THE FUTURE OF DRIVING: A LOOK INTO THE TECHNOLOGY BEHIND AUTONOMOUS VEHICLES

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Introduction

Imagine how life would be like if a car could simply drive its passengers around anywhere they wanted to go without any manual control. Passengers would not have to worry about controlling the steering wheel, paying attention to the roads, slowing down, braking, or even knowing any directions. They would not have to worry about a pedestrian suddenly running out in front of the vehicle, or if a sudden traffic jam causes a horrific accident because they could not stop in time. Passengers would be able to catch up on sleep, eat, watch a movie, or even read a book, as the car fully operates by itself and drives them safely to their destination. All of these different scenarios introduce the new idea of an autonomous, or self-driving, car. By definition, an autonomous car is a vehicle that is capable of sensing its environment and navigating without any human input. It is able to detect its surroundings using a variety of techniques including Radar, Laser Illuminating Detection and Ranging (LIDAR), GPS and computer vision (Wright 2015). An autonomous vehicle is essentially a “smart” car that would be able to constantly detect its surroundings and safely prevent passengers from encountering any incidents. It would sense an upcoming road blockage or traffic jam from miles away. It would be familiar with its environment and quickly react to and prevent any sudden driving encounters. It would alert the passengers if there is an emergency, and more importantly, it would help prevent numerous car crashes that occur every single day. As impossible as this may sound, autonomous vehicles have quickly become a reality. “Google says that driverless cars will dominate the roadways in the near future and that 90% of the 1.2 million global fatalities due to auto accidents could be avoided with driverless cars” (McDonald 2013). From this day forward, the powerful technology behind autonomous vehicles could eventually change the world.

Autonomous vehicles would be an improved resource for those who are not physically capable of driving a vehicle. The technology would be so intelligent and dominant that an incapable individual could simply sit in the car and arrive safely to their destination. Technology is very powerful nowadays, and this revolutionary idea could actually become a reality one day. In fact, it already has become part of our reality in 2016. Recently, there have been many manufacturers and automotive companies that have begun the process of creating autonomous vehicles. Companies like Tesla, Google, BMW, Ford and Delphi, have even begun testing their vehicles on roads to see how well the vehicle interacts with different environments. Other companies have even proposed timelines as to when their self-driving vehicles will be available to the public. A recent article from MIT stated that "Ford and BMW have promised to have an entirely autonomous vehicle on the road by 2021" (Condliffe 2016). Additionally, Nissan has also announced that they will be introducing a "revolutionary, commercially-viable autonomous drive in multiple vehicles by the year 2020" (McDonald 2013). It is extraordinary to think that in less than a few years, autonomous cars will be available to the public and could eventually dominate the automotive industry, changing the lives of millions of drivers. With all the research and technology that is accessible today, there is no doubt that autonomous vehicles are going to have a huge impact on humans and change the future of driving.

Current Research

There is an abundance of research as well as discussion about how future advancements in technology will eventually transform the automotive industry. According to McDonald, there have been many improvements made to radars, cameras, and motion sensors, in order to create autonomous vehicles (McDonald 2013). McDonald mentions how self-driven cars will eventually take over the automotive industry within the next decade, due to the new technological innovations. However, for this to happen, there will need to be significant changes made to normal vehicles. For example, manufacturers of these autonomous vehicles would need to enhance the connectivity and sensors of the car, so that it can be programmed to think and react accordingly. One article titled "Self-Driving Cars," explains how some autonomous vehicles use Advanced Driver Assist Systems (ADAS), which basically uses "a combination of advanced sensors, such as stereo cameras and long- and short-range radar, combined with actuators, control units, and integrating software, to enable cars to monitor and respond to their surroundings." In other words, an autonomous car would need to have the technological intelligence and capability to think and navigate entirely on its own.

Furthermore, there have been a few institutions that have started to test their autonomous vehicles by creating real-life driving scenarios. For example, The University of Michigan has recently created what is known as Mcity, which is a "32-acre microcosm of motoring complete with faded stop signs, roundabouts, lousy weather and out-of-date traffic signals" (Shankland 2015). They are creating their own autonomous operating system and testing it in within their institution. Mcity is ultimately trying to see if the cars can overcome even the most difficult driving scenarios, so that they can determine how to further improve upon them.

There are also data reports published by various companies working on autonomous technology, such as Google and Delphi, that provide autonomous driving data, including the autonomous vehicle's average miles driven, the number of emergencies encountered, and the overall disengagement conditions of the vehicles. The Department of Motor Vehicles (DMV) defines a disengagement as the time when "a failure of the autonomous technology is detected," and also "when the safe operation of the vehicle requires that the autonomous vehicle test driver disengages the autonomous mode and takes immediate manual control of the vehicle" ("Google

Self-Driving Car Testing Report…”). Examining the vehicle’s disengagement report would provide a tremendous amount of feedback to the manufacturers, especially when it comes to identifying and improving the overall causes of the disengagement. Ultimately, this data could help in significantly reducing the number of faults that autonomous cars currently incur.

