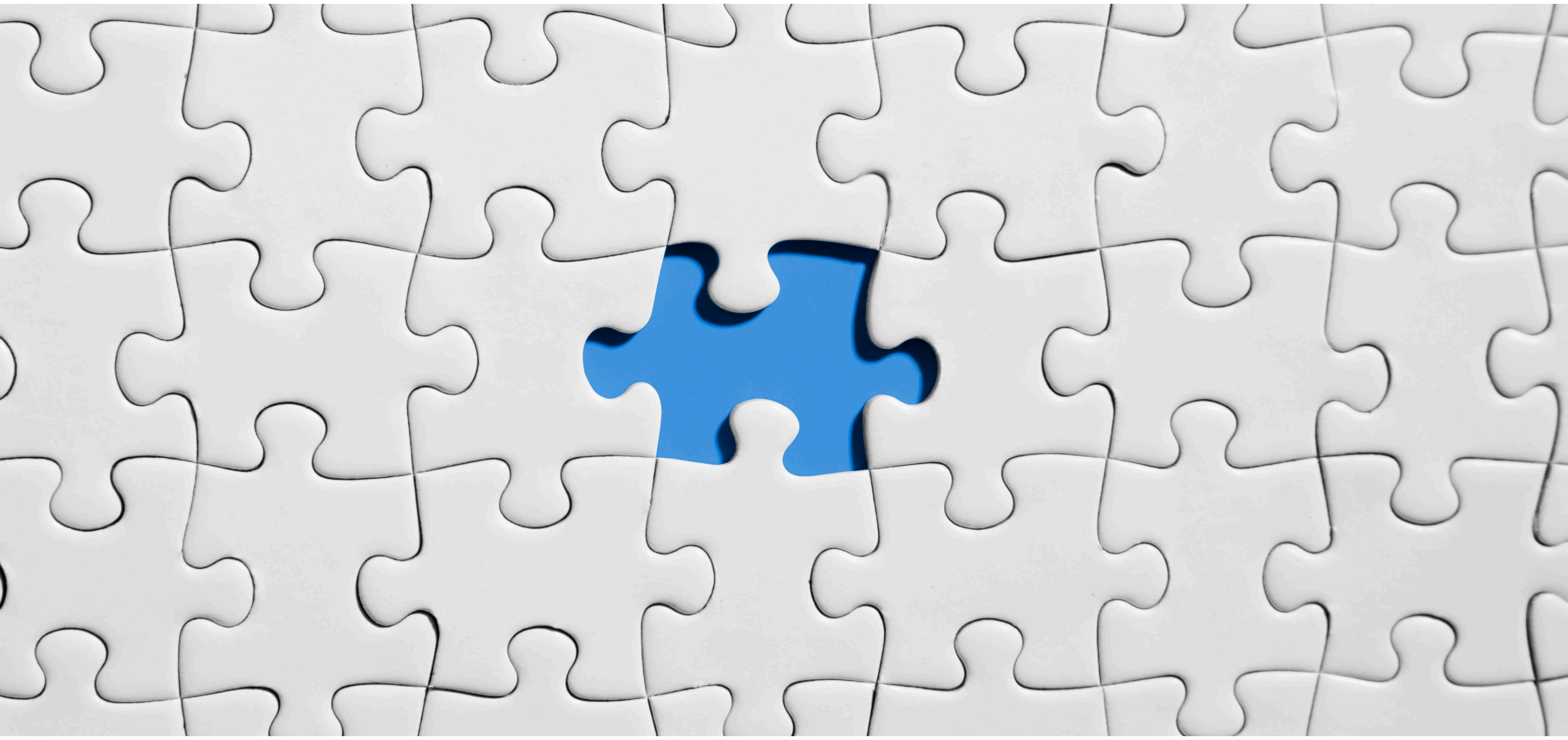
HOW COMPUTER SCIENCE HELPS CAR TECHNOLOGY



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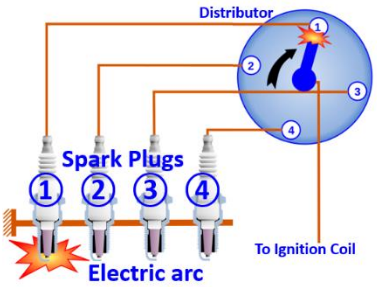
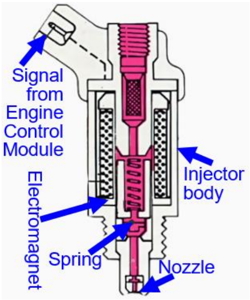
Introduction

My wife Alice and I were driving down the road in our 2012 Chevy Malibu when we heard a strange scraping noise coming from the back of the car. That’s how this paper began. I wanted to ask my steering wheel’s Chevy logo “What’s that sound? Is it serious?”. However, my decade-old car lacked an embedded Alexa-type expert personal assistant to troubleshoot mechanical issues.



Up through the late 1960s, cars were almost purely mechanical. Turning the ignition key directed a high voltage through the center of a distributor cap to an enclosed rotating arm, completing a circuit with each spark plug. As the rotor made contact inside the cap, it channeled the coil’s voltage to the next sequenced spark plug causing it to ignite a vaporized air/fuel mixture in the cylinder that pushed the piston down. The further the gas pedal is pressed, the faster the distributor’s rotor arm would turn, and the more fuel that would be sent to each cylinder. Basic technology.

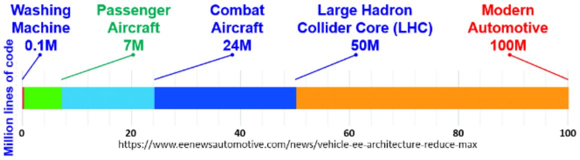
The oil crisis of 1973 and 1979 raised the price of oil from $3 to $40 a barrel, prompting manufacturers to gradually increase vehicle fuel economy by reducing vehicle weight, using lower horsepower engines, improving transmissions, revamping designs to be more aerodynamic, lowering tire rolling resistance, and other mechanical changes. The major fuel economy improvement came from the incorporation of the microprocessor into automobiles.



Digital ignition distributors emerged in the mid-1970s and the carburetor was eventually replaced by computer-controlled fuel injectors as shown to the right.[1] As predicted by Moore’s Law, car computers got more powerful and smaller, allowing for advanced engine monitoring and control. It resulted in cleaner emissions, higher-performance, improved dependability, and better fuel-efficiency. The microprocessor orchestrated spark plug cylinder firing with a sensor-adjusted air-fuel mixture by leveraging fuel quality, engine temperature, exhaust oxygen, and how much pressure is applied to the gas pedal circuit.

Today’s vehicles rely on programmable circuits for Light Detection And Ranging (LiDAR) anti-collision and braking safety, navigation, climate controls, cloud-telematics, infotainment, degrees of automation, and more. It has also introduced practical hybrid and all-electric cars and trucks.

To support this rapid microprocessor evolution, vehicles need a complex set of interconnected specialized embedded data processing computers. **Automotive computers** are supported by 10 to **100 million lines** of highly-reliable software code.[2] In comparison, a **Boeing 787 passenger jet** needs just **7 million lines of code**. An embedded system uses a programmable microprocessor. It is not a general-purpose desktop PC since it lacks a traditional motherboard and does not permit expansion or component replacement.



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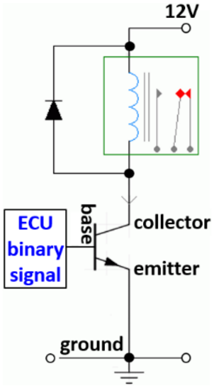
These networked processors are typically called Electronic Control Units (ECUs). They collect signal feedback from hundreds of sensors and communicate with other ECUs. Many sensors report analog voltage levels, such as 0.5 volts, requiring the ECU to perform an analog-to-binary value conversion. The processed data and information allow the ECU to issue commands to actuators and send data to other ECUs. For example, the engine temperature is analyzed to ensure proper combustion and exhaust oxygen allowing the catalytic converter to work properly. Another example is the 12-volt radiator fan. In this fan circuit diagram, 0.5 amps are needed to activate the relay, so the ECU sends a **binary signal** to a power transistor, triggering the 12-volt relay and providing a high amperage to the fan.



Modern cars and trucks require less maintenance and have become more dependable, allowing us to rely on them as an appliance. This is not the experience a PC user has, nor is a problem “repaired” by rebooting it or waiting for a monthly code upgrade.

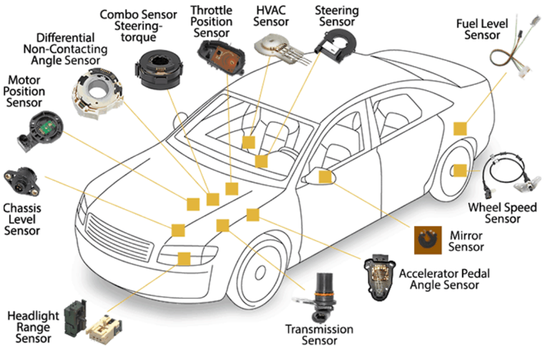
This paper covers a variety of car computing topics such as how microprocessors are used in cars, how they differ from your PC, how they are programmed, and the future of car computing.

NOTE: The automotive community’s rich set of acronyms are listed at the end of the paper.

Electronic Control Units

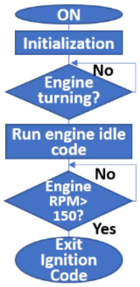
The Basis of an ECU - What happens when you turn the ignition key?

The ignition switch or push button has two main settings – **ON** which turns on the electronics and **START** which cranks the engine. **ON** powers up the ECU which begins working on instructions programmed at the factory and stored on the module in non-volatile flash memory. This is similar to how a PC boots by first loading a bootstrap program from its BIOS/UFEI.

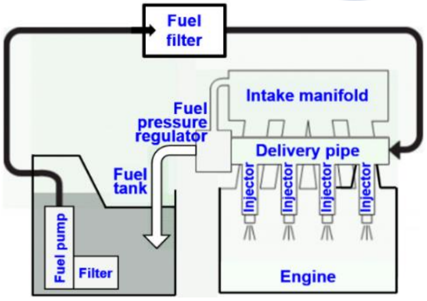


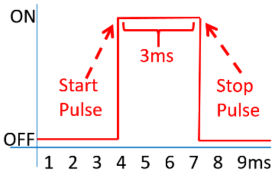
With the ignition in the **START** position, the starter motor begins turning the engine's crankshaft that triggers the process to run the engine. Relevant sensors such as this coolant temperature sensor store digital values in specific addresses in volatile ECU memory. The illustration to the left shows a modern car can have dozens to hundreds of sensors that monitor important functions and generate tens of thousands of status messages.[3]

ECUs monitor every sensor, including engine revolutions, programmatically looping on "**Is the engine turning?**" as shown in this flowchart. When the ECU determines the engine is turning, it runs flash-memory "engine idle" code. When the revolutions reach about 150 RPM, the ECU executes the next section of code getting the engine to 600 RPM through the injecting fuel and spark plug firing routines (not shown).



The amount of time each fuel injector dispenses fuel is stored in a factory lookup table developed during the engine's design. The time is communicated by the length of a pulse width measured in milliseconds (ms) and can be about 3 ms, increasing as more fuel is required for even higher RPM.[4] The spark plug timing is based on the position of the piston and crankshaft angle as reported by the crankshaft rotation sensor to ensure optimal fuel-air detonation.

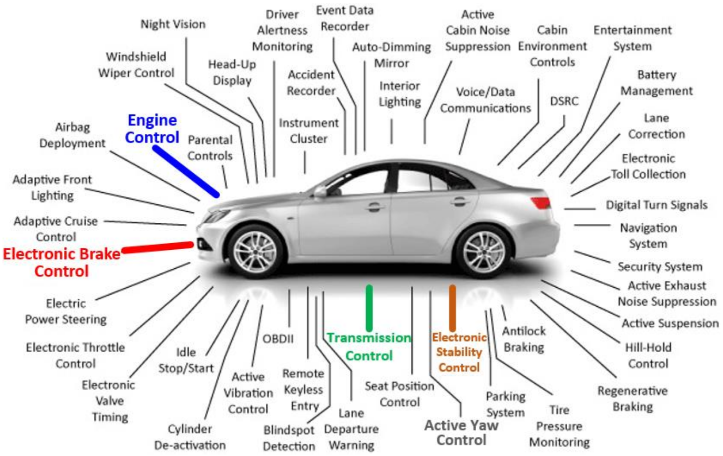




Modern cars can have over 100 ECUs running code for safety, ride handling, and more. They are programmed in C, C++, or any modern language that supports a Real-Time Operating System as specified by the 180-member AUTomotive Open System ARchitecture (AUTOSAR).[5] Other less critical systems such as the infotainment ECU can run Linux or Windows, and programmed in popular programming languages such as JAVA. This sample C++ code section shows how the **three gravity (G) values** are retrieved from an Intel-based Lanier ECU vehicle management computer that receives data from an Analog Device **ADXL345** Digital Accelerometer sensor.[6]

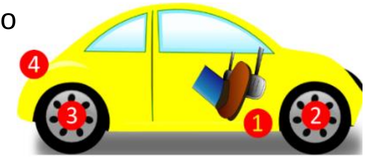
```
// main.cpp
// The adxl345.exe shows the 3 axis G value.
#include <winsock2.h>
#include <windows.h>
#include <stdio.h>
#include "ich7.h"
#include "adxl345.h"
void adxl345_init()
{
ich7_SM_WriteByte (0x1D, POWER_CTL, ACT_INACT_
SERIAL | MEASURE); // Power CTL:
Measure mode, Activity and Inactivity Serial
ich7_SM_WriteByte (0x1d, BW_RATE, RATE_100); //
Output Data Rate: 100Hz
ich7_SM_WriteByte (0x1d, DATA_FORMAT, FULL_
RESOLUTION | DATA_JUST_LEFT | RANGE_16G); //
Data Format: 16g range, right justified, 256->1g
}
int main(int argc, char* argv[])
{
adxl345_init () ;
while (1)
{
short x = (short) ich7_SM_ReadByte
(0x1d, DATAX1) << 8 | ich7_SM_ReadByte (0x1d,
DATAX0)<<0 ;
short y = (short) ich7_SM_ReadByte
(0x1d, DATAY1) << 8 | ich7_SM_ReadByte (0x1d,
DATAY0)<<0 ;
short z = (short) ich7_SM_ReadByte
(0x1d, DATAZ1) << 8 | ich7_SM_ReadByte (0x1d,
DATAZ0)<<0 ;
printf ("\rX=%.2f Y=%.2f Z=%.2f", ((float)
x)/2048,((float)y)/2048,((float)z)/2048) ;
}
}
```

What is an ECU?



A vehicle has many specialized embedded ECUs such as the **Engine Control Module** (**ECM**) to control engine timing, **Electronic Brake Control Module** (**EBCM**) which reads the anti-lock braking and traction control sensors, and **Transmission Control Module** (**TCM**) which interprets dedicated change gear sensors.[7] **Electronic Stability Control** (**ESC**) improves stability algorithmically by detecting and reducing traction loss through speed sensors on each wheel, steering wheel position, and actual vehicle path by sending control sequences to individual brakes through the **EBCM**. An ECU generally runs a single application and is responsible for the algorithmic processing of sensor inputs.

