Review of Electrical Architectures and Power Requirements for Automated Vehicles

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***Abstract*—Automated vehicles require sensors and computer processing that can perceive the surrounding environment and make real time decisions. These additional electrical loads expand the auxiliary load profile, therefore reducing the range of an automated electric vehicle compared to a standard electric vehicle. Furthermore, a fully automated vehicle must be fail-safe from sensor to vehicle control, thus demanding additional electrical loads due to redundancies in hardware throughout the vehicle. This paper presents a review of the sensors needed to make a vehicle automated, the power required for these additional auxiliary loads, and the necessary electrical architectures for increasing levels of robustness.**

I. Introduction

Automated vehicles have drawn increasing attention in recent years, where certain companies are pushing automated vehicles into consumers' hands. However, these vehicles are not fully automated, and to reach higher levels of automation, more sensors and systems must be implemented to control the vehicle in all real-world circumstances. The addition of advanced driver assistance systems (ADAS) to a vehicle is a task in itself [1]. A vehicle has limited space for sensors, wiring, power supplies, and computer processors. Additionally, all these new components, added to make a vehicle automated, consume power [2]. While individual sensors might not be large loads, the power drawn by a multitude of sensors can compound to be significant. How the addition of automated driving sensors affects the auxiliary load and the electrical distribution network of the vehicle is the topic of this paper.

Most new studies about automated vehicle systems use an electric vehicle (EV) instead of an internal combustion engine (ICE) vehicle. EVs are inherently easier to control using automated driving sensors and systems, because control is accomplished electrically rather than mechanically [3]. Furthermore, EVs have fewer moving parts than ICE vehicles, which can lead to improved reliability, and government regulations and policies in the U.S. are leading towards an all-EV future [4]. In addition, an optimized EV powertrain in a fully automated transport system only requires one-third of the energy of an equivalent ICE vehicle [5]. Therefore, this paper does not examine the effect of automated systems on ICE vehicles and only considers EVs.

Automated vehicle publications in the academic community have been increasing over the past several years [6]. Within these publications, multiple roadmaps for automated vehicles have been written that address the steps and challenges needed for automated vehicles to become more prominent in specific domains, such as technical, political, or ethical. A roadmap published in 2010 articulated what some of the challenges were, and still are, to commercializing automated vehicles [7]. Another report claims that sensors need a medium to high level of further development for the automated operation of vehicles. These improvements included fault rates in Global Positioning System (GPS) and Light Detection and Ranging (LiDAR) [8]. Automated vehicle commercialization challenges, such as legislation and cultural drivers, were further observed for emergent markets, specifically in Brazil [9]. Other studies were conducted on the architecture of controls and the connection between hardware and software for automated vehicles [10]–[12]. Some automakers have also published reports on their progress in bringing an automated vehicle to market [13], [14].

The remainder of this paper is organized as follows. Section II describes some of the auxiliary electrical loads that are common to electric vehicles. Section III discusses the sensor requirements for automated vehicles and gives examples of those used in industry today. Section IV goes into further detail about one of these automated driving sensors: LiDAR. Sections V and VI then discuss the effect automation has on the power consumption and wiring architecture of an electric vehicle. Section VII gives some measured results for automated driving sensors. Finally, Section VIII summarizes the findings of the paper.

II. Vehicle Electric Loads

Currently, vehicles have a multitude of sensors and electronics that are not directly related to the powertrain of the vehicle, called auxiliary loads. Depending on the size of these auxiliary loads, they can make a significant difference in the range of an electric vehicle. These auxiliary loads include heaters, fans, lighting, power steering, infotainment systems,

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and the air conditioning unit. The heating, ventilation, and air conditioning (HVAC) system is one of the largest auxiliary loads on an EV. Research has shown the HVAC electrical load is highly dependent on the ambient temperature, and HVAC systems can have up to a 35% impact on the range of the vehicle at extreme temperatures [15], [16]. Other research shows the range of an electric vehicle can drop to almost half of its maximum value at temperatures below freezing [17]. Studies have also shown the average auxiliary load of an EV is slightly above 1 kW when the ambient air is between 60–75°F. It can be inferred from these references that at least 500 W of auxiliary load are used for HVAC on average, and the remaining auxiliary loads consume around 500 W of power, independent of ambient temperature. The absolute minimum auxiliary load required to keep a standard non-automated EV operating was reported to be approximately 200 W [18].

