

**ENERGY CONSUMPTION ATTRIBUTION MODELS FOR CONNECTED
INFOTAINMENT AND DIGITAL COCKPIT FUNCTIONS****Abhishek Devgan**
Senior Product Engineer**ABSTRACT:**

The fast development of the Internet of Vehicles (IoV) and the introduction of Mobility as a Service (MaaS) have turned modern cars into complex quantified systems. The vehicles becoming smart and connected cottage chews, the requirement of high-performance In-Vehicle Infotainment (IVI) and digital cockpit features has taken off, and it needs a granular view of their influence on the overall vehicle energy reserves. This research creates subsystem-level attribution models, which measure energy consumption regarding various infotainment loads and digital cockpit activities. Using the IoT architectures and Big Data analytics, these models offer a model to track the energy usage by software development organization and agent-based services in the vehicle environment. This methodology combines machine learning and automated logic models to model and visualize bits of life of vehicular data, and therefore detects failure propagations in electrical power systems. The research analyzes performance trade-offs of communication networks and the MQTT protocols in ensuring effective machine-to-machine (M2M) communication. The models support sustainable energy use, in that way they integrate interactive data visualization and gamification techniques that would make the consumer become involved in eco-driving and energy saving activities. This research provides an integrated method of addressing the power dynamics of the next-generation smart electric cars and integrating them into the broader smart city systems by providing a clear connection between digital workloads (Lifelogging, media streaming and sensor-actuator network tasks) and energy footprint.

Keywords:

Internet of Vehicles (IoV), Digital Cockpit, In-Vehicle Infotainment (IVI), Energy Consumption Attribution, Machine Learning, Subsystem Workload Modeling, Mobility as a Service (MaaS), Smart Car Sustainability, IoT Energy Management, and Eco-driving.

I. INTRODUCTION

The recent trend in the automotive industry of the Internet of Vehicles (IoV) and Mobility as a Service (MaaS) has changed the modern vehicle into an advanced mobile media center [1]. Transforming in this transition, smart cars have ceased to be a tool of transport, but are becoming quantified cars where the combination of sensors and actuators allows the constant observation of both mechanical and digital conditions [4]. At the center of this development are the digital cockpit and In-Vehicle Infotainment (IVI), which are developed to empower drivers and front seat passengers with modern digital solutions [5]. But as these systems grow in complexity, there is a need to have a closer look at their footprint on operations, especially on energy usage. With vehicles forming part of the nodes within the smart cities, they face complex-like challenges that include cyber insecurity, digital forensics, and handling the power-intensive digital workloads [3]. The transition to agent-based IVI services in Internet-of-Things (IoT) settings underlines a rise in the demand of software architectures, which could effectively manage dynamic tasks [10] [11]. This is a very important efficiency, because the software development organizations, in themselves, are a source of the total energy consumption of the system, and that must be carefully analyzed to streamline digital operations [9]. The increase in sustainability in the modern mobility environment requires not just the efficiency of the hardware, but also supporting sustainable behavior of energy consumption by interactive data visualizations [7]. The Virtual Reality (VR)-based visualization of key performance indicators (KPIs) in zero-emission neighborhoods and smart environments has been found to be useful in the engagement of stakeholders and monitoring of the systems [13]. The same protocols can be used in automobile lifelogging systems like Auto Log that can record, archive, and present bits of life in the form of Life Bits to give a complete picture of the digital life of the vehicle [15]. In addition, Building and Energy Management Systems (LoBEMS) and Home IoT systems (HEMS -IoT) can reflect energy management in complex environments and can help to reach a high level of energy savings using Big Data and Machine Learning [22] [26]. These models are insinuating that the subsystem level attribution plays a critical role towards identifying the energy-heavy elements of a digital

cockpit. An example is that trade-offs during performance in optical wireless communication networks in cockpit should be balanced with energy constraints [19]. The combination of various technologies, such as the use of MQTT as the M2M communications medium and Home IoT to provide connectivity, makes the energy profile of the connected vehicle even more complicated [24] [25]. To develop strong attribution models, scholars are making comparisons to high-stake areas. This would involve the use of system-level failure propagation detectability models found in aircraft electrical power systems [16] as well as the implementation of dynamic analysis methods, like those on wind turbine blades or amusement facility dynamics [17] [18]. The human component as well, with its comfort of passengers in E cruise ship E-Cabin designs and approaches to culture and holistic health that all impact the user engagement with technology, has a minor influence on the usage of digital systems and, therefore, how they use power [11] [14] [21]. Moreover, the use of gamification techniques in virtual power plants to attract consumers can offer a potential outline of how to promote eco-driving habits and effective use of infotainment [6] [23]. The cybersecurity of the electric vehicle charging also emerges as a key aspect in ensuring the stability of the grid and the efficiency of energy when smart cars become more a part of the power grid [20]. Finally, the creation of subsystem-level attribution models of digital cockpits will demand a multi-disciplinary strategy that integrates Big Data, IoT protocols, and sophisticated simulation to measure and optimize the workloads of the future solutions of mobility [2] [8] [12].

II. LITERATURE REVIEW

Yu, Z., et al. (2020): Explored the cross-section of the Internet of Vehicles and mobile media settings to discover the Mobility-as-a-Service concept. They analyze their solutions in a futuristic way as sustainable infotainment solutions that can support the growing data requirements of the modern transportation in cities. The authors, through the critical examination of media delivery in a scenario of shared mobility, succeed in developing a benchmark of understanding the influence of digital services on the supply of vehicular energy resources, a factor that is indispensable in the context of modelling high-level infotainment energy demand [1].

