively used together in many situations. However, to use these sensors together effectively, extrinsic calibration is necessary, which requires precise estimation of their relative pose. LiDARs provide sparse point clouds with only positional information, whereas cameras provide high-resolution color images. Therefore, calibrating these different modalities accurately is a challenging yet crucial topic.

Another common issue in data-intensive sensing systems is data anomalies, which are prevalent in CV systems due to imperfect sensors and poor data transmission quality. These anomalies can lead to false alarms and impact structural performance assessment. Additionally, data preprocessing or cleansing can be costly in terms of time and labor. Therefore, there is an urgent need for effective data cleansing algorithms that can make CV data more reliable for online monitoring and further analysis.

Moreover, ensuring safe driving is of the utmost importance for autonomous vehicles, which must accurately analyze vast amounts of information obtained from a combination of attached sensors. These sensors are subject to extreme deterioration due to various mechanical and weather conditions, and the data they generate may lead to incorrect responses to vehicle surroundings. Even when the sensors are functioning correctly and capturing the correct information, the algorithms used by the vehicle may still not guarantee acceptable performance in adverse environments. However, there is currently no comprehensive study on the failure of sensors, sensor data, and algorithms. Furthermore, there is a lack of clear definitions and classifications for these failures.

Challenges in Vehicular Data Storage

Data storage is a significant challenge for connected vehicles or autonomous vehicles. First and foremost, these vehicles generate vast amounts of data that need to be processed and stored securely. Secondly, the data must be stored in a way that ensures its availability for real-time decision-making while maintaining data privacy and security. Additionally, the data must be accessible in the event of an accident or legal dispute. Lastly, it is necessary to establish and implement data management standards and protocols to guarantee interoperability between various systems and stakeholders. Addressing these challenges is essential to ensure the safe and reliable operation of connected and autonomous vehicles.

Opportunities

In order to tackle the aforementioned challenges and realize our vision, there is a need for open data analytics platforms that provide complimentary APIs and access to real-world vehicle data. The representative platforms include

- **OpenVDAP** [17]: It comprises an onboard computing/communication unit, an isolation-supported and security & privacy-preserving vehicle operating system, an edge-aware application library, and an optimal workload offloading and scheduling strategy. This configuration enables CVs to dynamically assess each service's status, computation overhead, and ideal offloading destination, ensuring that each service can be completed within an acceptable latency and minimal bandwidth consumption.
- **Auto API** [23]: It is developed by High Mobility. Accessed through the standardized API and with the consent of the customer, third-party service providers can use data from Mercedes-Benz vehicles for Pay-As-You-Drive (PAYD) Insurance and electric vehicle (EV) Charging.
- **Otonomo Automotive Data Services Platform** [24]: It offers vehicle data from 18 million passenger and commercial vehicles globally, including real-time data from various systems such as infotainment units, fuel systems, and advanced driver assistance systems (ADAS). It ensures secure data management and allows drivers control over their personal data. Patented technology also provides blurred data for use in traffic management, mapping & planning solutions, remote diagnostics, electric vehicle services, predictive maintenance, safety & emergency solutions, etc.

To support diverse vehicle applications, research in vehicle-pedestrian interaction (VPI) is needed to improve safety for both pedestrians and drivers in urban areas. Besides, vehicle-edge-cloud (VEC) collaboration [7] is also necessary for efficient and effective data processing and analysis. By leveraging the strengths of each component (vehicle, edge devices, and cloud), VEC collaboration can enhance the performance and reliability of connected vehicle systems. It can also enable new applications and services that require large-scale data processing and analysis, such as path planning and traffic control.

In addition, based on the communication between vehicle and IoT, vehicle and vehicle, and vehicle and infrastructure, enormous applications are enabled, such as IoT-enabled public safety applications, collaborative learning for EVs, multi-model federated learning framework on the wheels, and intersection intelligence to avoid potential fatal collisions in the left or right turn scenarios, distributed real-time systems.

Conclusion

In conclusion, this article has introduced the notion of Vehicle Computing, emphasizing its capacity to revolutionize CVs by transforming them into mobile computing platforms alongside their conventional transportation function. We have identified five primary functionalities of CVs that contribute to this vision: computation, communication, energy consumption and storage, sensing, and data storage. Furthermore, we have proposed a novel business model that fosters the development and adoption of CV technology while exploring the challenges and opportunities associated with these areas.

As we move forward, it is crucial to continue researching and developing solutions to address the challenges associated with Vehicle Computing, in order to fully unlock its potential and maximize its benefits for users, service providers, automotive manufacturers, and other stakeholders. By embracing a collaborative approach and fostering innovative business models, we can ensure that connected vehicles not only revolutionize transportation but also contribute significantly to the broader computing ecosystem.