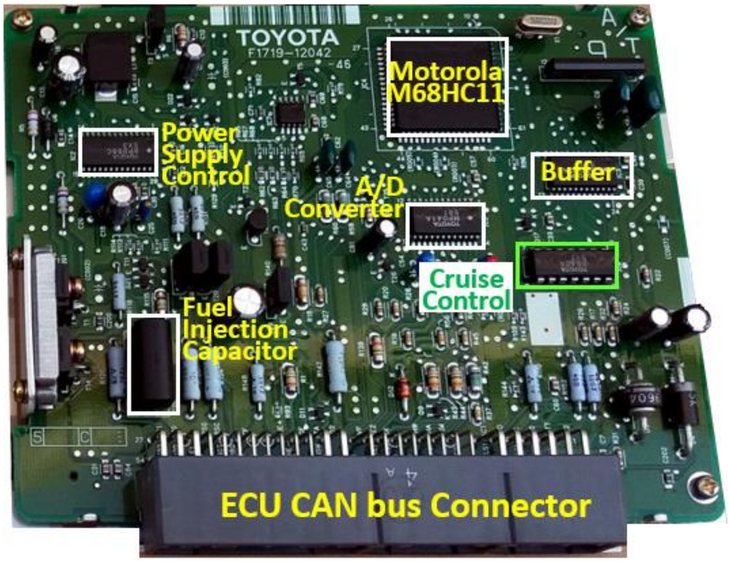
In this example, pressing the brake① causes four **brake modules** to sense the pedal pressure and calculate how tightly the front② and rear③ calipers should compress, and turn on the brake lights④.



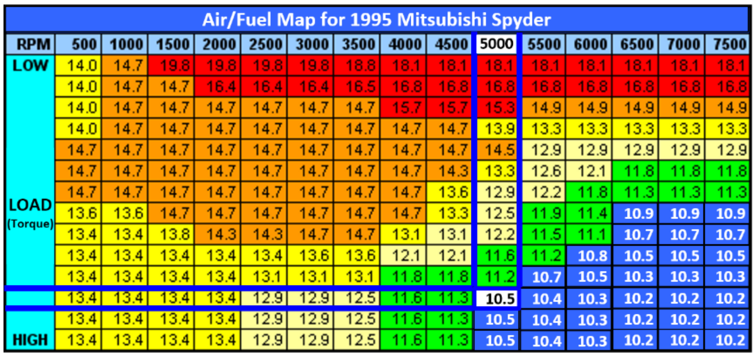
ECUs broadcast Controller Area Network (CAN bus) data packets to other ECUs over a dedicated internal automobile network. They are made by companies you may not be familiar with such as Bosch, Delphi, Denso, and others. ECUs perform millions of calculations on specific sensor inputs to coordinate the activity of pneumatic, hydraulic, and electronic actuators responsible for producing an action or mechanical motion. Its popularity can be traced to the need to reduce CO_2 emissions, improve fuel efficiency, and the creation of hybrid and electric vehicles. They perform calculations just like a PC, but they respond to the driver's steering wheel, brake and gas pedal pressure, infotainment requests, and other switches in the vehicle.

ECUs with an old 32-bit 40 MHz CPU and 1-2 megabytes of memory amazingly monitor and control in real-time the electronic fuel injection or anti-lock brakes that receive wheel sensor inputs every few milliseconds.[8] In contrast, a 64-bit PC's CPU operates at ~3 GHz with gigabytes of memory. ECUs must maintain high availability since a PC's "blue screen of death" at 60 mph could be disastrous. ECUs typically operate on small sections of specialized code, often cycling through the same code every few milliseconds, and the code they run differs greatly, such as with a Power Windows or Parking Assist ECU.[9]

At a high level, an ECU can have analog-to-digital converters for sensors with output voltages, digital-to-analog conversion for components that need input voltages, a transceiver for the CAN bus, a power supply, actuator drivers, high-power amplifiers, and bridges to enable a DC motor to run forward and backward for use in windshield wipers, convertible top motors, etc.[10]



Here is an ECM from an old Toyota Corolla that uses many of those items. This vintage car maintains discrete functions in small processors, such as the one for the **Cruise Control**. It still uses an 8-bit Motorola 6800 family 68 pin processor with 24K bytes of user ROM, 768 bytes RAM, and 640 bytes of EEPROM.[11] ECMs are shielded in a thermal metal case that protects them from extreme temperature swings of 125°C hot desert/engine temperatures and winter weather of -40°C.[12] The case also protects against engine vibration, moisture and salt spray from the road, oil and fuel exposure, and acts as a heat sink. The controller guards against voltage dips and surges from a weak battery or an alternator power spike. It can be mounted under the hood on the firewall or in the cabin under the dashboard and attaches to the CAN bus with a multipin wiring harness.



Air/Fuel Map for 1995 Mitsubishi Spyder

RPM	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500
LOW	14.0	14.7	19.8	19.8	19.8	19.8	18.8	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1
	14.0	14.7	14.7	16.4	16.4	16.4	16.5	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
	14.0	14.7	14.7	14.7	14.7	14.7	14.7	15.7	15.7	15.3	14.9	14.9	14.9	14.9	14.9
	14.0	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	13.9	13.3	13.3	13.3	13.3	13.3
	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.5	12.9	12.9	12.9	12.9	12.9
	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.3	13.3	12.6	12.1	11.8	11.8	11.8
	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	13.6	12.9	12.2	11.8	11.3	11.3	11.3
LOAD (Torque)	13.6	13.6	14.7	14.7	14.7	14.7	14.7	14.7	13.3	12.5	11.9	11.4	10.9	10.9	10.9
	13.4	13.4	13.8	14.3	14.3	14.7	14.7	13.1	13.1	12.2	11.5	11.1	10.7	10.7	10.7
	13.4	13.4	13.4	13.4	13.4	13.6	13.6	12.1	12.1	11.6	11.2	10.8	10.5	10.5	10.5
	13.4	13.4	13.4	13.4	13.1	13.1	13.1	11.8	11.8	11.2	10.7	10.5	10.3	10.3	10.3
	13.4	13.4	13.4	13.4	12.9	12.9	12.5	11.6	11.3	10.5	10.4	10.3	10.2	10.2	10.2
	13.4	13.4	13.4	13.4	12.9	12.9	12.5	11.6	11.3	10.5	10.4	10.3	10.2	10.2	10.2
HIGH	13.4	13.4	13.4	13.4	12.9	12.9	12.5	11.6	11.3	10.5	10.4	10.3	10.2	10.2	10.2

This Expert System ECU uses an EEPROM value table to know exactly how long the fuel injector needs to stay open at each RPM level. Factory programmed, engine load (torque) is the left axis with an RPM horizontal axis as shown in this example from a 1995 Mitsubishi Spyder.[13] Numbers are the duration a fuel injector must open in milliseconds, so 10.5 ms at 5,000 RPM under moderate-high load. Manufacturers typically use proprietary programming in each exclusive ECUs, and it is not uncommon to find code differences between levels of car trim of the same model such as the base car and the sports version.

Other types of ECUs

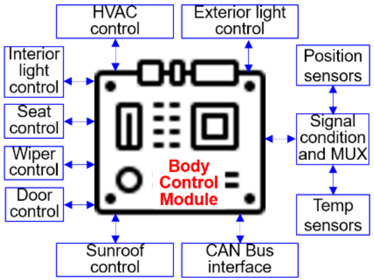
We touched on some of the capabilities of one Electronic Control Unit called the Engine Control Module which receives sensor input to send commands to various engine actuators. ECUs communicate with each other without regard to RAM, ROM, or processor type.[14]

All of these units are critical to the car operation, especially the transmission's TCM. Decades ago, the industry moved away from pure hydro-mechanical transmissions to ones that operate electronically. TCMs are programmed to handle all aspects of the transmission based on direct and indirect inputs to the Park-Drive-Neutral-Reverse operations including the gas and brake pedal position, engine torque, wheel speed, and more. It also tracks the cruise control system, monitors the transmission's fluid level and temperature, throttle sensor information, and other modules. All that information allows the module's logic to precisely and efficiently shift gears by sending signals to the transmission actuator, the torque converter clutch allowing it to spin at the same rate as the engine, and more.

This Denso TCM is found in Fiat's Abarth 500 and various Toyota/Lexus models and uses an NEC 208 pin CPU. Each ECM manufacturer designs the controller and selects components based on vehicle requirements. The **black connector** on the far right is the common design element that attaches to the same CAN bus network as other controllers.

Here are a few of the Jeep Cherokee ECUs that communicate with each other on the closed-loop CAN bus.[15] They have different shapes, CPUs, functions, and run different code. Its **Controller Antilock Brakes** (**CAB**) starts hydraulic actuators that circulate master cylinder fluid based on driver pedal pressure and emergency feedback sensors. The **Passenger Door Module** (**PDM**) handles door windows, power locks and mirrors, tailgate lights and motors, and more. In a collision, the **Airbag Control Module** (**ACM**), which monitors braking, engine speed, seat and restraint sensors, throttle position, impact speed, and other factors, signals the appropriate airbag to deploy and at a specific pressure. An important ECU not pictured is the Telematics Control Unit (TCU). Telematics monitors the vehicle's GPS location, ECU diagnostics, and "listens" to CAN bus messages to determine movements and other characteristics.

Compare today’s computerized engineering innovations to that of 40 years ago and you see design changes focused on passenger safety and comfort. A **Body Control Module** (**BCM**) uses sensors and switch inputs to monitor and control interior and exterior lighting, rear defogger, alarms, intermittent windshield, and rear wiper, heated seats, and other cabin functions.



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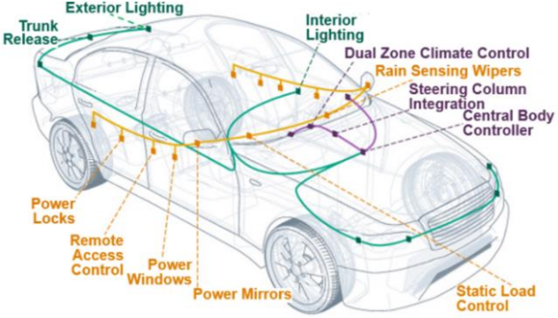
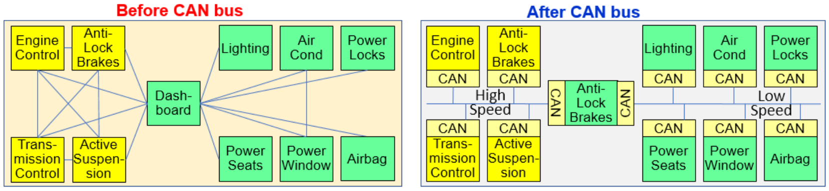
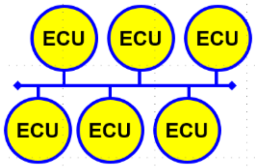


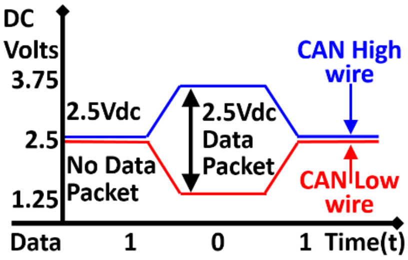
How do ECUs exchange information?

Wiring ECUs together is complicated given their independent design and function (see **Before CAN bus**). With the quantity doubling and tripling since its inception, the cable plant needed is enormous.[16] Enter the automobile CAN serial bus network. It specifically does away with dedicated intra-module point-to-point wiring and allows for software control of the vehicle (see **After CAN bus**).[17] Each connected device includes an electrical interface and a program to decode/encode CAN bus data packets. It is worth noting that other industries used similar high-speed networks in their complex environments such as MilCAN for the military and NMEA 2000 in marine applications.[18]



CAN bus is a centralized error diagnosis and failure prevention digital network that supports many ECUs simultaneously. It is also non-interruptible and uses a low-cost terminated twisted pair cable. A “bus” is a flexible network topology allowing different nodes and modules to connect, communicate, and share data over a common cable. Twisting the cable shields it from electromagnetic interference as electrical noise in one wire is canceled out by the noise flowing in the other wire’s opposite direction.[19] As shown to the left, **CAN high** and **CAN low** at idle carry 2.5 Vdc.[20] When active with a data packet, the **CAN high** wire reaches 3.75 Vdc, and the **low wire** drops to 1.25 Vdc for a binary 0 value and a differential of 2.5 Vdc. A binary 1 has the same 2.5 DC volts on the **high** and **low** wires in the pair.

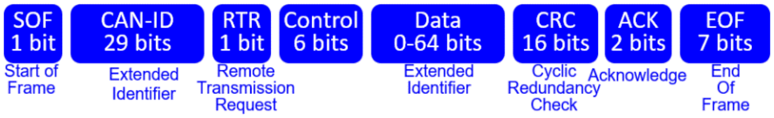




There have been different CAN bus implementations since Bosch first introduced it in the early 1980s. At a high level, it refers to the way electronic modules send and receive data from other modules such as the ECM, TCM, and Anti-lock Brake System (ABS) modules. Various CAN bus networks, which are optimized for real-time automotive control, are popular as well as derivative interconnects such as the General Motors standardized GMLAN.[21]

The CAN bus and others also allow for real-time vehicle issue notification as reported by software in each of the ECUs through the On-Board Diagnostics (OBD-II second generation) interface. A modern Ford Fusion has three high-speed 500kbps buses and one 125kbps medium speed bus, all accessible through the same OBD interface.[22] New vehicles either comes with a CAN bus or another functionally similar system.

As shown in this diagram, a CAN bus message contains eight parts.

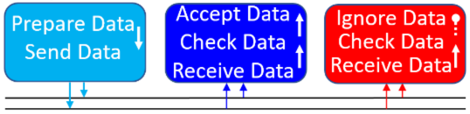


SOF: Start of Frame is a '0', letting all ECUs know a message is starting
CAN-ID: The message priority and address such as a fuel injector, and can be 11 or 29 bits long.
RTR: A Remote Transmission Request allows a "request" a message from another ECU.
Control: 0 to 8 bytes of **Data**
Data: Actual values
CRC: Cyclic Redundancy Check for data integrity
ACK: Indicates if the CRC is OK
EOF: End of message

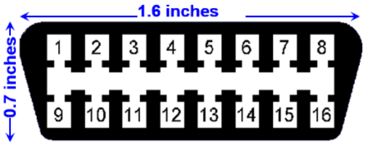
Here are two ECM RPM sample messages from an overall communications flow:[23]

```
ID   CAN Data 8 bytes    Comments
2D0  0000 08 ~~ F2       start engine
2D0  010B 00 ~~ F6       accel pedal on
```

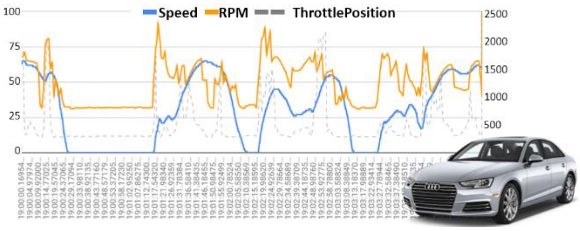
There are some similarities between CAN bus and the PC world's Ethernet protocol. The low-speed CAN bus operates at rates up to 125 kbps and the high-speed CAN bus can reach 1 Mbps with support for 110 nodes per bus.[24] The 3 Mbps Ethernet standard of 1976 supported 256 nodes.[25] CAN-FD reaches 5 Mbps while Ethernet can run at 10- 4,000 Mbps. The CAN bus priority scheme prevents packet collisions allowing ECUs like the ECM to have high priority and the sunroof low priority. ECUs scan for messages with their assigned ID and ignore others.