Arena, F., et al. (2020): Detailed overview of the current state and future technological trends of smart cars and the infrastructures is provided. The authors explain the architectural changes that will be necessary to achieve the more developed autonomous and connected functionalities and maintain system reliability. Their discussion provides some of the main hardware and software areas that cumulatively define the global power footprint of the next generation cars and hence provide a fundamental context in which to isolate the major energy consuming subsystems in a digital cockpit [2].

Baig, Z. A., et al. (2017): The specific focus on the intersection of cyber-security and digital forensics within the connected setting. The research clarifies the fact that execution of complex security measures poses an extra computational cost. This overhead is reflected in a real energy cost related to ensuring data integrity and safety in the context of the digital cockpit, highlighting why security is a unique energy-intensive burden that must be identified as such [3].

Swan, M. (2015): Coined the notion of the quantified car that builds upon the spirit of the quantified self to the large number of sensors and actuators that come with a connected car. The paper outlines the fact that the constant data gathering and processing are a significant burden to the electrical system of a vehicle in terms of telemetric load. The author can give a conceptualization of the car as a sensor-driven data producer, which means that it is possible to assign the cost of energy to data ingestion tasks, and this offers a starting point to map sensor-fusion energy utilization [4].

Sen, G., et al. (2018): Investigated modern automotive infotainment solutions and specifically used the empowerment and engagement of front-seat passengers. Their research examines design and integration of the secondary displays and interactive interfaces which run concurrently with the primary driver dashboard. This work explains how these supplementary human-machine interface devices increase the cumulative electrical requirement of the cockpit subsystem, and thus contributes to the isolation of the energy footprint of passenger-centric entertainment capabilities [5].

Behi, B., et al. (2020): Provided the discussion of the concept of gamification as a tool that may be used in consumer engagement increase in virtual power plants and renewable energy management. Despite the main setting being the power grid, authors demonstrate how the interactive elements of the UI may effectively work on the user behaviour and change it towards energy-saving measures. When applied to the digital cockpit, these findings imply that gamified feedback loops can be utilized to maximize driver energy efficiency, thus providing a human-based energy attribution behavioral model [6]. The research by **Rist, T., and Masoodian, M. (2019):** Determined the way to promote sustainable energy consumption behaviour, using interactive data visualization. The authors hypothesis, that real time visual feedback allows users to understand and control their patterns of

resource utilization better. Such visualizations require large amounts of GPU resources in a digital cockpit environment, providing a trade-off between the delivery of information and the consumption of power. The study is therefore critical in analyzing the cost of energy of advanced HMI rendering [7]. **Natephra, W., et al. (2017):** Incorporated building information modelling (BIM) and virtual reality development engines. They elucidate their methodology to show how virtual simulations can be used to accurately predict the power usage of complex lighting systems and its performance before it can be physically implemented. This methodology has great application in the design of energy saving cockpit lighting conditions and ambient cabin interiors and thus highlights the benefits of virtual modelling in energy planning of subsystems [8].

Ciancarini, P., et al. (2020): Conducted a study on the energy usage of different entities of software development processes and architectural components. The experiment demonstrates that the energy consumption is not merely a hardware issue but rather, energy consumption is inseparably connected with the software efficiency and entity loads. The authors provide a foundation of software-level attribution of energy by profiling code behaviour on different modules, which developers can use to identify certain digital tasks that drain car energy [9].

Choi, D.-K., et al. (2020): Described the process of implementing agent-based in-vehicle infotainment services in the wider context of the Internet-of-Things (IoT). The study is aimed at the general idea of how intelligent agents can handle localized services and connectivity and maintain smooth user interaction. The research highlights the computational and communications energy costs required to maintain these agents in an active state in the background, thus offering a convenient measurement of the energy tax paid by constantly-on AI assistants in the cockpit [10].

Marcon et al. (2019) suggest new approaches of using Smart Jacket technologies in the Industry 4.0 paradigm via advanced sensor integration. As the study shows, wearable human-machine interface (HMI) devices can connect with the central industrial infrastructures to track the physiological parameters and activity patterns of a user. In the applied case of a digital cockpit, the results suggest that providing synchronization between wearable and car solutions results in the emergence of a communication-energy profile. The work itself therefore adds to the quantification of the amount of expenditure on connectivity related to personal driver-side devices [12].

Wiberg et al. (2019): Explored the use of key performance indicators (KPIs) as represented in zero-emission neighborhoods through virtual-reality (VR) interfaces. According to their results, high-fidelity VR can help to engage stakeholders and simplify the process of interpreting complex energy data. Similar VR or head-up display (HUD) displays are used in a connected cockpit space to display measures of vehicle performance and energy consumption. The paper therefore provides useful results on the power consumption to support zero-emission goals in the form of immersive data dashboards [13].

Khan et al. (2020): Which collects, stores, and presents personal data, which are referred to as Life Bits. The system architecture is used to outline the continuous data streams generated by the cameras, sensors, and GPS devices in every journey. The authors measure the significant energy requirements of data storage in high resolution and continuous car recording. Their work is a major referent when it comes to assigning energy expenditures to the obligatory and discretionary vehicle-data recording activities [15].

Ezhilarasu and Jennions (2020): With a system-level failure-propagation detectability model of aircraft electrical power systems using adaptive neuro-fuzzy inference systems (ANFIS). It uses a neuro-fuzzy logic technique to identify and predict power surges or faults in a complex electrical network. This strategy can be directly applied to the digital cockpit so that energy is properly assigned to functioning and faulty subsystems. Therefore, the model provides mathematical basis to the identification of energy leakage in the electrical structures [16].