Additional auxiliary power will be needed to supply energy to sensors and computer processors for an automated vehicle to drive. Fig. 1 shows a general wiring diagram of an EV. The HVAC is connected directly to the high voltage battery due to its large voltage input and potential power demand. All other auxiliary components, including additional auxiliary loads used for vehicle automation, are powered by the 12 V bus running throughout the vehicle or by a DC/DC converter connected to the 12 V bus. The 12 V bus must have sufficient charge to engage the relays and connect the high voltage battery to the motor drive to start the EV. The additional auxiliary loads used for automation are listed with an asterisk in Fig. 1 and will be discussed in the next section.

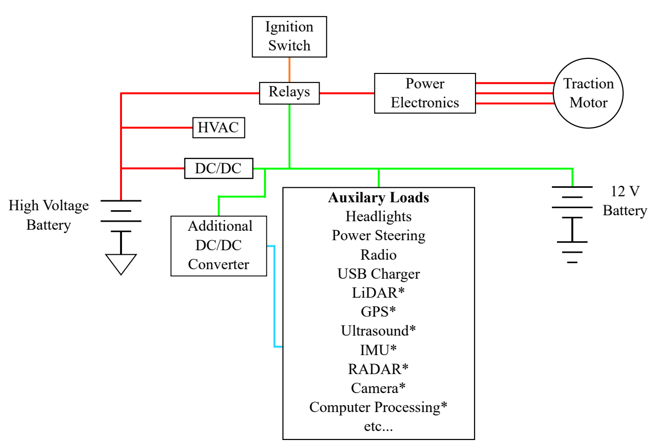

Fig. 1. Electrical wiring diagram of an automated EV.

III. Sensor Requirements for Automated Vehicles

The Society of Automotive Engineers (SAE) defines six levels of automation in their standard titled "Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems," shown in Table I [19]. As the level of automation increases, the number and complexity of sensors also increase. However, once level 3 automation is reached, the number of sensors no longer needs to increase from a functionality standpoint. The only changes in moving up to levels 4 and 5 are what/who is the back-up system and the circumstances in which the vehicle can operate, respectively. Monitoring the driving environment is the responsibility of the automated driving system starting at level 3.

Most automated vehicle laws in the United States are at the state level, and these laws acknowledge and allow testing of automated vehicles [20]. Audi announced in 2017 that the 2018 Audi A8 would be the first production level 3 automated vehicle to be commercially available. However, the vehicles sold will not come with all of their level 3 features enabled and will wait for laws and regulations to catch up to the technology. Currently Audi claims that if level 3 automation were to be enabled, their company would be responsible and liable for the vehicle's actions [21]. There are several more issues that need to be further addressed before highly automated vehicles can be commercially available. For now, companies are merely following their own judgment, along with standards and policies, to determine sensor placement and distribution [22]. Some researchers have addressed this issue and created testing and evaluation approaches for highly automated vehicles [23]. There is no formal process by which a vehicle is deemed safe to operate at a particular level of automation. Because of this lack of regulation, some companies believe that certain components, such as LiDAR, are not necessary to become fully automated.

Fig. 2 presents an example of the specialized sensors that could be used for automated vehicles at level 3 of automation or higher [24]. As shown in Fig. 2, the sensors used in automated vehicles are: cameras, LiDAR, Global Navigation Satellite System (GNSS) or GPS, Inertial Measurement Unit (IMU), and Radio Detection and Ranging (RADAR). Cameras, LiDAR, and RADAR are used to avoid collisions with other vehicles, pedestrians, and the environment, while GPS and IMU are used for navigation of the automated vehicle. A computer is added to the vehicle to receive and interpolate the data collected by the sensors and to drive the vehicle. Table II lists detailed information of the sensors shown in Fig. 2.