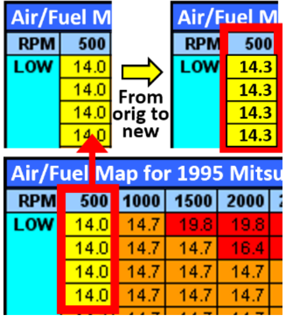
Ethernet originally used Carrier Sense Multiple Access with Collision Detection (CSMA/CD) which dictated retransmission and wait periods for packet collisions.[26] Understandably, it would be dangerous at 60 MPH to have to wait for collision retransmission due to a large number of active ECUs. Modern Ethernet avoids collisions, but the implementation cost is relatively high.



For easy ECU diagnosis and reporting, CAN bus uses an OBD-II 16-pin female pin port. Standard Diagnostic Trouble Codes (DTC) available through the port, identify the vehicle's problem, and turn on the Check Engine light. OBD-II also supplies real-time data on speed, braking, fuel usage, and more, making it useful for telematics. To the left is an Audi A4's OBD-II plotted data for **Speed**, **RPM**, and **ThrottlePosition**.[27]



The OBD-II is also used to reprogram an ECU such as the ECM. Older engines sometimes have performance issues due to increased friction, wear and tear, and other conditions. Engine tuning specialists can attach an OBD-II diagnostic scanner to adjust the factory values with new settings to alter the air/fuel mixture, ignition timing, and idle speed behavior.[28] From our Mitsubishi Spyder example, the air/fuel mixture EPROM data table could be adjusted to 14.3 ms at 500 RPM as shown to the right. Some ECUs can even adjust to a driver's habits, driving conditions, and car health by automatically modifying the stored settings.[29] ECU instructions do not change, just the data used by the instructions.



Air/Fuel M

RPM	500
LOW	14.0
	14.0
	14.0
	14.0

Air/Fuel M

RPM	500
LOW	14.3
	14.3
	14.3
	14.3

Air/Fuel Map for 1995 Mitsu

RPM	500	1000	1500	2000
LOW	14.0	14.7	19.8	19.8
	14.0	14.7	14.7	16.4
	14.0	14.7	14.7	14.7
	14.0	14.7	14.7	14.7

The Influence of Artificial Intelligence on Today's Automobiles

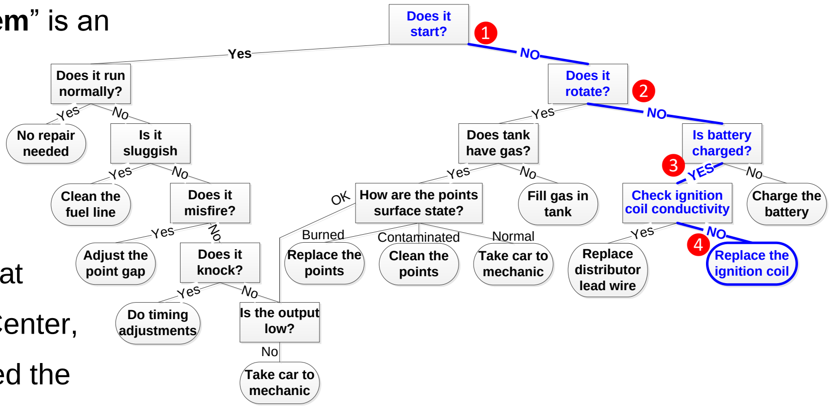
New vehicle features, such as the use of Artificial Intelligence (AI) to help the driver avoid a crash, often necessitate new ECUs. Automobile AI began with an area of computer science called Expert Systems, which helps make decisions as guided by a human expert.[30] Expert systems started appearing in the 1970s using logic rules and facts coded in the LISt Processor (LISP) programming language. They gained notoriety in diagnostic medicine where a patient's clinical data is entered into a system to help a physician prevent, diagnose, and treat a patient.

Here is a simple and powerful example of an expert system for the game of tic-tac-toe. Just seven rules are needed for the computer to have a "tie" or "win" regardless of who goes first:[31]

1. Take **Center**
2. Make 3 in-a-row
3. Block 3 in-a-row
4. Take any **Corner**
5. Take **Corner** next to an open **Side**
6. Take **Corner** next to two open **Sides**
7. Take any available position

Corner	**Side**	**Corner**
Side	**Center**	**Side**
Corner	**Side**	**Corner**

[An online Tic-Tac-Toe game is available at https://archive.org/details/AITIC if you want to play.]



This “**Automotive Expert System**” is an example of a mechanics approach to fixing vehicle issues.[32] Using a C Language Integrated Production System (CLIPS) tool developed in 1986 at the Lyndon B. Johnson Space Center, these rules and functions covered the engine, tires, suspension, headlights, and brakes. This simple repair framework could evolve into a more detailed and model-specific mechanics expert system to help diagnose issues based on customer answers and OBD-II data points, helping to quickly correct an issue.

Here is a segment of the query rules used by this expert system:

```
(defrule determine-problem-type ""
   (not (problem-type ?))
   (not (repair ?))
   =>
   (assert (problem-type
      (ask-question "What is the problem type (engine /tires
/suspension /headlight /brake)? "
       engine tires suspension headlight brake))))
```

In this sample system dialog, the questions are in **blue** and my responses are in **red.** In this case, the system suggests the ignition coil be replaced:

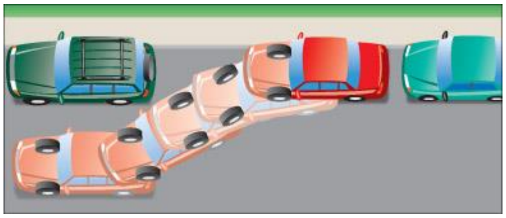
```
Does the engine start (yes/no)? no ①
Does the engine rotate (yes/no)? no ②
Is the battery charged (yes/no)? yes ③
Is the conductivity test for the ignition coil positive (yes/no)? no ④

Suggested Repair: Replace the ignition coil.
```

By adding an Alexa-type voice, the tool could have helped me diagnose my Malibu car problem. For the mechanic, it could suggest an air/fuel mixture change at a certain RPM if the engine was running rough, perhaps available as a data table on the manufacturer's service portal.

Fuzzy Logic Transmission

Fuzzy Logic is another form of AI found in today's vehicles. It uses imprecision to navigate an expert set of rules and logic. Instead of “absolutes” such as IF…THEN…ELSE or YES and NO, fuzzy logic uses adverbs such as **Certainly**, **Possibly**, **Very**, **Surely,** and others along with YES and NO. For example, a positive logic test outcome could be “Certainly Yes” or “Very, Very Cold” while a negative logic branch could be “Certainly Not” or “Possibly No”. Human value-oriented fuzzy logic ultimately maps to results that can be processed by a computer.

A way to remember fuzzy logic is the comparison of shades of grey versus black and white. We employ fuzzy logic in our everyday lives. For example, to parallel park a car, we find a spot that is bigger than our car's length and stop next to the parked car. With the transmission in reverse, we back up until the middle of our car is at the parked car's bumper. We turn the wheel and back up at a sharp angle until we see the front grill of the car behind us. We then straighten out the car. We do not precisely stop the car by applying pounds of brake pedal pressure, and we don't use a tape measure to know when 8½ feet of our car is at half the length of the 17-foot SUV we pulled up to. We do not turn our wheel 42º before applying 0.8 pounds of pressure to the accelerator as we back up, etc.



Depending on the vehicle's manufacturer, fuzzy logic has been employed for the last few decades and is part of the code running in the ECM, TCM, Brake Control Module, and more.[33]

For instance, the TCM tries to learn the driver's habits to algorithmically shift the transmission at more opportune times and smooth out sudden upshifts and downshifts. It uses the same sensor input as a less sophisticated rigid table TCM but instead employs fuzzy logic to modify factory shift patterns based on sensor readings and road conditions. A "heavy foot" driver might have a delayed shift based on higher engine RPMs.

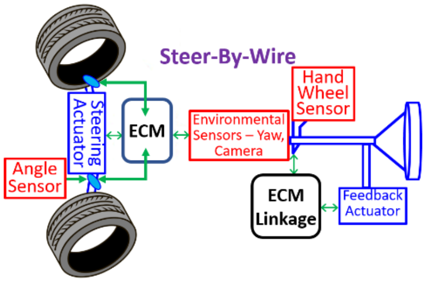
A TCM can also modify its behavior based on engine temperature as reported by the ECM. With a cold engine, it may shift more often to reduce transmission stress which helps it have a longer life, reduce fuel consumption, and improve the passenger experience. It must also reset those modifications to their default values since the vehicle can be shared amongst drivers, changing road conditions, etc.

Let the Car Park Itself

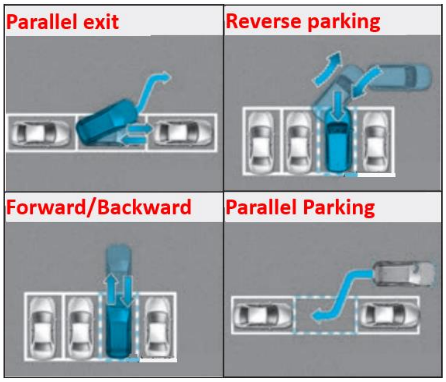
When my son was preparing to get his driver's license, the one thing that scared him the most was the dreaded parallel parking road test maneuver. He found the effort frustrating and humiliating as my car's tires hit the curb. In his mind, he's never going to have to parallel park after he gets his license since we live in the suburbs and stores have parking lots. I told him the practice would help him master the steering wheel, throttle, and brake, but it fell on deaf ears.

We were both amazed years later when his new SUV included a self-park system. Under its sheet metal are front, side, and rear proximity sensors that use LiDAR, cameras, RADAR, and processors to determine if a parking spot is big enough, a driveway, or has obstacles.[34] Using drive-by-wire, Ford's AI system lets the driver know when to shift the transmission, press the gas pedal, and brake. Some systems automatically maneuver the vehicle into a spot.[35]

With **steer-by-wire** systems, commands are sent to an ECU controlled electric motor rather than use direct mechanical connections.[36] Actuators following commands such as an accelerator pedal voltage signal allow a driver to expertly parallel park even if they have limited parking experience. In this illustration, the steering wheel orientation is registered by the **Hand Wheel Sensor.** All **sensors** communicate their reading to the **ECM**. The tires are actuator controlled using steering sensors. The **ECM** controls and monitors the steering rod angle.



Hyundai's **Parking Domain Control Unit** (**DCU**) interfaces with Ethernet networked cameras and ultrasonic sensors to calculate distances to objects. The **DCU** sends navigation commands to the drive-by-wire steering, braking unit, and transmission ECUs, allowing the car to get out of a tight spot as well as for self-parking.[37] Hyundai's Smart Parking Assist, which is activated by the driver, parks itself under AI computer control.[38] When the **DCU** senses an object, it issues a warning and signals the Braking Control Unit (BCU) over the CAN bus to stop the car.[39]

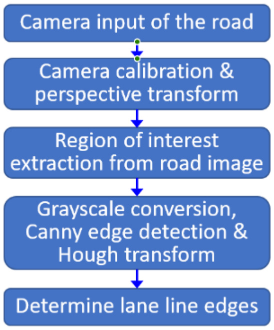


Whereas most drivers would be wary about scraping a parked car's bumper, or nervous in the nighttime rain, these sensors accurately measure the entire effort with real-time visual awareness. It backs up, goes forward, and turns with computer precision in under 24 seconds.[40]

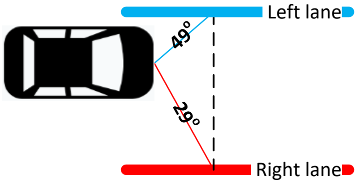
Blind Spot and Lane Departure Warnings

The AI family of lane safety features uses camera vision, proximity sensors on both sides of a vehicle, LiDAR/RADAR, driver behavior, and ECUs. They keep a vehicle within a driving lane, help the driver avoid high-speed accidents, and alert to driver fatigue. In particular, camera images, sometimes triggered by the use of a directional turn signal, are useful to classify objects using AI algorithms. When the algorithm determines another car is in a blind spot, it displays a ▲yellow triangle visual warning in the side mirror, triggers an audible **alert**, and in some cases steers the vehicle away from a possible accident if heading for a collision.

Assuming highway lane markings are not faded or obscured by snow, a Lane Departure Warning System (LDWS) will issue audible and visual warnings if a vehicle veers out of its lane. Digital camera images are processed using Paul Hough's 1959 image identification techniques as shown to the right, and a Gaussian filter to find lanes in an image. [41,42] These algorithms determine the distance from the left and right lanes using basic Euclidean geometry we learned in school to find the distance or angle between two points.

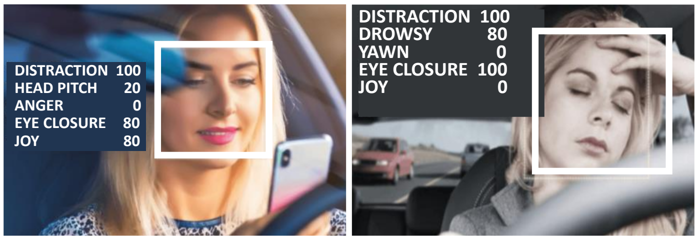


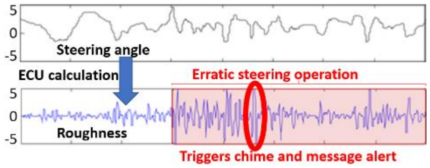
As shown in this illustration, the car has veered too far to the **left lane** as shown by the larger 49^{O} angle measured from the front-center of the car. Two cameras on the front of the vehicle help calculate the distance to an object, which is another Euclidean geometry exercise called stereo vision and the basis for how our eyes estimate distance. As a lane or object get too close, the LDWS can alert the driver through a haptic steering wheel vibration indicating which direction they should turn, or issue commands directly to the drive- and brake-by-wire ECUs.[43] Intended lane changes as indicated by a directional signal negate this feedback, and in effect, encourage the driver to use turn signals for lane changes.



Facial Recognition

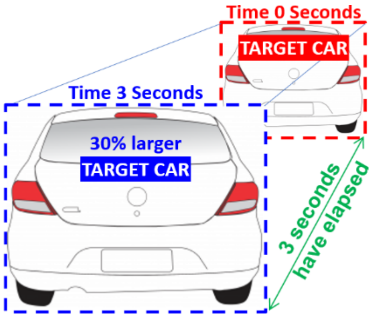
A study showed 28% of drivers were too tired to drive, distracted by a passenger or text messages, and affected by non-driving environmental factors – a major cause of accidents. [44] A "selfie" camera can monitor a driver's alertness level. Alertness is calculated through steering patterns, facial imagery analysis, frequent lane departures, physiological heart rate monitoring, breathing patterns, and a seat sensor.[45] A neural network database of human facial emotions helps score facial attention and deduce drowsiness, emotion, smartphone usage, and a distracted driver.