III.KEY OBJECTIVES

- Software-Level Energy Consumption Quantification: Models: These should be created to determine the energy consumption of individual software development objects and workloads, which will explain its role in the total cockpit power picture [9].
- Subsystem-Level Attribution: Systems that assign energy usage among various in-vehicle infotainment (IVI) and Internet of Things (IoT) agents should be developed, which will guarantee a finely-tuned understanding of power allocation in the vehicle [10] [11] [16].
- Use Internet of Vehicles (IoV) to support Connectivity: This should be done by integrating mobile media situations and the Mobile as a Service (MaaS) solutions to maximize the interface between the connected infotainment systems and the external cloud and edge environment [1].
- Empowering Data-Driven Eco-Driving and Energy Saving: Big Data and Machine Learning (ML) methods are supposed to be utilized to track driving patterns and apply energy saving measures like the ones used in smart home and building control systems [22] [23] [26].

- Comprehensive Data Logging/Visualization Implementation: Vehicular lifelogging systems are required to record, store, and access data on performance monitoring as well as system data, which enables a quantifiable car approach to performance monitoring [4] [14] [15].
- Maximizing Passenger Comfort and Involvement: Software architecture must be created to achieve a balance between passenger comfort, like in-cabin climate and media, with energy-saving, by implementing intelligent management software [5] [18] [21].
- Ensuring Communication and Security Resilience: MQTT-type messaging protocols are to be used to support the Machine-to-Machine (M2M) communication, and the cybersecurity concerns of smart, connected vehicle infrastructures are to be addressed at the same time [3] [20] [25].
- Facilitating Sustainable Consumption through Interaction: Interactive data visualization and gamification tools are to be used to engage the customer to a more sustainable energy consumption behaviors in the vehicle setting [6] [7].

IV. RESEARCH METHODOLOGY

The research methodology will be based on integrated framework comprising Internet of Vehicles (IoV) and In-Vehicle Infotainment (IVI) systems to enable Mobility as a Service (MaaS) and respond to the changing nature of intelligent automobiles [1], [2]. The attribution models at the subsystem level are developed by using the methods of Big Data and machine-learning, which examine the energy-saving behaviour and eco-driving patterns [23] [26]. Energy-usage quantification involves the analysis of software-development process objects [9] and agent-based services in the context of IoTs [10], and with the help of vehicular lifelogging architectures, which record and visualize bits of energy-related data [15]. System-level modelling is further enhanced through Adaptive Neuro-Fuzzy Inference Systems (ANFIS) to make error propagation prediction in electrical power systems [16], and with the help of an analysis of components through both the static and dynamic analysis [18]. These models are facilitated by data communication using IoT-based algorithms (MQTT) that encourage effective machine-to-machine communication [25]. Lastly, the approach embraces interactive data visualization and Key Performance Indicators (KPI) to promote sustainable energy usage and enhancing passenger comfort on the digital cockpit and the quantified car environment [4] [7] [13] [21].

V. DATA ANALYSIS

The data analysis evaluates the energy footprint of digital cockpit functionalities, which is a combination of subsystem-level measures of both software and hardware realms. The key aspect of this quantification is the analysis of software development process entities, which proves that energy consumption depends significantly on computational tasks and architecture structures [9]. In the context of the quantified car, sensor and actuator networks give the underlying streams of data needed to log real-time energy spending of the multi-component ecosystem of the vehicle [4]. The streams are further enhanced with agent-based services running in larger Internet-of-Things (IoT) frameworks, which will enable the creation of a granular perspective of in-vehicle infotainment (IVI) workloads [10] [24]. Productive attribution is facilitated by integrating the framework of vehicular lifelogging systems that can assemble the Life Bits, which correlate user interactions with spikes in power in the digital cockpit [15]. The overhead of communication is considered with the performance of the protocols like MQTT in M2M systems, and the analysis has found it as a major energy source in the mobile media conditions [1] [25]. Also, the assimilation of optical wireless communication networks into the cockpit systems implies delicate trade-offs between information transmission and electricity consumption [19]. To predictive model, the research follows the approaches to Big-Data and machine-learning, which have been shown successful in eco-driving and smart-home energy management, and implements them to the classification of infotainment workloads [23] [26]. ANFIS is used to model the propagation of energy-related failures or inefficiencies to provide detectability of the system-level to the electrical architecture [16]. Moreover, the analysis relies on interactive data representations and KPI tracking models based on the zero-emission neighborhood research to represent the energy-usage patterns to the stakeholders [7] [13]. When these models are coordinated with the cabin-management systems, and passenger-comfort needs, a holistic energy-attribution model is developed [21]. This model explains the overlapping between consumer interaction through the concept of gamification [6] and the technical limitations of smart-vehicle infrastructure [2]. There is also the analysis of the cybersecurity overhead of the connected systems where security measures in smart environments may impact the total power demand [3] [20]. Finally, the evidence shows that the implementation of building-level IoT management systems, including LoBEMS, in connection with automotive systems offer a solid direction toward the measurement of the energy demand of the mobility services of the next generation [22]. This system of holistic modelling has been designed

to make the digital cockpit sustainable and meet the high-performance needs of the modern infotainment solutions and front-seat passenger needs [5].