Several companies have a different number of sensors in addition to a variety of placements throughout the vehicle. General Motors, in their 2018 Self-Driving Safety Report, shows the Cruise AV to have 5 LiDARs, 16 cameras, and 21 RADARs [13]. On the other hand, Waymo, in their 2017 safety report, claims to have 3 sets of LiDAR systems, a vision system mounted on the top of the vehicle, and 1 RADAR on each corner of the vehicle, for a total of 4 RADARs [14].

A. Vehicle Communication

Vehicle to vehicle (V2V) communication is a protocol of short range communication, where two vehicles can provide each other information, such as vehicle speed and GPS coordinates [25]. This type of communication, when extended to other devices, such as stop lights or communication towers, is known as vehicle to everything (V2X). When an automated vehicle is on the road, a clear picture of its surroundings should be formed. This image is generated by a computer receiving data from automated driving sensors, but some details could

TABLE I
SAE DEVELOPED LEVELS OF AUTOMATED DRIVING [19]

SAE Level	Name	Execution of Steering and Acceleration/Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
0	No Automation	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	System	Human driver	Human driver	Some driving modes
3	Conditional Automation	System	System	Human driver	Some driving modes
4	High Automation	System	System	System	Some driving modes
5	Full Automation	System	System	System	All driving modes

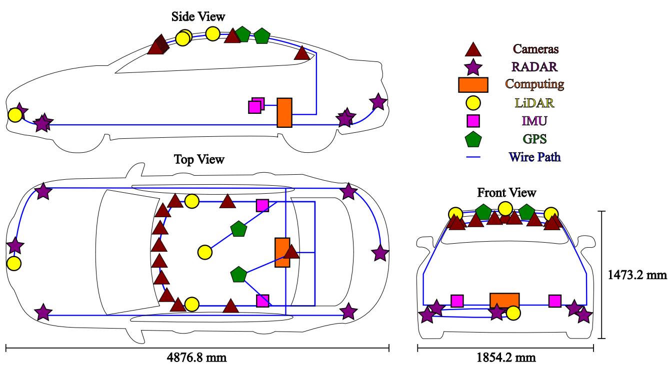

Fig. 2. Diagram of the sensors and wiring paths required for an automated vehicle.

TABLE II
SENSOR POWER REQUIREMENTS FOR AN AUTOMATED VEHICLE

Sensor	Power (W)	Amount	Total Power (W)
LiDAR			
(Velodyne VLP-16)	8	2	16
(Velodyne HDL-32E)	12	1	12
(ibeo LUX 4L)	8	1	8
RADAR			
(Delphi ESR 2.5 24V)	18	2	36
(Delphi SRR2)	7	4	28
IMU with GNSS			
(NovAtel IMU-IGM-S1)	7	1	7
(Xsens MTi-G-710)	<1	1	≈ 1
Computer			
(Nvidia Drive PX)	80	1	80
Camera			
(Sekoix SF332X)	<1	11	≈ 11
Total			199

be added to make the image clearer by communicating with the other vehicles on the road. A drawback of this technology is that each vehicle must contain this system in order to communicate. Thus, until more vehicles possess this V2V or V2X technology, it should not be considered a reliable method to detect a vehicle's surroundings. AT&T, Delphi, and Ford are developing and testing V2X modules to communicate with other vehicles and possibly other devices in smart cities [26]. V2V modules have been included in some vehicles, such as the Cadillac CTS, since 2017 [27].

IV. LIGHT DETECTION AND RANGING

LiDAR is a sensor used to detect the presence of objects around the vehicle, so the computer can interpret the vehicle's relation to its surroundings. LiDAR accomplishes this task by emitting an infrared laser beam and measuring the time it takes for the reflection to return once the beam strikes an object. However, there are several inherent problems with LiDAR from both an optical and power point of view. In this paper, only the power issues will be discussed, and probable solutions will be considered.