Nissan's Driver Attention Alert (DAA) tracks and statistically analyzes steering angle sensors and compares these results to previous patterns at speeds above 37 mph.[46] In this sample illustration, if the DAA deduces the driver is getting drowsy as a result of frequent steering corrections, it chimes and displays messages on the instrument panel about the need to stay alert. Cadillac's Super Cruise monitors the driver's eye movement to detect inattention or drowsiness. They couple this feedback with their OnStar telematics ECU which can connect the driver to a customer service representative or even pull the car over to a highway's shoulder.[47]

Collision Avoidance and Adaptive Cruise Control

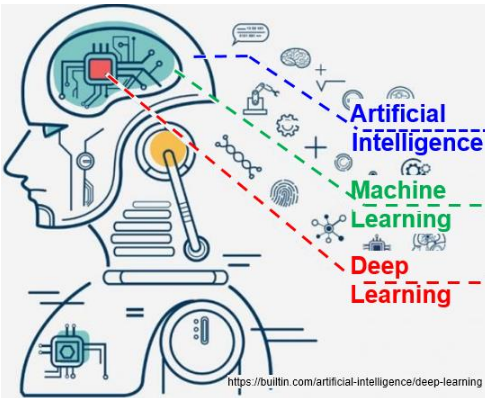


To detect an impending front-end collision with a single camera, the system calculates the rate the object's image grows in size. At a high level, a camera in your car traveling at speed spots  the **target car** in front of them at **Time 0 Seconds**. **Three seconds later**, the **target car** image is perhaps **30%** larger, and Advanced Driver Assistance Systems (ADAS) time to collision calculations deduce if an event is imminent.[48] Based on your vehicle's speed, specifications, occupied weight, and other variables, if a crash is looming, an ECU can signal the Brake Control Module to apply the brakes and send a command to the Dashboard Control Module to display a collision alert and sound warning chimes.[49] It might close the windows, adjust seat position and belts, and take other actions to help reduce injury. Whereas an average driver needs 1.4 seconds to apply a vehicle's brakes in an emergency, the ADAS needs less than 0.1 seconds. That 1.3-second improvement can save 180 feet of stopping distance at 56 MPH.[50]

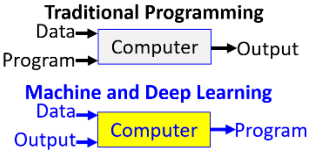
ADAS and a RADAR sensor can work with the Adaptive Cruise Control (ACC). Old cars with static cruise control allow a driver to set a highway speed, and if they got too close to the car in front, they disengage it and slow down. ACC constantly monitors the highway "gap distance" to the vehicle in front. Based on the set speed and time to collision, algorithmic calculations slow the car or brake as necessary. ACC is useful in heavy traffic, allowing a car to maintain a safe speed in line with the vehicles around it. Volvo's steering assist capability automatically follows the car in front, turn-for-turn at the correct speed, and can change lanes or apply the brakes.[51]

How do vehicles see other vehicles?

The topic of how vehicles see other vehicles to accomplish Level 5 autonomy is lengthy and detailed, and many approaches are still under development. At a high level, these methods all use sensors such as ultrasonic, LiDAR, RADAR, and cameras to generate data. With a machine intelligence approach, the system learns through image recognition to identify data patterns and road objects based on previously captured human-labeled pictures and videos of humans driving vehicles. Similar to a teenager learning to drive alongside an instructor, every new image and video helps the machine intelligence system refine its interpretation of live streaming data.



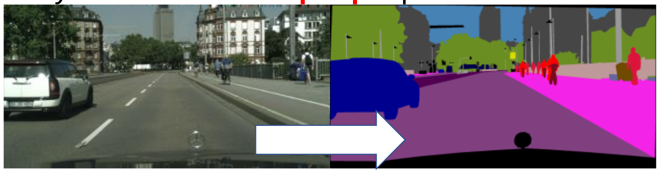
https://builtin.com/artificial-intelligence/deep-learning



There are two basic AI learning practices – **Machine Learning** (**ML**) and **Deep Learning** (**DL**). **ML** deals with structured data to modify algorithms. **DL** is a subset of **ML** and focuses on modifying algorithms based on neural networks that mimic the way our brain works, especially as it relates to clustering and classifying data.[52] To allow AI to make driving decisions, the learning algorithms are faced with a complicated problem that requires a great deal of training. Unlike traditional programming where a programmer designs statements to process data in a pre-described way, **ML** uses data and the output of other systems to alter, modify, and generally improve a processing program.

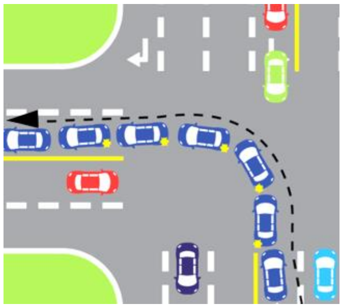
Assume you need a DL algorithm to spot bicycles in an image. Humans instantly spot the bicycle, but the algorithm initially doesn't comprehend a wheel with spokes, never mind what a bicycle looks like. An algorithm must be trained by numerically analyzing thousands of pictures with and without bicycles. When the algorithm finds a bicycle in a never before processed photo with a high degree of certainty, it moves to the next object classification.

Using LiDAR image processing and other sensors, ML and DL define each object in real-time. For example, an ML segmentation algorithm called Pyramid Scene Parsing Network divides this image into uniquely colored objects that are readily classified.[53] **Red people** pixels have attributes such as **height** and **speed**, **deep purple** areas are the **roadways** and **bright purple** are **sidewalks**. AI uses objects and algorithms to safely direct a vehicle around perceived obstacles en route to a destination.

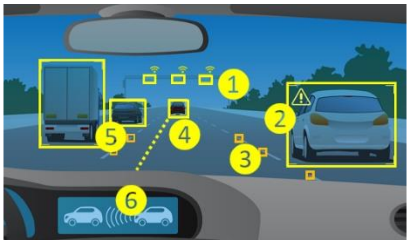


Expert systems, from our tic-tac-toe example, are not very useful for L5 automation. Designing expert rules such as “Don't hit a bicycle” and “Avoid hitting a tree”, while true, are a hard way to create a driverless car, and not a practical approach to real driving situations.

These types of ML systems require safeguards until they are perfected. That means using different sensors to overlap and arrive at an agreed course of action since an interpretation of a single sensor may not be perfect. RADAR verifying LiDAR readings is critical, especially when the limits of a sensor class are reached such as in foggy weather. If there is a failure to agree or an unusual condition arises, the human driver would have to take over.



A self-driving car needing to turn left must decide if an approaching car is far enough away or traveling at a slow enough speed. It must monitor traffic turn signals, how fast it needs to travel and issue drive-by-wire steering wheel commands. The system must determine from camera imagery if pedestrians are trying to cross the street, road conditions, perhaps which lane to turn into, and a myriad of other factors. It might have to examine and process multiple LiDAR and RADAR real-time sensors and issue multiple ECU commands to make that safe determination.



Traveling down a highway, LiDAR and RADAR are the most important sensors feeding the machine intelligence and AI systems.[54] The cameras find lane markings while GPS mapping helps the AI guide the L5 vehicle. Simplistically, the L5 systems must be in agreement on these types of real-time facts:

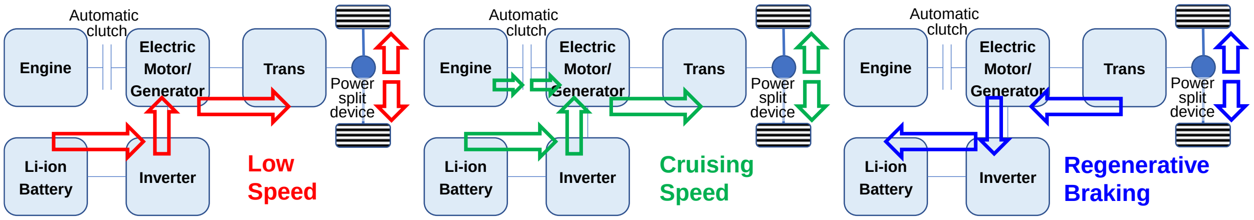
❶ Each lane has a sign in 100 yards. What do they say?
❷ A car 20 yards ahead in the right lane is going 55 mph without Vehicle-to-Everything (V2X) communications.
❸ Road markings show the relative position of each vehicle.
❹ There is a car 80 yards ahead traveling at 60 mph.
❺ Two vehicles are in the left lane. Both a truck and a car are traveling at 65 mph.
❻ The L5 vehicle is in adaptive cruise control mode following the car 80 yards ahead based on RADAR data that is calculating distance and using lane-centering steering.

ML effectively 3D maps the L5 vehicle's surroundings. AI uses this data, its yellow dashed line destination, and GPS mapping to send ECU commands, plotting a safe course. If vehicle ❷ veers into the center lane, AI will slow the L5 vehicle with ECU braking orders to avoid a crash.

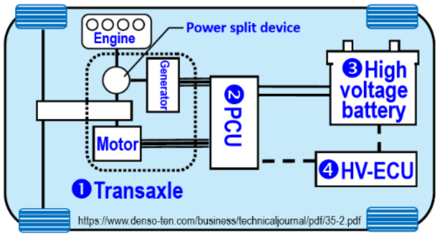
Hybrid vs Electric Vehicle Computing

A dealer can sell you gasoline, diesel, hybrid, or an electrically powered vehicle. At a high level, gasoline, diesel, and hybrid have an internal fuel tank.[55] Gas engines compress air and fuel in a cylinder before igniting it with a spark. The cylinder explosion spins the motor's shaft. Diesel engines first compress the air, then add fuel. The heat of the compressed air explodes the mixture and turns the shaft. Hybrid Electric Vehicles (HEV) use battery-powered electric motors and a gas engine to charge the batteries. Batteries, pre-charged through a plug, power Electric Vehicle (EV) motors.

In the diagram below, you can see the discharge/recharge directions when the HEV is traveling at **low speed**, **cruising,** or **braking**. There are many variants on this design, and they all rely on ECU software. Some hybrids use electric motors and a small engine simultaneously with an integrated battery motor/combustion engine transmission called a parallel hybrid. At a certain speed, the electric motors handle the entire load, while other designs use a small engine to recharge the battery to power the vehicle with electric motors called “series hybrid”.[56] HEV is a great solution for those who want to distance themselves from fossil fuels but live in an urban area or park on the street and do not have access to electric charging needed for EVs.



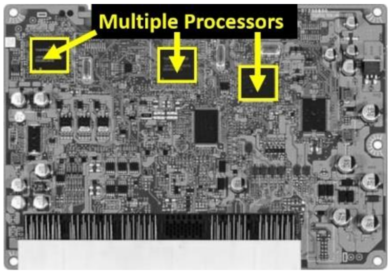
Denso makes Toyota Hybrid Vehicle ECUs (HV-ECU) used in the Prius and other models. The dual-power Prius has four basic code paths: idle stop, acceleration assist, battery-motor driving, and regenerative braking.[57] Some of the unique features that differentiate a hybrid from a gasoline car include:

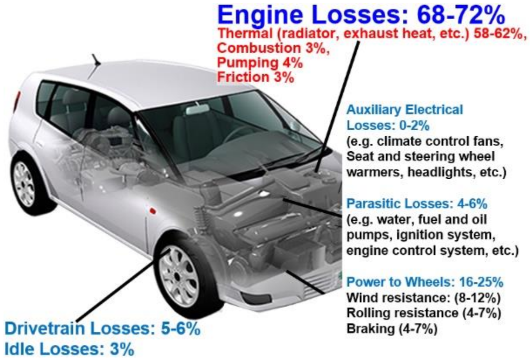


https://www.denso-ten.com/business/technicaljournal/pdf/35-2.pdf

① Transaxle including a motor, an electric generator, and a power split device.
② Power control unit (PCU).
③ High voltage battery. A variant charges the battery with an electric plug and an inverter.
④ ECU that controls the hybrid system.

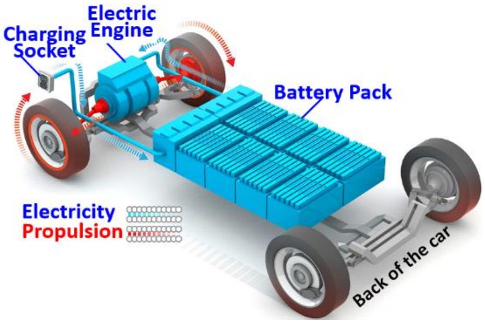
The HV-ECU is more sophisticated than the pure gasoline ECM. A Prius needs three CPUs to manage the combustion engine, electric motors, and battery levels to optimize fuel economy and vehicle performance. In addition to normal combustion engine duties, the HV-ECU also handles hybrid vehicle responsibilities of "idle stop," using the generator to start the engine, electric motor acceleration assistance, battery-mode during slower cruising speeds, and recharging activities in coordination with the Power Control Unit during regenerative braking.





Ten gallons of fuel gives the gas-powered car about 1.2 million BTUs of potential energy.[58] Perhaps 12%-30% of those BTUs move it down the road. As shown, about **70%** of the energy is lost to various mechanical inefficiencies such as **engine heat** dissipated through the **tailpipe**. ECMs and other ECUs can help reduce the loss through cylinder deactivation when engine demand is low, fuel injection timing, and engine start-stop functionality in traffic or at a stoplight.

EVs lessen our dependence on fossil fuels and reduce CO_2 greenhouse emissions up to 90% since they do not emit harmful gases.[59,60] Even with road and environmental conditions such as outside temperature playing a role in EV efficiency, cars like Nissan's Leaf use 1/5th the potential energy of a 30 MPG car, consuming 833 BTUs per mile or 0.25M BTUs for a 300-mile trip. Instead of a gas tank, it leverages an ECU to plug into the electrical grid and store potential energy in large lithium-ion batteries. Battery solutions using nickel-metal hydride and others are being explored.[61] EVs can cost more than combustion engine vehicles but can save the driver money in the long run.



Electric car ECU functions are simpler than those used by gas or diesel cars, and much simpler than those for hybrid vehicles. A classic ECM is replaced by a powerful Electric Drive Controller that focuses on electric motors and battery logic. A TCM is replaced by a Battery Management System (BMS) that monitors temperature and charge/discharge of series-connected cells to keep them in a safe operating range. EVs do not have transmissions since the wheels are directly connected to full-torque electric motors.[62] Also absent are the typical ECUs and sensors since there are no emissions, spark plugs, fuel injectors, transmission gears, turbo boost, etc.