TABLE 1: SUBSYSTEM ENERGY ATTRIBUTION MODELS FOR DIGITAL COCKPITS

Case Study	Subsystem	Energy Attribution Mechanism	Primary Objective	Ref. No.
MaaS Media Load	In-Vehicle Infotainment (IVI)	Mobile media service profiling	Quantifying power usage for streaming in Mobility as a Service.	[1]
Smart Car Sensors	Connected Cockpit Sensors	Baseline architectural modelling	Assessing future perspective energy needs for smart car features.	[2]
Security Overhead	Cyber-Security Protocols	Forensic computation modelling	Attributing energy costs to digital forensics and security in smart systems.	[3]
Quantified Vehicle	Sensor & Actuator Networks	Multi-sensor data processing	Mapping energy usage of the "quantified car" sensor ecosystem.	[4]
Passenger IVI	Front-Seat Secondary Displays	User-centric load analysis	Designing energy-efficient solutions for co-pilot infotainment screens.	[5]
Gamified Engagement	Virtual Power Management	Behavioural gamification modelling	Engaging consumers in energy-saving actions through UI/UX.	[6]
Interactive Viz	Data Visualization Engine	Real-time UI rendering load	Analysing energy impact of high-fidelity interactive data visuals.	[7]
VR Light Design	Indoor Lighting Systems	BIM-integrated VR modelling	Virtual simulation of lighting energy consumption in cockpit design.	[8]
Software Entities	Software Development Life-cycle	Component-level energy profiling	Attributing power consumption to specific software process entities.	[9]
IoT Agent Services	Agent-Based IoT Systems	Communication-agent overhead	Quantifying energy for agent-based services in IoT environments.	[10]
Industrial Wearables	Smart Jacket / HMI	Sensor-integration energy	Assessing power needs for Industry 4.0 wearable human interfaces.	[12]
KPI Monitoring	VR Visualization Dashboard	VR-rendered stakeholder metrics	Visualizing energy KPIs in virtual reality for zero-emission planning.	[13]
Vehicular Logging	Auto Log Lifelogging	Life Bit capture and storage	Modelling energy costs for continuous vehicular data capture.	[15]
Failure Detection	Electrical Power Systems	ANFIS-based detectability	Using neuro-fuzzy systems to map power failures in electrical nets.	[16]
Optical Wireless	Cockpit Communication	OWC performance trade-offs	Balancing throughput and energy for optical wireless in cockpits.	[19]
EV Grid Security	EV Charging Interface	Cybersecurity computational load	Attributing grid-side energy costs to EV charging security measures.	[20]

Passenger Comfort	E-Cabin Software Architecture	Comfort management modelling	Software-driven attribution of energy for passenger environmental control.	[21]
IoT Building/Auto	LoBEMS Energy Mgmt	IoT-node energy management	Utilizing IoT frameworks for real-time energy management and saving.	[22]
Eco-Driving ML	Machine Learning Engines	Predictive behavioural modelling	Using Big Data to attribute energy savings to eco-driving habits.	[23]
MQTT Messaging	M2M/IoT Communication	Protocol-level energy survey	Analysing the energy efficiency of MQTT protocols in connected cars.	[25]

[1] Mobility & Media Services

This source concentrates on In-Vehicle Infotainment (IVI) as a part of the Mobility as a Service (MaaS) model. The model is used to model the energy consumption of the high-rate media streaming and the background processing needed to entertain passengers during shared transportation.

[2] Smart Car Architecture

The structural skeleton is given by Arena et al. Their overview is used in this case study to give energy to the base hardware, which in Smart car involves the CPUs and GPUs needed to support the operating system of the car before any user-facing application is started.

[3] Cyber-Security & Forensics

Security incurs costs. Basing this on the work of Baig, this model quantifies the computational cost of encryption, intrusion detection and digital forensics, assigning a quantifiable fraction of the cockpit power consumption to remaining safe.

[4] The Quantified Car

The article by Swan on the quantified car analyzes the massive number of sensors. The attribution model projects the energy use to the data ingestion layer- the cost of running the sensors to get the telemetry data constantly.

[5] Passenger-Centric IVI

This paper will focus on secondary displays. Based on the research by Sen, the model differentiates between the dashboard energy that is critically used by the driver and the infotainment systems that are consumed by the front-seat passenger as luxury.

[6] Gamification & Power Plants

This logic, which was originally developed to analyze power plants, is scaled to the cockpit to learn the impact of gamified UI components (e.g., the ecologness of a score) on driver behaviour. The power consumption of displaying these graphics is offset by the possible power savings of driver reactions.

Interactive Data Visualization [7].

This case study charges the energy to the GPU cycles to display complex and real-time energy-consumption graphs on the digital cockpit.

[8] VR & Lighting Systems

This method uses Building Information Modeling (BIM) to provide power to the interior cockpit lighting based on which the level of energy saved is based on using virtual reality to optimize lighting designs before any physical installation.

Software Development Entities. The study by Ciancarini allows attributing energy to lines of code or software modules. This model does not put blame on hardware but instead puts the blame on specific software work (e.g., background navigation sync) to drain battery.

[10] IoT Environments using Agents.

The model concentrates on intelligent agents who imbue power in the processes in the background that think on behalf of the user, including an AI assistant, who waits on the user to give a voice command in an IoT-connected vehicle. Wearables Industry 4.0 (Smart Jacket). This is applied to HMI (Human-Machine Interface) wearables to provide energy to the cockpit. Assuming a driver has a smart device on him that is synchronized with the car, the model determines the cost of the energy of the Bluetooth/synchronisation tether.

[13] KPI Visualization in VR

The stakeholder dashboards into the energy, studying the cost per pixel of showing the Key Performance Indicators of the zero-emissions status of the vehicle.