LiDAR sensors require a large, quick current impulse to generate high distance resolution data, which could cause an increase in ripple on the DC bus [28]. Fig. 3 shows a simple schematic of a LiDAR circuit and waveforms. When the FET is turned on, the small capacitor is effectively shorted to ground though the laser diode, causing a large spike in current. This current spike should have a very high slope and amplitude in order for the laser beam to turn on almost instantaneously. If the incident beam is sharp, then the reflection will be as well. This quick turn on means that the LiDAR system will have a higher resolution of depth. If using the topology shown in Fig. 3, the key to having a quick current impulse lies with the FET selection. This provides an excellent application for wide-bandgap (WBG) devices, specifically Gallium Nitride (GaN), whose fast turn on and turn off times can improve resolution. Other new topologies are also dependent on fast switching [29]–[32]. An example of how a LiDAR sensor sees its surroundings is shown in Fig. 4.

V. POWER AND RANGE OF VEHICLE

The total power required for a mid-size sedan to reach a high level of automation with the setup shown in Fig. 2 is almost 200 W, as shown in Table II. Although only one design is shown in this paper, most other automated vehicle sensor layouts are around 200 W and only make minor adjustments, such as replacing RADAR with LiDAR on the front and rear of the vehicle and utilizing different cameras. The main additional electrical load for an automated vehicle is the computer, and the computer is one of the main stepping points between levels 3-5 of automation, due to the need to handle more real-world circumstances and also be fail-safe. Most companies do not

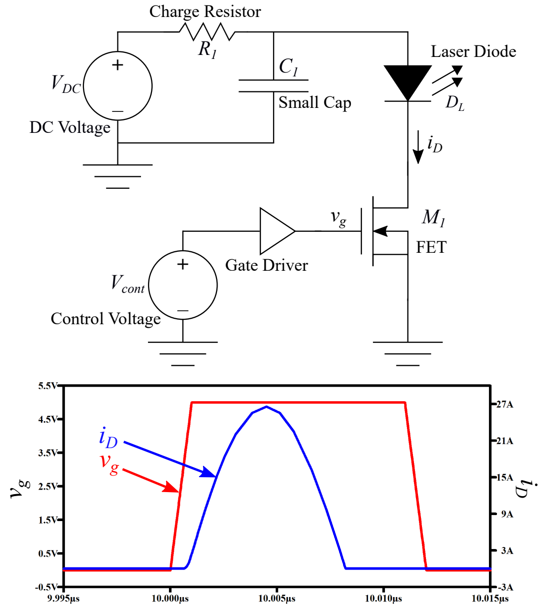

Fig. 3. LiDAR circuit schematic and waveform of one laser pulse. When the threshold voltage is applied to the FET, the small capacitor is shorted to ground causing a current spike that emits a laser pulse via the laser diode.

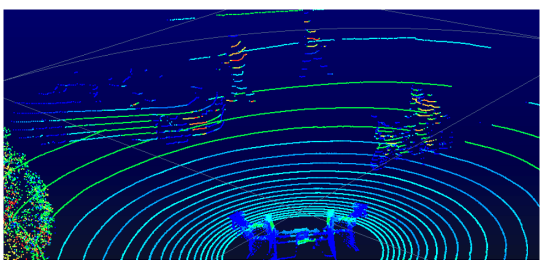

Fig. 4. LiDAR output graphic of a parking lot at Oak Ridge National Laboratory.

release the electrical power requirements of their computer packages, while others speculate the power demand will be at least a few kilowatts, thus making comparisons difficult. Therefore, this section will focus mainly on the sensors and the total estimated power consumption of an automated EV from the data provided.

Passenger entertainment loads are also expected to increase for fully automated vehicles. For higher levels of automation, when a person is not responsible for monitoring the environment or fallback performance of the automated vehicle, it is reasonable to assume passengers will want to be on electronic devices while they are waiting to arrive at their destination. These additional loads, such as a laptop or entertainment system, can range from 50–100 W in some cases. Therefore, two or three of these passenger-induced loads could double the amount of power calculated in this paper to have a highly automated vehicle.

As stated in Section II and shown in Fig. 1, all additional sensors for automation are connected to the 12 V bus or a DC/DC converter connected to the 12 V bus. This architecture could potentially cause concern in the reliability of an EV. The addition of the automated driving sensor loads could increase the total load on the 12 V battery bus by almost 50%. Though the 12 V battery is continuously charged by the high voltage battery through a DC/DC converter, the vehicle is still reliant on the 12 V battery to start. These additional loads could reduce the life of the battery and have a small but significant impact on the overall range of an EV. Though the HVAC will have a greater impact on the range of an automated EV, the addition of automated vehicle sensors could impact the range of an EV by 2–3% [15].