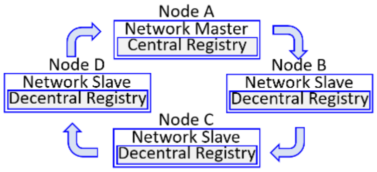
The dual-electric motor EV design is different from the combustion engine architecture. For example, as each lithium-ion battery cell ages, cell changes can harm the entire battery pack. That's where the BMS leverages software to control the large battery pack made up of hundreds of independent cells. The in-series batteries are charged via 110-380 volt external power, and the BMS protects against disastrous overcharge and balances individual cell charge/discharge.[63] At a low-level, an integrated circuit such as the Texas Instruments' 64-pin chip might be monitoring 3-6 battery cells to extend the range and life of the battery packs.[64]

One of the EV trends is the reduction of ECUs since they need fewer unique sensors and consolidate functionality into more sophisticated control units. Many EV sensors deal with battery charging and discharging, and much of this functionality can be centralized. Centralization and fewer sensors lead to reduced electric cabling which improves vehicle reliability and reduces space, weight, and costs.[65] Reduced complexity lends itself to smaller development teams which can shorten development time and make vehicles more affordable. Tesla Model 3's can have as few as three ECUs.

Will Ethernet Replace CAN bus in Vehicles?

With the number and responsibility of sensors, actuators, and ECUs rising, packet data protocols will continue to run through optical or electrical pathways. There are multiple, sometimes competing standards used in a vehicle that contribute to complex wiring, the 3rd most expensive part of a car, accounting for half of its labor cost.[66] This is a typical 2010 automobile wiring harness.[67] The 35-year old CAN bus rose to popularity because of its low cost and survivability in electromagnetically noisy vehicle environments. Here are four network topologies that can be used, perhaps together with CAN bus:

1. **Local Interconnect Network (LIN)** – The 1999 LIN Consortium created a low-cost one-wire sensor and actuator network using a vehicle's DC power system and the metal chassis for the return circuit.[68] At 20 Kbps and a 16 node limit, LIN cannot replace the 1 Mbps CAN bus, but it succeeds in low throughput subsystems such as the sunroof sensor/motor control, door/mirror motor mechanisms, power windows, door locks, and more.
2. **Media Oriented Systems Transport (MOST)** – A popular 1998 network for vehicle video, audio, and data transmissions.[69] Analogous to a switched telephone network, it supports 64 inexpensive Plug-n-Play devices with a supplied clock pulse and multiple channels. Used by 16 manufacturers, its synchronous and asynchronous modes support three transfer rates – MOST25 uses a Plastic Optical Fiber up to 25 Mbps, MOST50 over coax cable doubles the bandwidth, and Ethernet MOST150 up to 150 Mbps.[70] MOST is not found in control systems because of its unidirectional ring topology, multimedia focus, and master/slave arrangement.



3. **FlexRay –** BMW's 2006 X5 was the first to use the FlexRay consortium's network for its ride and handling chassis dampening system. It's 10 Mbps shared serial bus is used for active suspension, adaptive cruise control, drive-by-wire, and other powertrain and safety systems. FlexRay's unshielded twisted pairs provide fault tolerance compared to CAN bus's single twisted pair cable and ten times the bandwidth. It can use a CAN-like bus, a star, or a bus-star configuration, and replace multiple CAN networks to reduce cable weight.[71] FlexRay costs more than CAN bus and is slightly slower than the latest 12 Mbps CAN Flexible Data Rate (CAN FD) successor.

4. **Ethernet –** This popular network can be used alongside a CAN bus, allowing it to be phased in. It is not a replacement in Level 1/2 (L1/2) automation vehicles since it is relatively expensive, uses a switch, and requires a point-to-point design meaning each sensor, for example, would require a separate connection. As Level 4/5 (L4/5) becomes popular, ADAS will necessitate higher Ethernet speeds reaching 400 Mbps as a LiDAR sensor can require a 70 Mbps connection. Work is underway to develop a 100 Gbps automotive Ethernet standard.[72,73] Hyundai, BMW, and others already include Ethernet in some of their models.

CAN bus, CAN FD, and FlexRay are slow compared to Ethernet. Ethernet payloads are also larger with 1,500 bytes per packet compared to CAN bus with 8 bytes and CAN FD with 64 bytes.[74] CAN bus's interconnect flexibility is a plus in contrast to Ethernet which needs a fixed port-count switch. Volkswagen has expressed interest in the 10 Mbps, 2,048 bytes per packet payload CAN XL standard which is just now being marketed.[75]

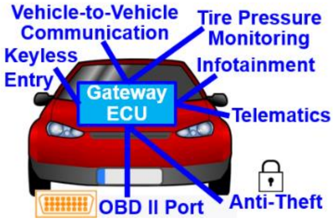
Security

In 2010, a disgruntled laid-off mechanic hacked a hundred of his customer's cars, preventing them from starting and triggering their car alarms.[76] In a separate incident, researchers sent messages to a moving car's ECM through the wireless tire air pressure sensor to indicate a low-pressure situation, eventually damaging the computer.[77] Security scientists took control of a Jeep Cherokee's ECUs at 70 mph that controlled its brakes, engine, transmission, door locks, and more by remotely transmitting commands to change its behavior and disable the SUV.[78]

Fortunately, these incidents are exceptions and a cyberterrorist would need vehicle specific make/model/year virus attack software. L1/2 vehicles tend to be on a closed-loop CAN bus that does not lend itself to remote attacks. Adding ADAS features increases attack vectors. While vehicles segregate multimedia devices from operational controls, V2X allows vehicles to communicate with each other and roadside infrastructure, opening them up to attacks.

Manufacturers do not want a self-driven car to ever hold its passengers hostage in exchange for a bitcoin deposit, nor have a car stolen by a thief spoofing an auto-parking ECU to maneuver a parked car out of its spot and unlocking the doors. Vehicle crime is not new but threats increase as technology is added, making cybersecurity a necessary component of L4/5 ADAS systems.

Modern cars have hacker attack entry points as shown in this diagram. Attack rates could increase as manufacturers use open source code for their car computing ECUs. Occupant safety may require a real-time ECU security scanner. For instance, GuardKnox’s ECU uses an ARMv8 Reduced Instruction Set Computing (RISC) processor to verify a data packet was sent from a genuine internal CAN bus ECU or V2X outside the vehicle, and valid for a purposeful ECU.[79]

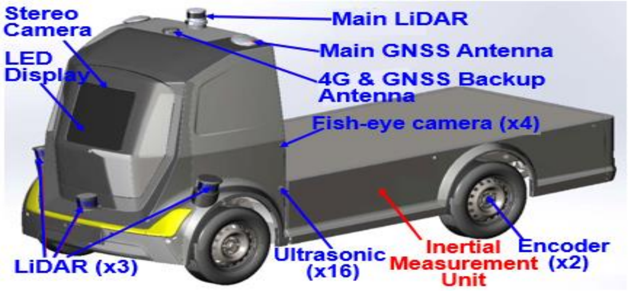


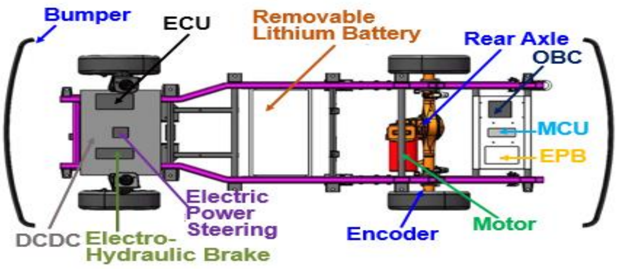
Possible actions include having the vehicle pull over if it senses it was hacked. Autonomous features and V2X communications could be disabled, allowing a driver to take control with a limited ECU subset such as steering, gas pedal, and brakes, and a mandatory safe destination such as a police station. Long term, ECUs need code to authenticate messages. Vehicles with a MOST network need security gateways to check bus messages just like antivirus software protects our PC since occupants can unknowingly bring infected multimedia into the car. That capability could be extended to automotive Ethernet with security-aware Ethernet switches and specialized anti-virus ECUs sniffing for malicious messages and malware.

Coronavirus Fighters

The 2020 pandemic and lack of a vaccine or useful treatment led nations into life and death lockdowns. China used 2,600 self-driving robot vehicles to spray disinfectant in COVID-infected neighborhoods.[80] These programmable machines were originally designed to navigate farmland and spray nutrients or insecticide on particular crops without trampling fruits and vegetables. Instead of traversing farms, they were software dispatched to infected marketplaces, a particular address, park, or densely populated public place trying to “flatten the curve”.[81] Using satellite and land-based Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS, of which GPS is a subset) coordinates, they drove planned routes and sprayed 24 hours a day without risking a driver to deadly pathogens.[82]

The virus fight was aided by driverless L4 Neolix electric delivery trucks that brought food and other items to scared people. ECUs guided by GNSS, inertial navigation, and digital maps steered the trucks through Chinese cities, automatically passing obstacles to their destination.[83]

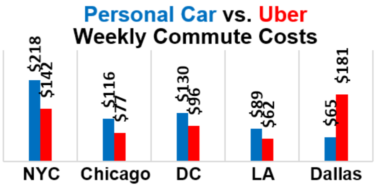




L4 was achieved on streets and highways through a combination of cameras, multi-channel LiDAR, ultrasonic short-range sensors, and RADAR.[84] The cargo bay is not shown, but you can see the **Inertial Measurement Unit**, **electric motors**, **removable lithium-ion battery**, **ECU**, **Motor Control Unit** (**MCU**), **Electric Power Steering**, **Electro-Hydraulic Brake**, **Electronic Parking Brake** (**EPB**), **On-board Battery Charger** (**OBC**), and **Direct-Current-to-Direct-Current** (**DC/DC**) converter.

Cars-as-a-Service and Robot Taxis

In major cities, parking costs, congestion pricing, and bumper-to-bumper traffic have drivers turning to ridesharing services such as Uber instead of their vehicles. Partiers also count on these services by not risking themselves or others by driving a car when they leave a bar.



Economic arguments have been made for abandoning car ownership and instead relying on rideshare when vehicle repairs, fuel costs, insurance bills, and parking fees are factored in. A 2017 Kleiner Perkins study showed it can be cost-effective in some cities to use a Uber-like service instead of owning a car.[85] When garage costs, cost of money, and the fact that a car typically is parked 20+ hours a day, ride-hailing becomes attractive.

What if rideshare costs could be further reduced through self-driving cars? If Toyota had a fleet of electric autonomous vehicles in your neighborhood that they charged, maintained, and cleaned, would you summon one to:[86]

- drive you to work?
- pick up your young daughter and drop her off at soccer practice?
- use it to drive you to a hospital if you had Covid-19 and didn't want to infect a driver?

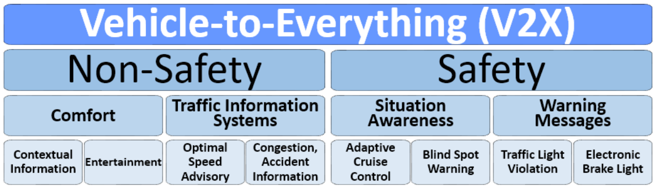
Cars-as-a-Service (CaaS) is a theoretical rideshare capability that summons an empty self-driving vehicle to your location.[87] It can take you wherever you want at any time of day and in any weather condition. A smartphone “touch” kicks off the entire rideshare transaction for the optimal vehicle based on the number of passengers, whether you wish to pick up others along the way, special equipment such as a wheelchair ramp, hauling capacity for boxes, and more. The CaaS software would select the appropriate electric vehicle from a nearby lot, automatically disconnect it from its charging port, and direct it to your location. It would be like a Uber ride but without a driver. This is all possible with L5 computing advances.

CaaS may sound far-fetched, but vehicle manufacturers are concerned that it could erode their traditional market share. In America, 88% of families own at least one vehicle.[88] One estimate predicts that 12 million autonomous vehicles could be on the road by 2035, and that translates to fewer owned and manufactured vehicles in the future. Manufacturers are exploring other approaches such as subscription pricing where a customer pays a monthly/yearly base fee to summon an autonomous vehicle of their choice.[89] The fee could include insurance and maintenance costs. If CaaS reduces car ownership, it would impact gas stations, local repair shops, shopping mall parking spots, and possibly turn car manufacturers into service providers instead of masters of assembly-line production.

Thermal Imagery versus Ultrasound versus LiDAR versus RADAR

Each sensor category has its strengths and weaknesses. Our brain spots the truck’s front wheels and the rear cutoff from the grass field in this image, yet camera image algorithms have difficulty determining where it begins and ends on a cloudy day as it blends in with the sky.[90] Imaging algorithms might test for color and contrast changes to find boundaries, but objects blending into backgrounds with low contrast can reach a wrong conclusion. A system relying solely on RADAR to make decisions has a tough time on a curved road. It would not spot dashed or solid lane markings and the outside guard rail could create a serious situation. The green car in this image is out of the RADAR’s field of view. With lives at risk, no one wants an L4/5 ECU making a poor decision based on sensor data.

As a result, engineers design fusion solutions that combine multiple sensor types with overlapping missions.[91] Sensor fusion collectively improves the system's alerting ability and sensitivity under all weather conditions. General Motors and others provide V2X traffic and ADAS solutions that use cameras, ultrasound, LiDAR, and RADAR sensors.[92,93]



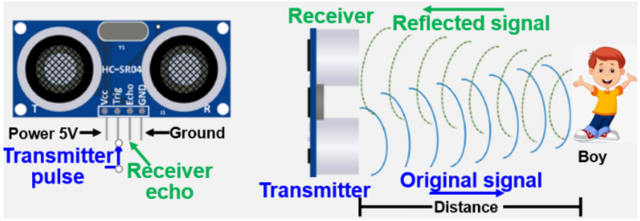
Thermal Imagery

Standard cameras are useful sensors in general conditions but are poor in low-light and inclement weather. Thermal cameras work well in poor conditions by forming a temperature image from an object's reflected infrared radiation. An array of microbolometer pixels, as shown to the right, detects infrared 8-14 µm range wavelengths. A pixel has a **cap wafer** attached to a **ReadOut Integrated Circuit** silicon wafer of thermally sensitive **Vanadium Oxide** pixels. When **infrared radiation** strikes the **Vanadium Oxide**, the circuit's resistance changes.[94]

Thermal cameras are useful to L4/5 ADAS since they function in complete darkness, making them useful for detecting animals darting in front of your vehicle at night, during periods of sun glare, and fog where a regular camera and LiDAR are less effective.[95] This image shows a man walking his bicycle across a road. Compare the extra visibility a thermal camera provides in autonomous vehicles.