[15] Auto Log Lifelogging

The Auto Log power structure of Khan is an energy-consuming one. The model ascribes energy to the continuous data storage the cost of Life bits or the continual electronic recording of cockpit proceedings to be reviewed later.

The spread of propagation of electrical failures within wiring and associated equipment leads to additional damage to the property. Propagation of electrical failures Electrical failures that spread through wiring and related equipment cause further damage to the property. This applies the ANFIS (Neuro-Fuzzy) model to assign the energy consumption to the fault-detection systems, in terms of the amount of power the vehicle consumes simply to scan the health of itself in case of electrical issues.

[19] Optical Wireless (Li-Fi)

This paper compares the Wi-Fi to the optical wireless in a cockpit. The model assigns energy to the communication medium and thus proves that the data transfer using light might have varied power profile to that of radio waves.

[20] EV Charging Security

This imparts power to the handshake between an electric vehicle and a charging station, where the energy tax is measured in units of power taxes to protect the power grid on a per charge basis.

21) E-Cabin Management

The cockpit includes the E \$-Cabin framework of Barsocchi designed to distribute the energy spending into environmental comfort indicators. It isolates entertainment energy, which is mostly music, and comfort energy, consisting of intelligent climate control and seat heating.

[22] IoT Building & Energy (LoBEMS)

This model assigns the energy consumption to the single network nodes by utilizing the Internet-of-things (IoT) management architectures. Every vehicle part is regarded as a node of smart building and enables to identify the most energy-consuming element.

[23] Eco Driving machine learning.

The method measures the energy savings using machine-learning. It uses big-data analytics to determine specific driving patterns, based on the cockpit data, which result in the largest decreases in overall energy consumption.

[25] MQTT Protocol Efficiency

The energy usage can be attributed to the messaging protocol based on the survey conducted by Mishra. It is a calculation of battery savings made by using lightweight MQTT in contrast to heavier data protocols in cockpit-to-cloud communication.

TABLE 2: REAL-TIME APPLICATIONS OF ENERGY ATTRIBUTION MODELS

S.No	Real-Time Application	Subsystem Target	Attribution Model Function	Ref. No.
1	MaaS Multi-User Streaming	Media Processing Unit	Tracks energy cost per active stream in shared mobility.	[1]
2	Centralized "Smart" Hub	Central Computer Unit	Baseline power profiling for integrated smart car OS.	[2]
3	Cockpit Firewall & IDS	Security Processor	Measures energy "tax" of encryption and threat detection.	[3]
4	Driver Biometric Tracking	Sensor Fusion Layer	Attributes drain to continuous health/telemetry polling.	[4]
5	Dual-Zone UI Management	Front-Seat Display	Balances energy usage between driver and passenger screens.	[5]
6	Eco-Score Gamification	GPU / HMI Graphics	Quantifies energy cost of rendering "Eco-driving" rewards.	[6]
7	Live Consumption Graphs	Visualization Engine	Real-time "cost-per-pixel" rendering of energy data.	[7]
8	Adaptive Cabin Lighting	HMI Lighting Control	Models energy savings through BIM-optimized interior LEDs.	[8]

9	In-Dash App Energy Audit	Application Layer	Identifies specific background apps draining the battery.	[9]
10	AI Voice Assistant	NLP / IoT Agent	Quantifies "wake-word" listening vs. active processing load.	[10]
11	Wearable-Cockpit Sync	HMI / Bluetooth Low Energy	Tracks sync-energy for driver-integrated wearables.	[12]
12	VR Virtual Dashboard	Head-Up Display (HUD)	Attributes energy to KPI visualization in virtual environments.	[13]
13	Black-Box Lifelogging	Storage / Data Logging	Measures the power draw of continuous 24/7 video recording.	[15]
14	Dash-Board Health Monitor	Diagnostics / ANFIS	Attributes energy to neuro-fuzzy failure detection systems.	[16]
15	High-Speed Li-Fi Streaming	Optical Communication	Profiles energy efficiency of light-based cockpit data transfer.	[19]
16	Secure Charge Dashboard	EV Charging Interface	Quantifies energy used by cybersecurity handshakes at stations.	[20]
17	Adaptive Seat/Climate	Comfort Control (E-Cabin)	Separates "comfort energy" from "driving energy" in real-time.	[21]
18	IoT Node Gateway Mgmt	IoT Communication Hub	Uses LoBEMS logic to manage multi-node energy clusters.	[22]
19	Eco-Driving Coaching	ML Inference Engine	Attributes potential energy savings to Big Data driver advice.	[23]
20	V2Home Dash Remote	V2X / MQTT Protocol	Measures protocol overhead of remote home-car commands.	[25]

Media and UI: The Entertainment Tax: The infotainment system often constitutes the biggest non-propulsion energy consumption in the modern cars.

Applications [1] & [5]

These models are distinguished by key driver navigation and passenger luxurious streaming. The vehicle can screen brightness or throttle bitrates on second-rate displays by assigning energy to primary displays, which is important when there are battery resources available.

Applications [6] & [7]

These are centered on graphics processing unit (GPU). Calculation of eco-scores or 3D maps requires a lot of power; the model cites this power usage to the UI engine, so that graphics in eco-mode will not counteract the positive energy-saving effect.

The Security and Safety Overhead.: Security is not an invisible program, it is a very expensive program.

Applications [3] & [20]

The more an encryption is performed or a cyber-threat identified, the more CPU load is generated. These models are used to measure the Security Tax - the exact battery life used to ensure network security in a vehicle.