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REFERENCES

1. A. M. Research, "Connected Car Market Size, Share, Growth & Trends Analysis Report by Technology, Connectivity Solution, Service, End-Use, And Segment Forecasts, 2020-2027," https://reports.valuates.com/market-reports/ALLI-Manu-3Z1/connected-car, 2019.
2. AECC, "Distributed computing in an aecc system (online)," https://aecc.org/resources/publications/, August 2021.
3. S. Lu and W. Shi, "The emergence of vehicle computing," *IEEE Internet Computing*, vol. 25, no. 3, pp. 18–22, 2021.
4. ——, "The emergence of vehicle computing," *IEEE Internet Computing*, vol. 25, no. 3, pp. 18–22, 2021.
5. Q. Zhang, Q. Zhang, W. Shi, and H. Zhong, "Distributed collaborative execution on the edges and its application to amber alerts," *IEEE Internet of Things Journal*, vol. 5, no. 5, pp. 3580–3593, 2018.
6. S. Lu, Y. Yao, and W. Shi, "CLONE: Collaborative learning on the edges," pp. 10 222–10 236, 2020.
7. S. Lu, X. Yuan, and W. Shi, "EdgeCompression: An integrated framework for compressive imaging processing on CAVs," in *2020 IEEE/ACM Symposium on Edge Computing (SEC)*. IEEE, 2020, pp. 125–138.
8. L. Liu, X. Zhang, Q. Zhang, A. Weinert, Y. Wang, and W. Shi, "AutoVAPS: An IoT-enabled public safety service on vehicles," in *Proceedings of the Fourth Workshop on International Science of Smart City Operations and Platforms Engineering*, 2019, pp. 41–47.
9. L. Liu, Y. Yao, R. Wang, B. Wu, and W. Shi, "Equinox: A road-side edge computing experimental platform for CAVs," in *2020 International Conference on Connected and Autonomous Driving (MetroCAD)*. IEEE, 2020, pp. 41–42.
10. G. A. Association *et al.*, "The case for cellular V2X for safety and cooperative driving," *White Paper, November*, vol. 16, 2016.
11. Teraki, "Autonomous cars' big problem: The energy consumption of edge processing reduces a car's mileage with up to 30%." https://medium.com/@teraki/energy-consumption-required-by-edge-computing-reduces-a-autonomous-cars-mileage-with-up-to-30-46b6764ea1b7, May 2019.
12. R. Bryce, "How google powers its 'monopoly' with enough electricity for entire countries," https://www.forbes.com/sites/robertbryce/2020/10/21/googles-dominance-is-fueled-by-zambia-size-amounts-of-electricity/?sh=19fc3bd168c9, October 2020.
13. G. R. Parsons, M. K. Hidrue, W. Kempton, and M. P. Gardner, "Willingness to pay for vehicle-to-grid (V2G) electric vehicles and their contract terms," *Energy Economics*, vol. 42, pp. 313–324, 2014.
14. W. Kempton and J. Tomić, "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," *Journal of power sources*, vol. 144, no. 1, pp. 268–279, 2005.
15. "Flood of data will get generated in autonomous cars," https://autotechreview.com/features/flood-of-data-will-get-generated-in-autonomous-cars, accessed: 2020-2-18.
16. L. L. Ruijun Wang and W. Shi, "HydraSpace: computational data storage for autonomous vehicles," in *IEEE Collaborative and Internet Computing Vision Track (CIC)*, December, 2020.
17. Q. Zhang, Y. Wang, X. Zhang, L. Liu, X. Wu, W. Shi, and H. Zhong, "Openvdap: An open vehicular data analytics platform for cavs," in *2018 IEEE 38th International Conference on Distributed Computing Systems (ICDCS)*. IEEE, 2018, pp. 1310–1320.
18. S. Lu and W. Shi, "Vehicle computing: Vision and challenges," *Journal of Information and Intelligence*, 2022.
19. A. Sam, "Automotive over-the-air updates: A cost consideration guide(online)," https://www.auroralabs.com/wp-content/uploads/2021/05/OTA_Update_Cost_Consideration_Guide_Apr2021.pdf, April 2021.
20. O. Joel, "Connected car – all that data – cost and impact on the network (online)," https://blogs.cisco.com/sp/connected-car-all-that-data-cost-and-impact-on-the-network, February 2019.
21. T. Lida, "Is data transmission the new fuel? (online)," https://www.auroralabs.com/is-data-transmission-the-new-fuel/, June 2021.
22. Y. Gorkem, "Edge computing: operator strategies,

use cases and implementation (online)," https://marketing.analysysmason.com/acton/attachment/3183/f-e3b754dd-b4d2-4924-af3c-c36f72e8ecb7/1/-/-/-/-/Analysys_Mason_edge_computing_strategies_Jun2020_RMA16.pdf, July 2020.

23. T. Zehelein, "Evaluation of machine learning methods for diagnosing automotive damper defects," Ph.D. dissertation, Technische Universität München, 2021.
24. J. W. Koupal, A. DenBleyker, G. Manne, M. H. Batista, and T. Schmitt, "Capabilities and limitations of telematics for vehicle emissions inventories," *Transportation Research Record*, vol. 2676, no. 3, pp. 49–57, 2022.