VI. Wiring Architectures

Wiring is vital to the reliability and operation of automated vehicle sensors. Sensors require both power and communication wiring that must be well protected to avoid interference. Some sensors use Controller Area Network (CAN) messages, while others have a very high data stream, such as LiDAR, which require separate auxiliary power and Ethernet connections.

A typical large, non-automated sedan can have up to 3657 m of wire weighing over 50 kg [33]. Assuming the layout of Fig. 2 for a mid-size sedan, the total amount of additional wiring is around 85 m. However, after considering RADAR and LiDAR need separate power and communication wires, the total length becomes almost 122 m. This length still does not consider the additional power distribution that would be needed for several components on both the front and rear of the vehicle or the required connection for the computer to control the vehicle. Furthermore, this does not take into consideration the fail-safe requirement of level 5 automation. For example, if the vehicle suddenly loses one of its main communication or power lines to a set of sensors or the computer processor, the system would need to have enough redundancy to safely bring the vehicle to a complete stop out of danger. The practice of overlapping critical components has already been adopted in another form of transportation where failure of one of these components could result in fatal consequences: airplanes. Most aircraft have multiple sensors and components, as well as double and triple redundancies for flight critical systems and controls throughout the plane. Other applications that require this level of redundancy include server farms and microgrids. The following subsections describe some of the power architectures and a comparison between their cost and ability to remain fail-safe.

A. Central Power and Computing Source

The first and simplest power architecture contains the computational power and electrical power within a single space in the vehicle, as shown in Fig. 5. In this configuration, the high voltage battery, low voltage battery, and computation hardware all lie in the same general space within the vehicle. The configuration could allow for redundancies within the localized computing and power space; however, this design falls short of being fail-safe due to the central positioning of all critical power, computing, and control resources while not providing power and control redundancies to the sensors.

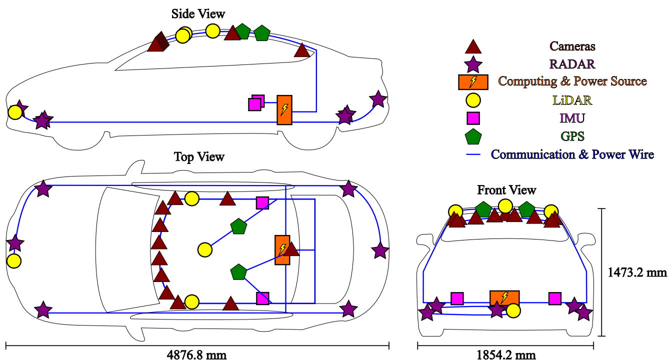

Fig. 5. Diagram of the sensors and wiring paths required for an automated vehicle.

B. Distributed Power Sources

Another solution that could be implemented to distribute power to the automated vehicle sensors is to have two separate 12 V batteries on either end of the vehicle. General Motors has mentioned using this technique and shows multiple power sources for sensors in their automated vehicle [13]. The topology shown in Fig. 6 could function similarly to the grid. A few power sources are scattered across a region with multiple loads assigned to each energy source. In the event that an energy source is no longer operational, redundancies are in place to allow the other sources to compensate for the dysfunctional power source or wire. To be complete, there would also need to be a redundancy in communication lines between a centralized or distributed computing system and the automated driving sensors. Power sources are scattered throughout the vehicle, which would require additional costs and wiring. However, this configuration is more fail-safe than the centralized configuration due to its redundancies.