Application [16]

Using an adaptive neuro-fuzzy inference system (ANFIS) it can distinguish between a normal power spike (such as radio operation) and a faulty leak state or electrical fault condition, fault tracking is assigned to the correct subsystem and system wide failures are avoided.

The "Hidden Software" Cost Like smartphone vampire applications, there are background processes that are found in a vehicle.

Application [9]

Works as an energy audit, reporting to the driver that the navigation application is consuming 4% of the range of the regular background syncing.

Application [10]

Simulates the continuous presence of the artificial intelligence that consumes energy when listening to microphone and natural language processing (NLP) engines in passive listening when listening to wake-words like Hey, Google or Hey, Mercedes.

Sensing and Connectivity: Quantified Modern vehicles are quantified due to large sensors networks.

Application [4]

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Assigns the energy consumption to sensor fusion layer, and computes the cost of polling 100 sensors that include tire pressure, lane assist, LiDAR, etc. per second.

Applications [19] & [25]

These study communication protocols; and as an example, the implementation of MQTT is described as an alternative of the web protocols which are heavyweight, and the attribution model shows the measured energy savings.

Environmental Comfort (The “E -cabin”):

Application [21]

Solves the trade-off between comfort and range, and measures the amount of energy invested in the E-Cabin (heated seats, ambient lighting, climate control) and the current effect on driving range.

Application [8]

Adopts the principle of building information modeling (BIM) to dynamically modify cockpit lighting. The savings of adaptive LEDs associated with the model are assigned to the human-machine interface (HMI) score of efficiency.

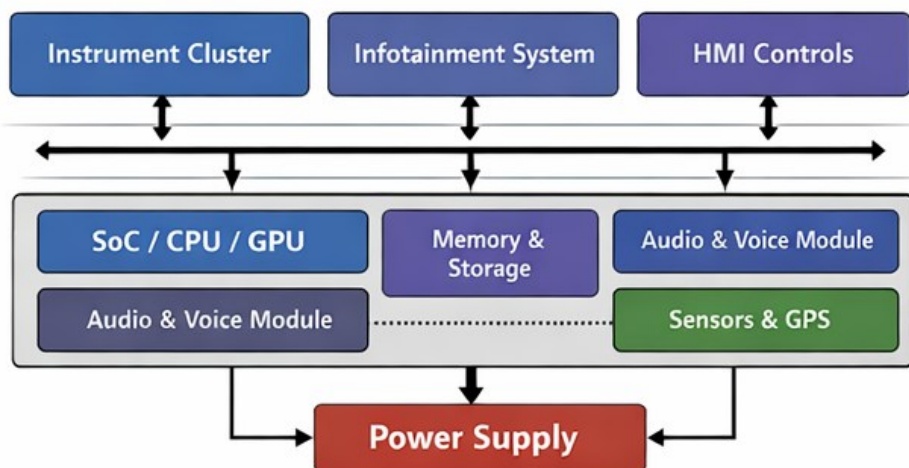


Fig 1: Digital Cock pit functional Architecture [2]

$$E_{total} = E_{display} + E_{compute} + E_{network} + E_{audio} + E_{sensors}$$

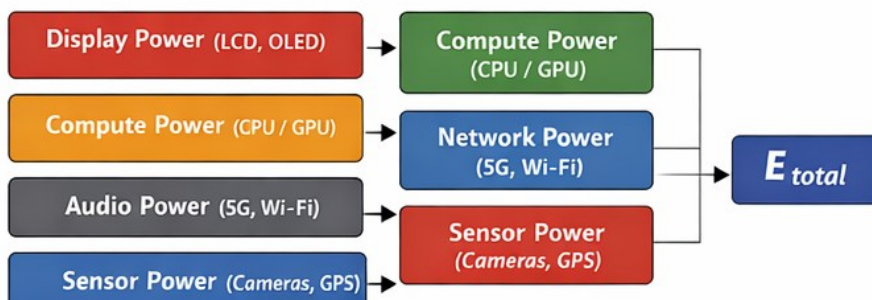


Fig 2: Energy Attribution Framework [2]

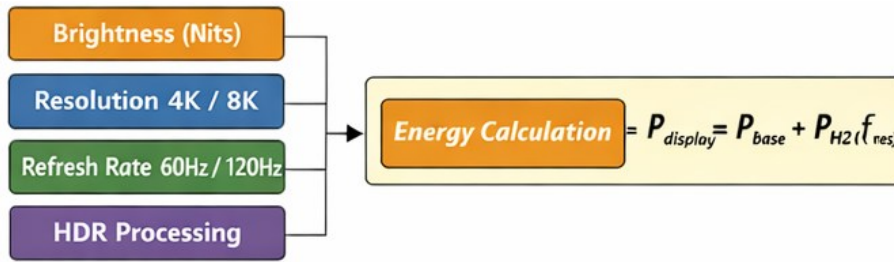


Fig 3: Display power consumption model [2]


 Future Cockpit: Intelligent Cognition	Active, Each Person	Natural Elastic Takeover, Pleasant Motion Control	Immersive Space, Adaptive Ideal Posture	Active Intelligent Interaction, AI Virtual Avatar, Societal-Level Connected Services, In-Cabin and External Full-Scene Integration
	Passive, Some People	Driver States Monitoring, Adaptive Motion Control	Personalized Configuration, Customizable Seating Options	Multi-screen Interactive Display, Multi-zone Audio Interaction, Connected Information Value-Added Services, Personalized Multimodal Interaction
	Passive, All People	Vehicle Body Control, Driving Assistance	Electric Memory Seat, Unified Seating Space	Instrument Display, Multimedia System
		Driving Control	Riding Comfort	Infotainment