Ultrasonic Sensors

Ultrasonic parking sensors have helped drivers for decades. They are even found in a simple Arduino hobbyist board as shown here. At a high level, a small **Transmitter pulse** signal causes a transducer to emit a **high-frequency directional sound** signal. When the signal hits an object such as a boy, it bounces back to the **Receiver** and the **Receiver echo pin** gets a voltage. In this Arduino code sample, a 10 µs pulse is sent to the **transmission** "**Trig**" pin:



```
digitalWrite(trigPin, HIGH);
delayMicroseconds(10);
digitalWrite(trigPin, LOW);
```

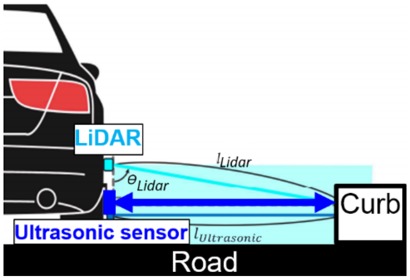
The duration of the signal bouncing off an object is obtained through the **Receiver** “**Echo**” pin:

```
duration = pulseIn(echoPin, HIGH);
```

This approach allows the object’s distance to be easily calculated:

$$Distance = \frac{Speed\ of\ sound\ x\ Return\ pulse\ time}{2}$$

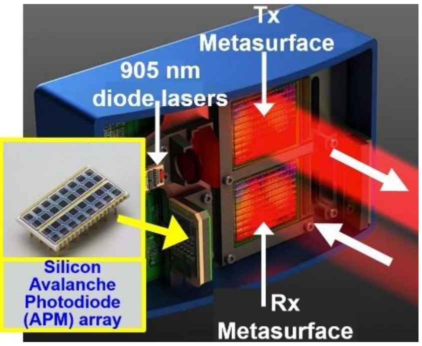
Inexpensive vehicle ultrasonic sensors use a single transmit/receive element with a range of a few meters and emit a frequency beyond our hearing range. They are found in low-speed applications such as curb detection as shown and are usually deployed with other sensors such as LiDAR.[96] Sound waves bounce off glass, liquid, curbs, and irregular shapes such as mesh or springs, but their range limits their L4/5 use to low-speed parking and basic mapping services.



LiDAR

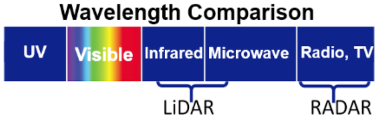
Over 50 years ago, Apollo 11 astronaut Buzz Aldrin set up a mirror on the moon that was targeted by a laser from Earth to measure the distance between the two bodies.[97] The formula used was simple: $Distance = \frac{Speed\ of\ light\ x\ Return\ pulse\ time}{2}$

When first tested with autonomous cars, LiDAR emitted laser pulses from a rotating vase-shape housing and GPS coordinates to find, range, and construct a live map of neighboring objects. These days, manufacturers favor a solid-state non-spinning LiDAR microchip housed in a small box about the size of a deck of playing cards as shown to the left. [98]



The new shape costs less and uses 11,000 **Vertical Cavity Surface Emitting Lasers** (**VCSEL**).[99] **VCSEL** laser light comes from the surface of a planar wafer that resembles a semiconductor microchip sandwiched by mirrors.[100] An array of **VCSEL**s is the size of a pencil-point. With **VCSEL** modules at the front and back of a vehicle pulsing billions of times per second, a real-time map can be constructed as well as a sensitive alerting system. Apple’s 2017 iPhone X used **VCSEL**s for facial recognition.

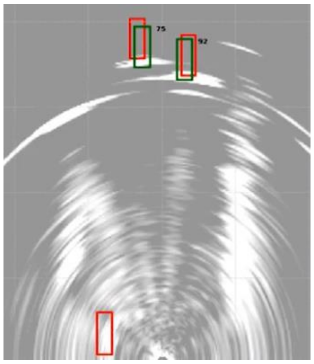
LiDAR can use various non-visible infrared light wavelengths between 850 – 1550 nm, each with advantages and disadvantages.[101] A green visible 532 nm laser is not used since it would distract other drivers. Infrared 905 nm lasers could hurt the retina if the range exceeds 100 meters. Frequencies of 1550 nm are safer but cost more. Velodyne's LiDAR uses 905 nm while TriLumina's VCSEL uses 940 nm.[102,103] Similar to bats using echolocation with ultrasonic sound waves to bounce off objects, LiDAR's millions of light pulses reflect off a person, bicycle, or another vehicle to about 100 meters. Pulses are sent at the speed of light and the time until the ping is received determines distance and angle. An ECU running a vision algorithm creates a 3-D point map of its surroundings.



RADAR

RADAR has been used in automotive applications for over two decades, achieving the same road signature goal as LiDAR - it uses the roundtrip radio wave time instead of light to calculate distance. Results are mapped like LiDAR as shown to the left.[104] RADAR is useful when the exact size and shape of a detected object is less important and in harsher conditions of rain, fog, or a snowstorm where optical LiDAR and camera technology have issues. It can calculate the speed of an SUV 800 feet in front of you and detect when it slows down or stops using the doppler effect as wave frequency varies with distance changes. RADAR costs about 90% less than LiDAR and has a much longer range:[105,106]

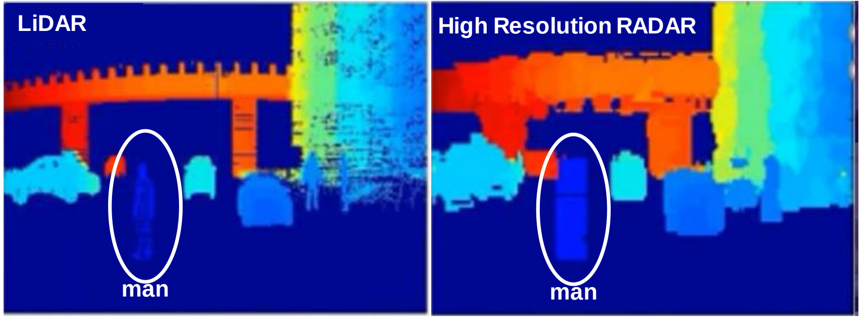
LiDAR	RADAR
Uses shorter light waves	Uses longer radio waves
Detects small objects	Detects large objects
Offers greater detail	Less detail
Usually shorter distance	Longer distance
Weather dependent	Weather independent



Radio Frequency	Examples	Type
24 GHz	Blind Spot Detection (BSD) Lane Change Assistance (LCA) Collision Mitigation (CM) Parking Aid (PA) Rear Cross Traffic Alert (RCTA)	SRR
76-81 GHz	Adaptive Cruise Control (ACC) Forward Collision Warning (FCW) Emergency Braking Systems (EBS)	LRR MRR

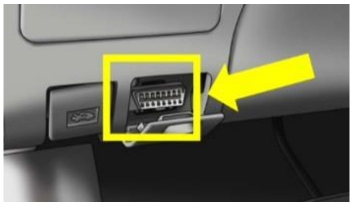
- **Short-range RADAR** (**SRR**) up to ~30 m
- **Mid-range RADAR** (**MRR**) up to ~150 m
- **Long-range RADAR** (**LRR**) up to ~250 m[107]

Here are the LiDAR and high-resolution RADAR comparisons of the same scene. There is a person circled in white in both 3D created images. LiDAR provides more detailed image information than the high-resolution RADAR sensors.[108] LiDAR and RADAR must also use a camera sensor since traffic sign recognition is required.



Given the L4/5 market opportunity, companies that make cameras, LiDAR, and RADAR sensors are trying to add functionality to grow their market share, resulting in products that accomplish more than they were originally capable of. For example, lane change applications that once required short-range RADAR sensors can now solve the same problem with LiDAR. Further advances may reduce the types of sensors needed for autonomy.

Insurance



Your Telematics Control Unit provides data on your driving habits through WiFi, 4G, Bluetooth, and the OBD-II port as shown to the right.[109] Owners appreciate live traffic updates that help safely speed their journey, assist with parking spot availability, issue weather alerts, and more. Others may feel it brings “big brother” privacy concerns. The port allows for ECU data to be collected on sudden stops, rapid acceleration, the time you drive, U-turns made, and how sharply you turn, which can help a car insurance company score a driver’s habits.

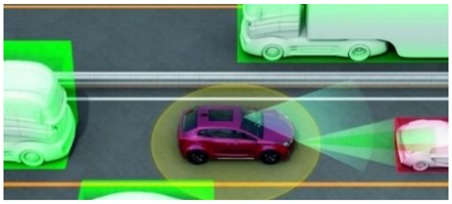
Usage-Based Insurance concepts like Pay-How-You-Drive use current driving history based on the odometer, GPS, vehicle speed, rate of acceleration and deceleration, and other variables to price insurance policies based on individual driving patterns.[110] For instance, one insurance company defined heavy braking as the vehicle decelerating faster than 7 mph/second.[111] My insurance company gave me a 17% premium reduction based on the number of miles I drive during daylight hours, and my acceleration and braking habits. If I was a safer driver, my discount could have reached 30%.

Inducements directly benefit safe drivers and indirectly create a safer driving environment for everyone, but raise privacy issues by identifying aggressive drivers. Telematic data is useful to parents monitoring their teenager’s driving habits, especially if they trigger a forward collision alert. Fleet management systems can monitor driver behavior, track vehicle location, and check driver compliance with regulations.

Vehicular Networking

For the longest time, engineers dreamt of cars that could communicate with each other. Industrial designer Norman Bel Geddes wrote in 1940 about a mechanism that “could transmit visual traffic light signals directly to miniature signal lights within the car”, and “maintain control of speed and spacing of cars in the same traffic lane”.[112] Some of his ideas are coming true. Vehicles collect an enormous amount of sensor data that is useful to other vehicles.

The groundwork for V2X networking began with GM's 1996 OnStar cellular subscription system. It activates automatic emergency services when sensors detect a collision or aid the driver to provide voice GPS/navigation, remote diagnostics, and more.[113] With the advent of powerful microprocessors and higher-speed networks, systems evolved to include Vehicle-to-Vehicle (V2V) intelligent inter-car communications and Vehicle-to-Cloud (V2C) communication for over-the-air software updates, infotainment services, vehicle remote starting, and more.[114] The V2C future may combine driver profile data, vehicle condition, and other cloud-based third-party data to enhance the driver experience through traffic information, crime, retail promotions, and more. Helping to increase bystander safety, Vehicle-to-Pedestrian (V2P) communication can sense the local environment to help protect a passerby, cyclist, and others outside the vehicle. V2P can be accomplished through camera sensors and appropriate audio and visual alerts.



At a high level, V2X augments onboard sensor data beyond-line-of-sight by supplying external live road safety and traffic information. V2X can receive "swarm intelligence" about a hazardous road condition miles ahead to give the driver time to slow down, such as a black ice condition as sensed by tire traction sensor data. Coupled with autonomous driving, a shared information transportation network could be created to reduce traffic congestion and vehicle collision events. Road efficiency would improve, traffic accidents would decrease, fuel economy would increase, the air would be cleaner, and we would enjoy our commutes a lot more. Hazards posed by potholes, gravel falling from a dump truck at highway speeds, flooding, deer crossing, lane closure, and other conditions could be circumnavigated or avoided by reducing speed.

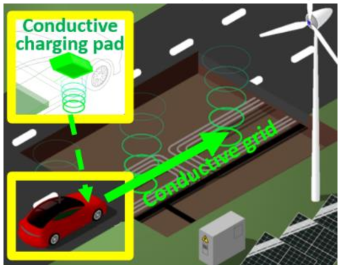
Future of Automotive Computing

According to Mark Twain, "It is difficult to make predictions, particularly about the future." That is certainly true when thinking about vehicles. When I visited the 1963 World's Fair, Chrysler exhibited a car of the future that used a 44,000 RPM gas-turbine jet engine. It ran on an assortment of fuels including peanut oil. It never caught on for many reasons, among them was the cost of the heat-resistant metals that were needed to make a jet engine.

The 1948 Tucker Torpedo used a helicopter motor mounted in the rear and a center directional headlight that followed the steering wheel.[115] Seat belts were thought of as implying a car was unsafe, so Tucker addressed the safety issue by including a forward safety well that you could dive into if you were about to crash.

The Chrysler and Tucker vehicles of the future were sales failures, and no one from the 1950s could have imagined that today's cars do not fly. Hybrids and EVs are gaining momentum and we talk about self-driving autonomous cars, hydrogen power, inter-vehicle communications, and flying drone-like personal vehicles. Some speculate the Uber/Lyft model and a movement towards robot taxis will mean fewer or car-less family ownership models, while others dream of less pollution, lower monthly expenses, reduced road congestion, and pedestrian safety improvements. If technology prevents vehicles from crashing, they could be made of much lighter materials such as carbon fiber and be made more eco-friendly.

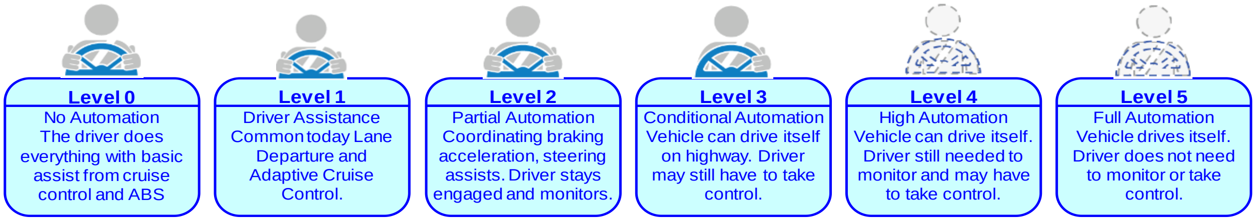
The self-driving EV may be able to recharge itself. An EV charging **robot** in your garage would be summoned by a V2X message to find the vehicle's charging port and automatically plug/unplug the 220V power cord as shown to the right. It is possible to have the autonomous EV **drive** over an **inductive wireless charging pad** as shown to the left, just like putting a smartphone on an electromagnetic inductive wireless charger.[116,117] Just get into an EV, enter a destination, and be taken there. The EV would recharge itself when it needs power in under 5 minutes if battery technology company StoreDot has its way. StoreDot is leveraging computer science and lithium-ion cell organic chemistry to rapidly charge an EV in just 5 minutes.[118] Their FlashBattery product was designed using an AI fast-charging algorithm to reduce charging times and extend battery life expectancy. StoreDot's BMS ECU design gives an EV a 300 miles range in just two minutes longer than it takes to fill up a gasoline car.[119]



The automotive industry is completing its mechanical/digital transformation. The next phase incorporates greater computer sophistication to support intelligent V2V and V2C connected infrastructures. It includes new interfaces such as gesture controls that allow drivers to keep their eyes on the road at high speed and theft deterrent biometric security.[120,121] Domain controller technologies, automotive Ethernet, 5G, and RADAR are expected to play significant roles in tomorrow’s transportation. Other emerging AI technologies include an Alexa-style voice user interface to proactively alert to an imminent accident. The future holds higher degrees of electrified factory-enabled self-driving vehicles as drivers explore CaaS ownership models. Regardless of the future style and mode, they will all be highly dependent on the computer.