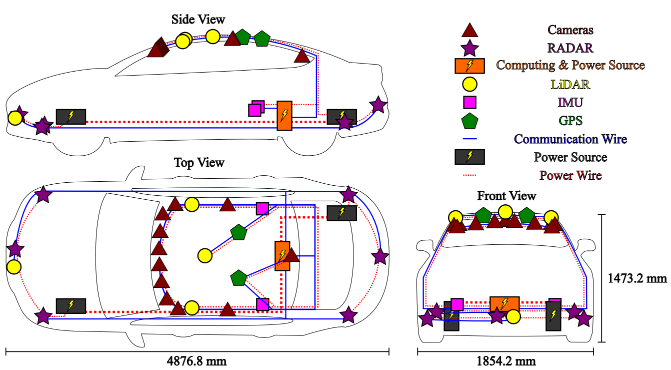

Fig. 6. Diagram of the sensors and wiring paths required for an automated vehicle with two separated power sources.

Another approach is to have two separate low voltage power sources, as in the last approach, with a small amount of energy storage located next to each sensor, as seen in Fig. 7. This would enable the sensors to operate even if there is a wire fault in the immediate vicinity of a sensor. A sensor could then operate independent of any physical connections for a short amount of time while the vehicle could divert to a safe location to further analyze a disturbance in the vehicle. Powering the sensor is only part of the challenge—data must still be transferred between the central computer and the sensors in order to obtain positioning information. This could be accomplished by wireless communication. The additional power sources, along with wireless communication, would add to the cost of the system; however, it would make the system more fail-safe.

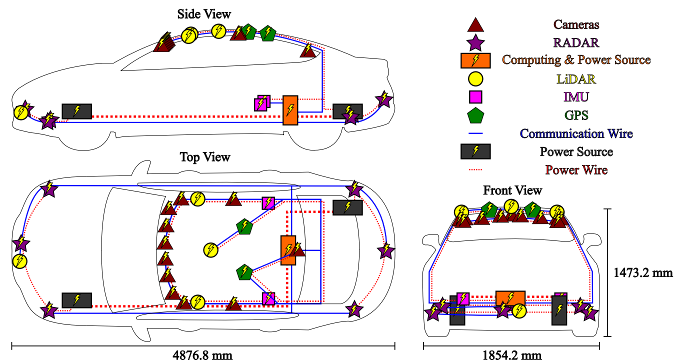

Fig. 7. Diagram of the sensors and wiring paths required for an automated vehicle with two separated power sources and backup power sources located with each sensor indicated by yellow lightning bolts.

VII. Sensor Power Measurements

To confirm the data sheet power consumption values for the sensors shown in Table II, a test bench platform was built to test the power requirement for some of the automated driving sensors and determine if they had any effect on the 12 V bus. The results are shown in Table III.

TABLE III
Sensor Power Requirements Data Sheet vs Measured Results

Sensor	Data Sheet Power (W)	Measured Power (W)
LiDAR		
(Velodyne HDL-32E)	12	10.1
RADAR		
(Delphi ESR 2.5 24V)	18	10.8
(Delphi SRR2)	7	5.4
IMU with GNSS		
(NovAtel IMU-IGM-S1)	7	4.8

As stated in Section IV, LiDAR was initially discussed as a concern due to its high sampling rate and fast, high current pulses. However, experimental results show that the voltage harmonics on the DC bus did not pose an issue. This was likely due to a good filtering system designed by the manufacturers. Other measurements showed slightly lower power consumption compared to data sheet values. In addition, measurements taken on RADAR and LiDAR sensors indicated their power consumption does not vary significantly when objects are moving around them. For example, the power is constant if there are multiple moving objects or if all objects are stationary around the LiDAR sensor. Moreover, the IMU with GNSS did not vary significantly while the vehicle was moving.

VIII. Conclusion

Automated vehicles are now being rapidly pushed into consumers' hands. However, there are still many steps that need to be taken before full automation will be implemented on roadways. This paper reviewed some of the major requirements for a vehicle to reach a high level of automation. The basic sensor requirements have been discussed and presented for different levels of automation, as well as the impact vehicle automation could have on the auxiliary power, reliability, and range of the vehicle. The wiring architecture necessary to power these additional automated vehicle sensors has also been discussed, and consideration has been given to communication and power wires along with potential hardware fail-safe measures. Moreover, sensor measurements were compared with data sheet values, and inferences were made about the effect of sensors on the 12 V bus. Highly automated vehicles still need improvement from an sensor, legislative, and computing standpoint before they become a commercial method of transportation.

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