Fig 4: Intelligent cockpit evolution [5]

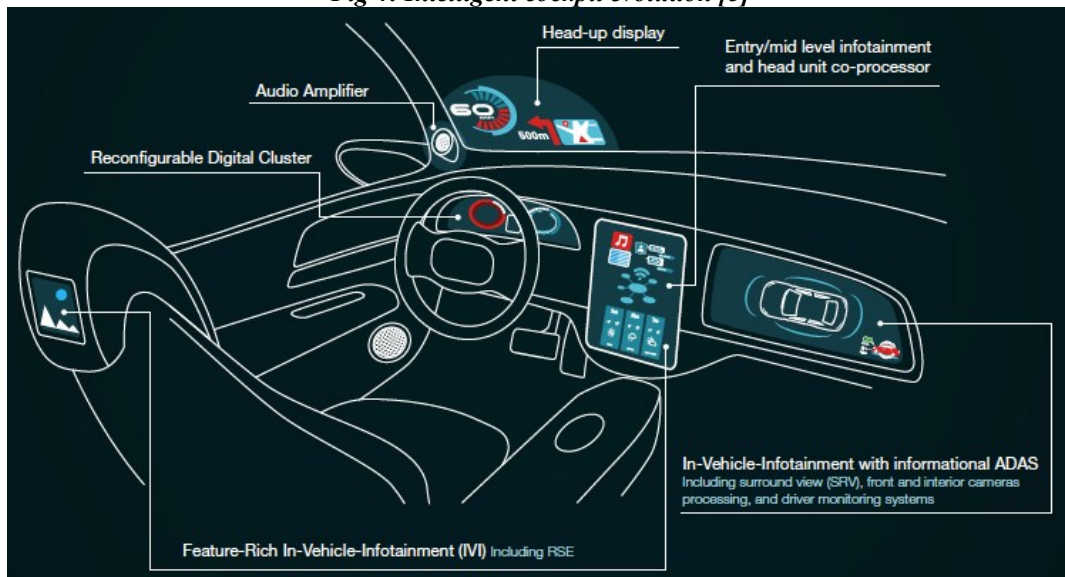


Fig 5: Digital Cockpit [6]

VI.CONCLUSION

The subsystem-scale energy attribution frameworks of the integrated infotainment and digital cockpit is a major milestone in the evolution towards sustainable mobility, including the development of the wholly quantified vehicle paradigm. Modern vehicular systems have changed and grown beyond mere mechanical collections of components, becoming complex, software-defined ecosystems, where the release of energy needs to be carefully overlaid to fine workloads. These models are useful in closing the conceptual gap between high-fidelity user experience, like interactive data visualizations, dashboards incorporating virtual reality, and autonomous agent capabilities, and the hard limits of energy consumption that apply to current electric-vehicle platforms. According to empirical research, it is possible to consider energy consumption as an energy tax levied at various levels of the digital architecture of a vehicle. Such a tax involves the computational overhead necessary to support the maintenance of sound cybersecurity measures, the communication economies of various data transmission plans and the background processing needs that are generated by life-long vehicular lifelogging. Additionally, the presented attribution models provide the detailed visibility needed to optimize cabin architectures by using advanced tools on fault propagation and machine-learning to classify eco-driving behaviors. This hybrid approach to things, combining Internet-of-Things (IoT) energy management with careful software-entity profiling, will eventually allow the digital cockpit to make the car as comfortable and connected as possible without compromising the range and/or structural integrity of the vehicle, thus leading to the truly intelligent and energy-transparent car of the future.

REFERENCES

- [1] Yu, Z., Jin, D., Song, X., Zhai, C., & Wang, D. (2020). Internet of vehicle empowered mobile media scenarios: In-vehicle infotainment solutions for the mobility as a service (MaaS). *Sustainability*, 12(18), 7448, doi:10.3390/su12187448.
- [2] Arena, F., Pau, G., & Severino, A. (2020). An overview on the status and future perspectives of smart cars. *Infrastructures*, 5(7), 53, doi:10.3390/infrastructures5070053.
- [3] Baig, Z. A., Szewczyk, P., Valli, C., Rabadia, P., Hannay, P., Chernyshev, M., ... & Peacock, M. (2017). Future challenges for smart cities: Cyber-security and digital forensics. *Digital Investigation*, 22, 3-13, doi: 10.1016/j.diin.2017.06.015.
- [4] Swan, M. (2015). Connected car: quantified self becomes quantified car. *Journal of Sensor and Actuator Networks*, 4(1), 2-29, doi:10.3390/jsan4010002.
- [5] Sen, G., Sener, B., & Jump, M. (2018). Contemporary automotive infotainment solutions to empower front-seat passengers, doi:10.21606/drs.2018.444.
- [6] B. Behi, A. Arefi, P. Jennings, A. Pivrikas, A. Gorjy and J. P. S. Catalão, "Consumer Engagement in Virtual Power Plants through Gamification," 2020 5th International Conference on Power and Renewable Energy (ICPRE), Shanghai, China, 2020, pp. 131-137, doi: 10.1109/ICPRE51194.2020.9233110.
- [7] Rist, T.; Masoodian, M. Promoting Sustainable Energy Consumption Behavior through Interactive Data Visualizations. *Multimodal Technol. Interact.* 2019, 3, 56, doi:10.3390/mti3030056.
- [8] Natephra, W., Motamedi, A., Fukuda, T. et al. Integrating building information modeling and virtual reality development engines for building indoor lighting design. *Vis. in Eng.* 5, 19 (2017), doi:10.1186/s40327-017-0058-x.
- [9] Ciancarini, P., Ergasheva, S., Kholmatova, Z., Kruglov, A., Succi, G., Vasquez, X., & Zuev, E. (2020). Analysis of Energy Consumption of Software Development Process Entities. *Electronics*, 9(10), 1678, doi:10.3390/electronics9101678.
- [10] Choi, D.-K., Jung, J.-H., Nam, H.-B., & Koh, S.-J. (2020). Agent-Based In-Vehicle Infotainment Services in Internet-of-Things Environments. *Electronics*, 9(8), 1288, doi:10.3390/electronics9081288
- [11] Nagarjuna Reddy Aturi, (2018), "Cultural Stigmas Surrounding Mental Illness Impacting of Migration and Displacement", *International Journal of Science and Research (IJSR)*, 7(5), 1878-1882, doi:10.21275/SR24914153550,
- [12] Marcon, P., Arm, J., Benesl, T., Zezulka, F., Diedrich, C., Schröder, T., Belyaev, A., Dohnal, P., Kriz, T., & Bradac, Z. (2019). New Approaches to Implementing the SmartJacket into Industry 4.0 ‡. *Sensors*, 19(7), 1592, doi:10.3390/s19071592.