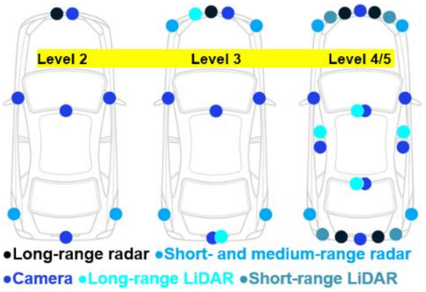
The ECU and Autonomy

It is impossible to ignore the vision of self-driving vehicles, even as human nature is hesitant to adopt radical technology changes. As with the transformation from combustion engines to hybrid and eventually all-electric vehicles, autonomous capabilities are slowly making their way into our machines. Autonomous levels are defined by the Society of Automotive Engineers:

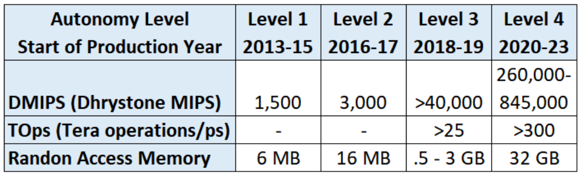


L0 **No automation** – The driver is needed. Minor cruise control and ABS assist.
L1 **Driver assistance** – Intelligence begins with lane centering and adaptive cruise control.
L2 **Partial automation** – The system provides more control through simultaneous features like lane centering and adaptive cruise control, but a driver is still needed.
L3 **Conditional automation** – Navigation and monitoring automation begins with a driver who is still needed for unexpected conditions.
L4 **High automation** – The vehicle can drive itself with the driver ready to take control in conditions such as inclement weather and off-road situations.
L5 **Full Automation** – Computers have full autonomy. The driver is optional.

Most of the current ECUs were designed years ago when drivers were still in control and the CAN bus had the bandwidth to handle the needs of a multitude of sensors, actuators, and inter-ECU traffic. Each new feature required a new programmed ECU, putting pressure on profit margins. More code meant increased complexity which reduces reliability. The number of ECUs needed to layer technology on vehicles is rapidly outgrowing the CAN bus/ECU architecture. This pushes car makers further into becoming Ethernet-based hardware/software component integrators just as computer makers design new PCs and servers from a marketplace of available subcomponents like keyboards, power supplies, DIMMs, and processors.



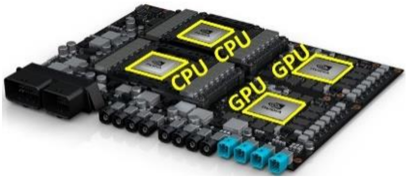
As cars add L3-5 features, more high-bandwidth sensors are needed to support greater levels of autonomy. L2 **Long-range RADAR** sensors and **cameras** in the front of the vehicle support basic ADAS features of adaptive cruise control, lane departure warnings, emergency braking, assisted parking, and driver attentiveness. Technology helps the driver but they maintain control. L3 **Short-range** and **Long-range LiDAR** help with nighttime conditions that impair cameras. At L4/5, self-driving sensors provide a comprehensive 360-degree view of the vehicle.

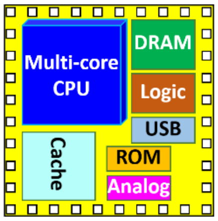


Autonomy Level Start of Production Year	Level 1 2013-15	Level 2 2016-17	Level 3 2018-19	Level 4 2020-23
DMIPS (Dhrystone MIPS)	1,500	3,000	>40,000	260,000- 845,000
TOps (Tera operations/ps)	-	-	>25	>300
Randon Access Memory	6 MB	16 MB	.5 - 3 GB	32 GB

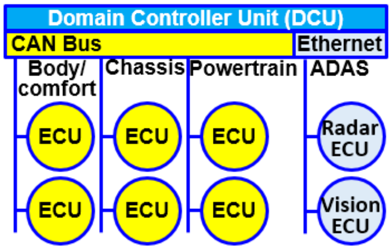
http://docplayer.net/150421480-The-smarter-car-for-autonomous-driving.html

Bosch projected the 64-bit CPU and memory requirements needed at each autonomy level. The rapid progression occurs between L2/3 and L3/4. The massive amounts of real-time data transmitted and received for self-driving create a traditional control unit design bottleneck.[122] L5 requires far greater CPU power and memory. Companies like NVIDIA with their DL Pegasus AI computer handle many ECU functions with dual ARM CPU and Graphical Processing Units (GPU) yielding 320 Trillion Operations per second (TOps) as shown to the left.[123] As more computer power is needed, Qualcomm's Snapdragon Ride ECU aggregation platform on the right supplies 700 TOps for L4/L5 autonomy.[124] These superfast solutions seem to defy Moore's Law using a low-cost powerful System-On-a-Chip (SoC) design, shown on the left, that brings the multi-core **CPU**, **DRAM**, and other logic sections into a single chip.

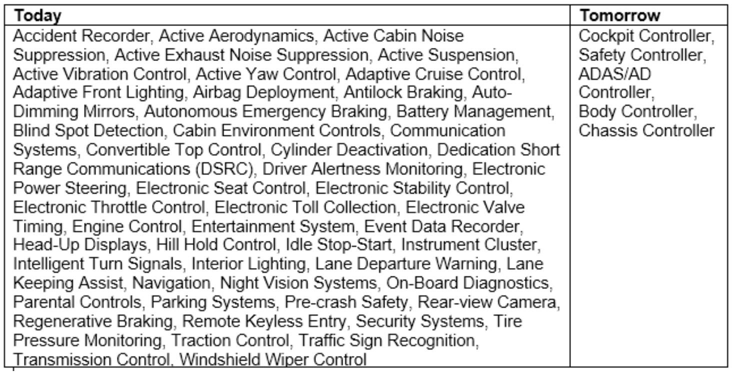




As engineers refine L5, Intel estimates a self-driving car could generate 4 terabytes of data/day.[125] In the U.S., forecasts show 259 million cars on the road by 2030, and 1 in 10 will be autonomous, equating to an eventual 4 Exabytes of data per hour of use.[126]



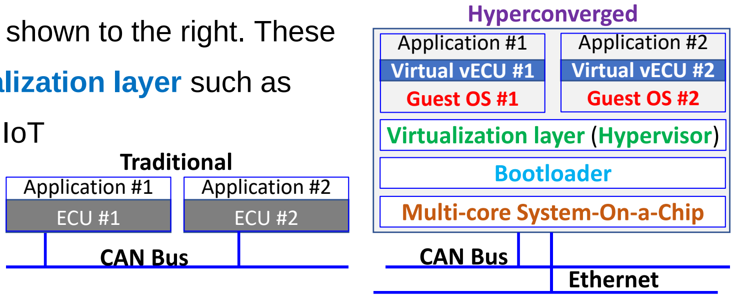
As existing vehicle communication paths become inundated with new data traffic, a new modernization phase is needed. Bosch and others are adopting a decentralized domain controller architecture that supports the traditional ECU/CAN bus and future networks such as Ethernet as shown to the left.[127]



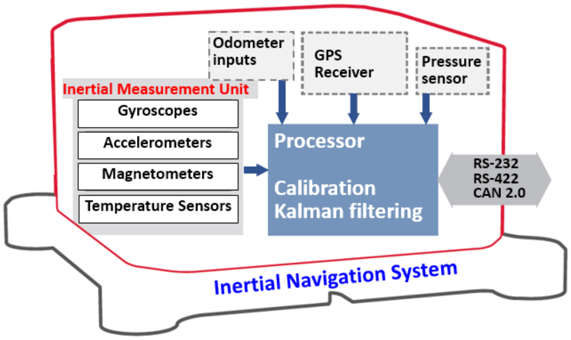
Today	Tomorrow
Accident Recorder, Active Aerodynamics, Active Cabin Noise Suppression, Active Exhaust Noise Suppression, Active Suspension, Active Vibration Control, Active Yaw Control, Adaptive Cruise Control, Adaptive Front Lighting, Airbag Deployment, Antilock Braking, Auto-Dimming Mirrors, Autonomous Emergency Braking, Battery Management, Blind Spot Detection, Cabin Environment Controls, Communication Systems, Convertible Top Control, Cylinder Deactivation, Dedication Short Range Communications (DSRC), Driver Alertness Monitoring, Electronic Power Steering, Electronic Seat Control, Electronic Stability Control, Electronic Throttle Control, Electronic Toll Collection, Electronic Valve Timing, Engine Control, Entertainment System, Event Data Recorder, Head-Up Displays, Hill Hold Control, Idle Stop-Start, Instrument Cluster, Intelligent Turn Signals, Interior Lighting, Lane Departure Warning, Lane Keeping Assist, Navigation, Night Vision Systems, On-Board Diagnostics, Parental Controls, Parking Systems, Pre-crash Safety, Rear-view Camera, Regenerative Braking, Remote Keyless Entry, Security Systems, Tire Pressure Monitoring, Traction Control, Traffic Sign Recognition, Transmission Control, Windshield Wiper Control	Cockpit Controller, Safety Controller, ADAS/AD Controller, Body Controller, Chassis Controller

ECU consolidation allows automakers to update existing features and likely embrace concepts found in the Internet of Things (IoT) edge and cloud-based environments. The transformation would support the complex development, testing, and deployment of ADAS/Autonomous Driving Controller system and AI/Expert-based human driver capabilities and behaviors, especially during unpredictable emergency maneuvers. This cannot be done with 8/16-bit processors, nor are 70-150 ECUs practical given each has its own CPU and memory. These controllers are targets for consolidation, and Intel believes merging just the infotainment and instrument cluster ECUs could save \$60 to \$100 per vehicle." [128,129]

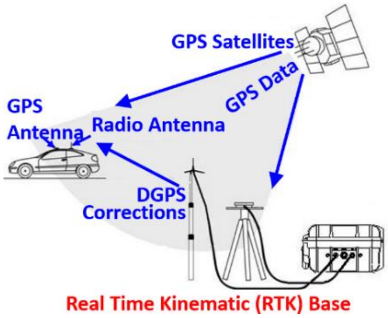
Software-defined designs found in familiar **hyperconverged** server computing models will begin to appear in vehicles. Each application would be hosted on **virtual ECUs** and supported by the necessary **guest operating system** as shown to the right. These systems could be supported by a **virtualization layer** such as Open Source ACRN which is a popular IoT **hypervisor**.[130] A **bootloader** kickstarts the controller that sits on top of a **multi-core SoC processor**.



A conscious vehicle that reacts to its environment using algorithms to make decisions based on sensor input, all without a driver, is viewed by many as an automobile panacea. Consciousness needs vehicle perception using cameras, LiDAR and RADAR, GPS mapping, planning based on intention, preferences, current conditions, precise control, and fault management. When the vehicle's outside signals are blocked or obscured by tunnels and tall buildings, an **Inertial Navigation System** on the right adds real-time information such as current heading through gyroscopes, accelerometers, magnetometers, and temperature sensors of the **Inertial Measurement Unit**.[131] This processor runs a "Kalman" filter algorithm that uses a linear quadratic estimation of sensor data over time to remove noise inaccuracies.[132]



The compute power to process real-time vision systems, illumination through laser light and its reflection, radio waves assisting with distance, angle, and speed already exists.[133] Augmenting **GPS** with **RTK fixed base station** signals, vehicular navigation accuracy is to within an inch and can determine if someone is on a curb or in a crosswalk.[134,135] Farmers use **RTK** to autonomously guide tractors through their fields. Behaviors derived from smartphones, social media, and Alexa-type devices can be combined with V2V data to determine road conditions, allowing a vehicle to automatically steer around potholes, move to the right for emergency vehicles, and more.



As seen in many industries, including the traditional PC market, today’s car computing model is ripe for disruption. BMW, Volkswagen, and others want to lower costs and simplify the process by adopting standards such as the OPEN Alliance’s Ethernet for at least a portion of their vehicle’s backbone rather than create a proprietary network.[136] Some have increased the use of readily available Commercial-Off-The-Shelf parts.[137] Standardization tends to bring new narrow-focused suppliers as traditional vehicle manufacturers take on more of an integration role.

The age of the simpler, smarter, and smaller ECU architecture where a single device can do the work of many traditional units is coming. It must be secure since it runs so much critical code and is connected to the world. It will include support for the 5G technology to allow the code to be remotely updated, provide drivers with current traffic data, and allow vehicle technology to assist in avoiding potentially hazardous issues. Greater wireless vehicle bandwidth increases predictive sensor service data available to the mechanic to improve service and reliability, adds driver alerts to open parking spots, and directs the driver to no-waiting electric charging stations.

Smarter cars with more autonomous features necessitate ECU consolidation and likely introduce Domain Control Units to the new architecture. The design still needs to support basic real-time operations such as motor control and anti-lock braking, and advanced autonomy requirements of camera recognition or RADAR object detection. Memory needs, CPU processing, support for other operating systems, large storage requirements, in-memory processing with a 64-bit address space, and more will mandate these requirements coexist.

Conclusion

The first hundred years of vehicle development focused almost exclusively on their basic mechanics. Since the 1990s, most of the rapid advances in better fuel economy, safety, and comfort are attributable to software running in electronic control units.[138]

A state-of-the-art vehicle computing architecture is changing the driving experience. ECU sophistication and communication are at the core of connected automotive innovation as powertrains move towards electrification and away from total dependence on fossil-fuel. Passengers will be surrounded by electronic conveniences and Advanced Driver Assistance Systems that will get them to their destination with utmost safety. Level 5 autonomy will have a major societal impact, unburdening us from driver's licenses, car insurance, automotive smog, parallel parking, and provide children and those with disabilities seamless safe mobility.

Occupant safety and accident prevention will continue to be a persistent theme and become more evident as cars support V2V and V2X inter-vehicle communication, aided by 5G networks that speed up vehicle transmission rates and deliver larger data volumes. These improvements, which must be phased in until all or most other vehicles reach a Level 5 status, will also aid the transformation of vehicle insurance to a dynamic pay-how-you-drive model.

The popularity of less-complex electric cars will grow as their price comes down and range increases, allowing them to be thought of as a consumer appliance. Hybrid vehicles will also gain in popularity for those that either can't plug in their cars or for those whose daily mileage usage exceeds battery life. Initially, autonomous Level 3/4 will become popular must-haves as noted by Ford and Volvo in their 2021 product plans.[139]

Sophisticated ECU will take on even more functions as it remains at the heart of vehicle transformation. With a vision of greater autonomy, ECUs will also have to share and interpret data collected from other vehicles and elements of their environment.

Change is not limited to the automobile industry. With the pandemic, we have changed our behaviors and might be interested in taking an overnight autonomous EV trip a thousand miles away knowing it would charge itself. We would not own it nor worry about where to park it or service it. We could skip the ritual long-distance overnight hotel stay and instead snooze in the car, or maybe drive instead of fly to avoid airport delays and cramped airline seats. It could simplify long trips to Disney World with the kids.

Two-way streets would seem 18-feet wider without any parked cars. Road tests and driver’s licenses would be a thing of the past and our dreaded car buying experience would be over. It would be a boon to the package delivery business since their tasks would be to load up a truck and send it autonomously on its way without worrying about a tired driver. The need for mechanics would increase since the vehicles would be on the road 24/7.

The impact of half car, half computer driverless transportation will be experienced by the consumer, and it is the computer science industry that will supply the reality of electrified, automated, and connected vehicles. Engineers need to design, program, and test these autonomous creations, as well as create secure software lifecycles of updates, patches, and new feature sets based on autonomous feedback. As computer technology in the automobile proves itself, the demand for it will only increase, just as it does in our everyday lives.

So next time you get in your car and press the start button, think about the millions of data bits being processed and running through your car every second keeping you safe and getting you to your destination – happy travels!