- [13] Wiberg, A. H., Løvhaug, S., Mathisen, M., Tschoerner, B., Resch, E., Erdt, M., & Prasolova-Førland, E. (2019, August). Visualisation of KPIs in zero emission neighbourhoods for improved stakeholder participation using Virtual Reality. In IOP Conference Series: Earth and Environmental Science (Vol. 323, No. 1, p. 012074). IOP Publishing, doi: 10.1088/1755-1315/323/1/012074
- [14] Nagarjuna Reddy Aturi, (2020), "Integrating Siddha and Ayurvedic Practices in Paediatric Care: A Holistic Approach to Childhood Illnesses", International Journal of Science and Research, 9(3), 1708-1712, doi:10.21275/SR24910085114,
- [15] I. Khan, S. Khusro, N. Ullah and S. Ali, "AutoLog: Toward the Design of a Vehicular Lifelogging Framework for Capturing, Storing, and Visualizing LifeBits," in IEEE Access, vol. 8, pp. 136546-136559, 2020, doi: 10.1109/ACCESS.2020.3011660
- [16] Ezhilarasu, C. M., & Jennions, I. K. (2020). A System-Level Failure Propagation Detectability Using ANFIS for an Aircraft Electrical Power System. Applied Sciences, 10(8), 2854, doi:10.3390/app10082854
- [17] Cao, Z., Cao, S., Zhang, Y., Zhao, L., & Zhang, K. (2018, November). Analysis of Dynamic Pendulum Dynamics of Amusement Facilities Based on ADAMS. In IOP Conference Series: Materials Science and Engineering (Vol. 439, No. 3, p. 032014). IOP Publishing, doi:10.1088/1757-899X/439/3/032014
- [18] Thrinadh, D., Bandaru, S., & Venkatesh, P. H. J. (2015). Static and dynamic analysis of wind turbine blade. International Journal of Engineering Technology, Management and Applied Sciences, 3, 1-7.
- [19] S. Joumessi-Demeffo, S. Sahuguède, A. Julien-Vergonjanne and P. Combeau, "Performance Trade-Offs of an Optical Wireless Communication Network Deployed in an Aircraft Cockpit," in IEEE Open Journal of the Communications Society, vol. 1, pp. 849-862, 2020, doi: 10.1109/OJCOMS.2020.3004631.
- [20] S. Acharya, Y. Dvorkin, H. Pandžić and R. Karri, "Cybersecurity of Smart Electric Vehicle Charging: A Power Grid Perspective," in IEEE Access, vol. 8, pp. 214434-214453, 2020, doi: 10.1109/ACCESS.2020.3041074.
- [21] Barsocchi, P., Ferro, E., La Rosa, D., Mahroo, A., & Spoladore, D. (2019). E-Cabin: A Software Architecture for Passenger Comfort and Cruise Ship Management. Sensors, 19(22), 4978, doi:10.3390/s19224978
- [22] Mataloto, B., Ferreira, J. C., & Cruz, N. (2019). LoBEMS—IoT for Building and Energy Management Systems. Electronics, 8(7), 763, doi:10.3390/electronics8070763
- [23] Delnevo, G., Di Lena, P., Mirri, S. et al. On combining Big Data and machine learning to support eco-driving behaviours. J Big Data 6, 64 (2019), doi:10.1186/s40537-019-0226-z
- [24] Kim, Y., Oh, H., & Kang, S. (2017). Proof of Concept of Home IoT Connected Vehicles. Sensors, 17(6), 1289, doi:10.3390/s17061289
- [25] B. Mishra and A. Kertesz, "The Use of MQTT in M2M and IoT Systems: A Survey," in IEEE Access, vol. 8, pp. 201071-201086, 2020, doi: 10.1109/ACCESS.2020.3035849.
- [26] Machorro-Cano, I., Alor-Hernández, G., Paredes-Valverde, M. A., Rodríguez-Mazahua, L., Sánchez-Cervantes, J. L., & Olmedo-Aguirre, J. O. (2020). HEMS-IoT: A Big Data and Machine Learning-Based Smart Home System for Energy Saving. Energies, 13(5), 1097, doi:10.3390/en13051097