List of Acronyms

ABS	Anti-lock Brake System
ACC	Adaptive Cruise Control
ACM	Airbag Control Module
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
BMS	Battery Management System
CaaS	Cars-as-a-Service
CAB	Controller Antilock Brakes
CAN bus	Controller Area Network
CAN FD	CAN Flexible Data Rate
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DAA	Driver Attention Alert
DC/DC	Direct-Current-to-Direct-Current
DCU	Parking Domain Control Unit
DL	Deep Learning
EBCM	Electronic Brake Control Module
ECM	Engine Control Module
ECU	Electronic Control Unit
EPB	Electronic Parking Brake
ESC	Electronic Stability Control
EV	Electric Vehicle
G	gravity
GNSS	Global Navigation Satellite System
GPU	Graphical Processing Units
HEV	Hybrid Electric Vehicles
HV-ECU	Hybrid Vehicle ECU
IoT	Internet of Things
LDWS	Lane Departure Warning System
LiDAR	Light Detection And Ranging
LIN	Local Interconnect Network
LISP	LISt Processor programming language
LRR	Long-range RADAR
MCU	Motor Control Unit
ML	Machine Learning
MOST	Media Oriented Systems Transport
MRR	Mid-range RADAR
ms	milliseconds
OBC	On-board Battery Charger
OBD-II	On-Board Diagnostics second generation
PCU	Power control unit
PDM	Passenger Door Module
RISC	Reduced Instruction Set Computing
RTK	Real-Time Kinematic
SoC	System-On-a-Chip
SRR	Short-range RADAR
TCM	Transmission Control Module
TOps	Trillion Operations per second
V2C	Vehicle-to-Cloud
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VCSEL	Vertical Cavity Surface Emitting Lasers

Footnotes

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[1] https://www.hemmings.com/blog/article/electronic-ignition-distributors/
[2] https://amp.usatoday.com/amp/86437052
[3] http://book.car2x.org/Vehicular_Networking_Slides.pdf
[4] http://web.iitd.ac.in/~achawla/public_html/736/18-Control Systems in Automobiles_v3.pdf
[5] https://www.autosar.org/standards/classic-platform/
[6] https://www.manualslib.com/products/Lanner-Lvc-5000-B3-8863869.html
[7] https://www.chipsetc.com/computer-chips-inside-the-car.html
[8] https://auto.howstuffworks.com/under-the-hood/trends-innovations/car-computer.htm
[9] https://www.slideshare.net/cisoplatform7/automotive-security-connected-vehicle-security-issues
[10] http://book.car2x.org/Vehicular_Networking_Slides.pdf
[11] pdf.datasheetcatalog.com/datasheet/motorola/MC68HC11KG4.pdf
[12] https://www.eeweb.com/profile/te-circuit-protection/articles/circuit-protection-automotive-devices
[13] http://www.formula1-dictionary.net/map_fuel.html
[14] https://www.youtube.com/watch?v=BG4N2dBgJrQ
[15] https://youtu.be/BG4N2dBgJrQ
[16] https://wiki2.org/en/CAN_bus
[17] https://www.andrew.cmu.edu/course/14-760-s19/applications/ln/14760-l17.pptx
[18] https://en.wikipedia.org/wiki/CAN_bus
[19] https://www.engineeringbookspdf.com/troubleshooting-automotive-computer-systems-by-happyson-gavi-and-charmaine-gavi/
[20] https://www.axiomatic.com/whatiscan.pdf
[21] https://en.wikipedia.org/wiki/General_Motors_Local_Area_Network
[22] https://news.voyage.auto/an-introduction-to-the-can-bus-how-to-programmatically-control-a-car-f1b18be4f377
[23] https://spaces.usu.edu/download/attachments/53053449/primer.pdf?version=1&modificationDate=1366417485000&api=v2
[24] https://knowledge.ni.com/KnowledgeArticleDetails?id=kA00Z0000019LzHSAU
[25] https://en.wikipedia.org/wiki/Ethernet#History
[26] https://en.wikipedia.org/wiki/Carrier-sense_multiple_access_with_collision_detection
[27] https://www.csselectronics.com/screen/page/obd2-data-logger-sd-memory-convert
[28] https://carcomputerexchange.com/blog/reprogramming-ecm/
[29] https://www.haltech.com/product-overview-elite-2500/
[30] https://en.wikipedia.org/wiki/Expert_system
[31] https://users.auth.gr/kehagiat/Research/GameTheory/12CombBiblio/TicTacToePilgrim.pdf
[32] https://github.com/utk3995/Automotive-Expert-System
[33] https://www.driverside.com/auto-library/fuzzy_logic_gearboxes-379
[34] https://www.bosch.com/stories/artificial-intelligence-community-based-parking/
[35] https://www.ford.com/technology/driver-assist-technology/enhanced-active-park-assist/
[36] https://cecas.clemson.edu/cvel/auto/AuE835_Projects_2009/pillai_project.html#Steer by wire
[37] https://youtu.be/jSg5UQlol0k
[38] https://owners.hyundaiusa.com/content/dam/hyundai/us/myhyundai/glovebox-manual/2019/nexo/2019 Nexo OM.pdf
[39] https://cn.mobis.co.kr/cmm/fms/FileDown.do?fileId=FILE_90000000017555&fileSn=0&fileNm=GMA_201812061151234800.pdf
[40] https://medium.com/@lance.eliot/parallel-parking-ai-ho-hum-challenge-for-driverless-cars-but-maybe-not-a28b75babbd7
[41] https://en.wikipedia.org/wiki/Hough_transform
[42] https://en.wikipedia.org/wiki/Canny_edge_detector
[43] http://pr.kia.com/en/innovation/adas/driving-assist.do
[44] https://thenextweb.com/artificial-intelligence/2018/03/23/affectivas-automotive-ai-could-keep-distracted-and-drowsy-drivers-from-causing-accidents/
[45] https://www.just-auto.com/analysis/pay-attention-drivers-your-car-is-watching-you_id173244.aspx
[46] https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/ida.html

---

[47] https://www.wsj.com/articles/gms-driver-assist-technology-promises-to-nag-1473413432

[48] https://www.mobileye.com/wp-content/uploads/2011/09/ForwardCollisionWarning.pdf

[49] https://www.hyundaiusa.com/us/en/vehicles/elantra

[50] https://docplayer.net/55006321-New-digital-services-powertrains-and-ownership-models-are-transforming-the-auto-industry.html

[51] https://www.media.volvocars.com/global/en-gb/media/videos/49628/adaptive-cruise-control-with-steer-assist

[52] https://www.zendesk.com/blog/machine-learning-and-deep-learning/

[53] https://medium.com/analytics-vidhya/ml-in-detail-1-pspnet-4527036af33b

[54] https://www.ansys.com/blog/challenges-level-5-autonomous-vehicles

[55] https://afdc.energy.gov/fuels/

[56] https://auto.howstuffworks.com/hybrid-car2.htm

[57] https://www.denso-ten.com/business/technicaljournal/pdf/35-2.pdf

[58] https://auto.howstuffworks.com/hybrid-car2.htm
ctric-hybrid-and-gas-powered-vehicles

[59] Introduction to Artificial Intelligence Second Edition ISBN 978-3-319-58486-7, P 15

[60] https://www.bmw.com/en/innovation/Plug-in-hybrid-and-other-kinds-of-electric-cars.html

[61] “Automotive Engineering” by David Crolla, ISBN 978-1-85617-577-7

[62] “Auto Repair For Dummies, 2nd Edition”, by Deanna Sclar, p. 193, ISBN 978-1-119-54361-9

[63] https://www.avnet.com/wps/portal/us/resources/article/technologies-components-designing-electric-vehicles/

[64] https://www.ti.com/product/BQ76PL536A

[65] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/what-a-teardown-of-the-latest-electric-vehicles-reveals-about-the-future-of-mass-market-evs#

[66] https://support.ixiacom.com/sites/default/files/resources/whitepaper/ixia-automotive-ethernet-primer-whitepaper_1.pdf

[67] http://delphi.com/news/pressReleases/pressReleases_2011/pr_2011_06_07_001/

[68] https://cecas.clemson.edu/cvel/auto/auto_buses01.html

[69] https://www.mostcooperation.com/

[70] “MOST - The Automotive Multimedia Network” by Andreas Grzemba. ISBN 978-3-645-65061-8

[71] https://www.ni.com/en-us/innovations/white-papers/06/flexray-automotive-communication-bus-overview.html

[72] https://www.cse.wustl.edu/~jain/cse570-19/ftp/auto_eth/index.html

[73] https://blogs.marvell.com/2020/10/ethernet-advanced-features-for-automotive-applications/

[74] https://cdn.intrepidcs.net/brochures/icsusa/Sample-AutomotiveEthernet-TheDefinitiveGuide.pdf

[75] https://www.automa.cz/downloads/streda15-00.pdf

[76] https://auto.howstuffworks.com/car-computer-virus.htm

[77] https://www.csmonitor.com/USA/2010/0813/Scientists-hack-into-cars-computers-control-brakes-engine

[78] https://www.wired.com/2015/07/hackers-remotely-kill-jeep-highway/

[79] https://www.guardknox.com/

[80] https://www.inceptivemind.com/xag-agricultural-robot-r80-conducts-disinfectant-spraying/12547/

[81] https://www.livescience.com/coronavirus-flatten-the-curve.html

[82] https://www.dell.com/community/Education-Services/How-Computer-Science-Helps-Feed-the-World/td-p/7080274

[83] https://spectrum.ieee.org/cars-that-think/transportation/self-driving/will-coronavirus-speed-adoption-of-driverless-technology

[84] https://www.sciencecover.com/3976-2-chinese-startup-udi-deploys-self-driving-vans-to-deliver-food-to-lockdown-areas/

[85] www.slideshare.net/joshsc/techcrunch-mary-meeker-2018-internet-trends-report

[86] Introduction to Artificial Intelligence Second Edition ISBN 978-3-319-58486-7, P 14

[87] https://towardsdatascience.com/the-future-of-technology-in-the-automotive-industry-11081c8a1999?gi=670445565768

[88] https://www.bloomberg.com/news/articles/2015-04-17/a-pew-survey-charts-global-car-motorcycle-and-bike-ownership

[89] https://en.wikipedia.org/wiki/Vehicle_subscription

[90] https://www.concannonbc.com/a-difficult-drive-autonomous-vehicle-sensor-limitations/

[91] https://en.wikipedia.org/wiki/Sensor_fusion

[92] http://book.car2x.org/Vehicular_Networking_Slides.pdf

[93] https://germanyenglishnews.com/german-news/2020/04/14/the-v2x-vehicle-to-everything-communications-ecosystem-2019-2030-opportunities-challenges-strategies-forecasts/

[94] https://www.teledynedalsa.com/en/products/imaging/infrared-detectors/microbolometers/

---

[95] https://www.designnews.com/electronics-test/open-source-solution-autonomous-vehicle-safety/158168972559137
[96] https://www.mdpi.com/1424-8220/19/6/1389/pdf
[97] https://en.wikipedia.org/wiki/Lunar_Laser_Ranging_experiment
[98] https://spectrum.ieee.org/cars-that-think/transportation/sensors/lumotive-says-its-got-a-solidstate-lidar-that-really-works
[99] https://arstechnica.com/cars/2020/01/most-lidars-today-has-between-1-and-128-lasers-this-one-has-11000/?amp=1
[100] https://www.fierceelectronics.com/components/jumping-hurdles-to-build-a-better-lidar
[101] https://www.laserfocusworld.com/blogs/article/14040682/safety-questions-raised-about-1550-nm-lidar
[102] https://velodynelidar.com/blog/guide-to-lidar-wavelengths/
[103] https://www.fierceelectronics.com/components/jumping-hurdles-to-build-a-better-lidar
[104] https://youtu.be/isjAYuwMsag
[105] https://www.thedrive.com/sheetmetal/16916/lidar-vs-RADAR-pros-and-cons-of-different-autonomous-driving-technologies
[106] https://www.fierceelectronics.com/electronics/to-lidar-or-not-to-lidar
[107] https://www.cetecom.com/en/news/frequency-ranges-for-automotive-RADAR-technology/
[108] http://site.ieee.org/rww-2018/files/2018/01/Sergio-Palma-Pacheco-RWW2018-presentation.pdf
[109] https://www.libertymutual.com/righttrack-plugin
[110] https://en.wikipedia.org/wiki/Usage-based_insurance
[111] https://www.lsxmag.com/news/would-you-plug-in-for-a-safe-drivers-discount/
[112] “Magic Motorways” by Norman Bel Geddes, p73
[113] https://en.wikipedia.org/wiki/OnStar
[114] https://www.airbiquity.com/product-offerings/software-and-data-management
[115] https://www.roadandtrack.com/car-culture/a33179/the-secret-story-of-tuckers-failed-massive-engine/
[116] http://www.cleanfuture.co.in/2020/03/06/kuka-automated-charger-for-ev/
[117] https://www.pluglesspower.com/learn/solve-last-mile-vehicle-autonomy/
[118] https://www.store-dot.com/ev
[119] https://www.audiworld.com/forums/a4-b5-platform-discussion-1/how-long-does-take-fill-your-car-gas-142749/
[120] https://techcrunch.com/2019/11/04/bmws-magical-gesture-control-finally-makes-sense-as-touchscreens-take-over-cars/
[121] https://www.aware.com/blog-biometrics-on-the-road-to-automotive-identity/
[122] https://www.vox.com/2017/5/23/15681058/digital-car-automotive-industry-software-designed-disruption
[123] https://www.nvidia.com/en-us/self-driving-cars/drive-platform/hardware/
[124] https://www.forbes.com/sites/tiriasresearch/2020/01/06/qualcomm-targets-autonomous-vehicles-with-snapdragon-ride-platform
[125] https://www.embedded.com/data-flow-issues-may-slow-down-robo-car-emergence/
[126] https://www.eei.org/resourcesandmedia/newsroom/Pages/Press Releases/EEI Celebrates 1 Million Electric Vehicles on U-S- Roads.aspx
[127] https://www.gsaglobal.org/wp-content/uploads/2019/05/Trends-of-Future-EE-Architectures.pdf
[128] https://www.ventureoutsource.com/contract-manufacturing/vehicle-electronic-control-unit-consolidation-targets-the-self-driving-autonomous-car
[129] https://www.intel.com/content/www/us/en/automotive/ecu-consolidation-benefits-paper.html
[130] https://projectacrn.org/
[131] https://www.sbg-systems.com/wp-content/uploads/Ellipse_Series_Leaflet.pdf
[132] https://en.wikipedia.org/wiki/Kalman_filter
[133] vboxautomotive.co.uk/index.php/en/how-does-it-work-rtk
[134] https://en.wikipedia.org/wiki/Real-time_kinematic
[135] https://www.extremetech.com/extreme/283632-self-driving-industry
[136] https://www.prnewswire.com/news-releases/automotive-ethernet-hits-the-road-in-wide-range-of-new-vehicles-300159260.html
[137] https://blog.samtec.com/post/connectors-for-the-automotive-world/
[138] https://www.perforce.com/resources/qac/autosar-basics-introduction-autosar-coding-guidelines
[139] https://www.fool.com/investing/what-does-the-future-hold-for-self-driving-cars.aspx