Disadvantages of Autonomous Vehicles

Although there have been countless discussions about the benefits of autonomous vehicles, there is still a large cloud of criticism surrounding this new technology. Since autonomous driving is a very new concept, it would be a tremendous change in the lives of many drivers. A large number of people are opposed to self-driving cars simply due to the preconceived notion that they are still a technological product, and therefore, could be subject to hazardous defects, especially when they are meant for everyday driving. Automakers are trying to make autonomous vehicles as flawless and as harmless as possible. The whole idea behind a self-driven car would be to program the vehicle exquisitely so that it could detect and be alert to every possible act of danger there could be while driving, while ensuring passengers simply remain seated in the vehicle. According to the article “Long Road Ahead,” around “65% of the 1,000-plus consumers surveyed felt self-driving vehicles were an ‘extremely dangerous idea’” (Kinkhammer 2015). That small survey alone is concerning to automakers, since they want their customer base to eventually be everyday drivers. To add to this, there has been more talk about the negative impacts of autonomous vehicles not only from consumers, but also from several different industries. One theory suggests that once autonomous vehicles are introduced in the market, they could negatively affect the economy and certain industries within it, such as insurance companies. Kinkhammer states that the costs of autonomous vehicles will cause “an economic stimulus of around two trillion dollars a year” (Kinkhammer 2015). This is due to the fact the vehicles will ultimately help reduce collisions, therefore minimizing the need of more paramedic assistance, auto repair shops, and more importantly, insurance companies. This would result in a massive unemployed population, and all of the companies associated with automobiles would undeniably lose significant amounts of money. Also, if autonomous vehicles help reduce accidents with other vehicles and objects on the road, the demand for car parts and vehicle maintenance would significantly decrease, ultimately leaving a huge negative impact on the economy.

Many people also are hesitant about autonomous vehicles due to the fact that the vehicle is essentially a robot that is replacing a human driver. Driving is already considered a risky activity; many people would agree that putting their lives in the hands of a robot is not safe, as technology may be unpredictable and can often malfunction. Although many uncertainties surrounding autonomous vehicles exist, there are more benefits than risks. This paper will mainly explore the benefits of having autonomous vehicles in the market and further explain the technology that creates these extraordinary systems.

Background of Autonomous Vehicles

It is extremely important for drivers to learn more about the technological changes being made to normal vehicles. This will help familiarize them with the technology behind autonomous vehicles, understand how the car will essentially operate by itself, and see how it will affect their travel in the future. This paper will explore the technology and software behind Google, Autonomous Vehicle Systems and Delphi's autonomous vehicles.

Many people are not aware of that fact that technological creators of self-driven vehicles are using the same software and technology that is currently being used on the road in normal vehicles (Clark 2015). When people think of autonomous vehicles, they believe that automakers are using an entirely different, non-tested software that might not necessarily be safe. However, this is not the case whatsoever. Automakers are using the same safe and tested technology that's currently used in a non-autonomous vehicle, and they are simply tweaking the mechanical aspects and software, in order to make the vehicle fully autonomous.

A Look into Google's Autonomous Technology

The technology used in a typical autonomous vehicle will be very similar; however, each company that invests in the creation of a self-driving vehicle will have their own unique operating system. First, it is extremely important for an autonomous vehicle to have a set of cameras around its entire body. This is essentially how the vehicle would be aware of its surroundings, and more importantly, be able to react accordingly within its environment. According to an article by Clark, "one of Google's prototypes uses cameras mounted to the exterior with slight separation in order to give an overlapping view of the cars' surroundings" (Clark 2015). Clark also explains how the majority of the cameras on Google's vehicles would have a 50-degree field of view and would ultimately be accurate to about 30 meters. In addition to cameras, an autonomous vehicle would require a unique programmed software to properly function. Google's software includes a combination of Laser Illuminating Detection and Ranging (LIDAR), sonar, radar, and positioning. LIDAR has a 3-D map and allows the vehicle to "see" any potential hazards before them. This process occurs by "bouncing a laser beam from surfaces surrounding the car in order to accurately determine the distance and the profile of that object" (Clark 2015). The LIDAR system is currently being used in Google's self-driven car, and "it can accurately see up to a range of 100 meters, using a Velodyne 64-laser beam that rotates 360-degrees, taking up to 1.3 million readings per second" (Whitwam 2014). This laser machine that is being used by Google is placed on top of the vehicle and it must be linked up to the "brain" of the vehicle. LIDAR has a very detailed preloaded map that includes all of the traffic signals and lights, followed by any crossways that are around the area. Figure 1 below shows what the LIDAR system currently looks like on Google's autonomous vehicle.

***Figure 1**: Google's current LIDAR system*

***Source:** Bryan Clark: "How Self-Driving Cars Work: The Nuts and Bolts Behind Google's Autonomous Car Program"*

In addition to LIDAR, radar technology would be used to monitor the speed of all the surrounding vehicles while driving. The way the radar works is that the vehicle would have a total of four bumper-mounted radar units on both the front and rear bumpers, allowing the car to sense its surroundings and alert the on-board processor, also known as the "brain" of the vehicle, to either apply the brakes or to move into a separate lane or available area in order to safely avoid any collisions (Clark 2015). Google's radar system can detect surroundings up to 200 meters away, while their sonar can only detect up to 6 meters away (Whitwam 2014). Both radar and LIDAR would work closely together to cautiously map out all of the vehicle's surroundings, and automatically apply either pre-tension on the seatbelts or the brakes in case of an emergency.

LIDAR and radar ultimately work together to help ensure that the vehicle is alert and ready to take action, in case of an unexpected situation.

The Positioning and GPS software technology has been greatly improved for autonomous vehicles as well. Google has created their very own map positioning system that includes GPS satellites, inertial measurement units, their unique map system, and a wheel encoder to accurately determine the speed of the autonomous vehicle, as well as the vehicles around it (Clark 2015). This entire positioning system works with the cameras embedded on the vehicle, so that it may determine the precise location of all other vehicles, "down to a few centimeters," as well as how far away the next stoplight or traffic signal is (Clark 2015). Google's positioning technology is so advanced that it also processes real-world information from the cameras so that the vehicle is made aware of any sudden changes while driving, such as unexpected road blockage or any accidents. Furthermore, the vehicle's software allows it to properly make adjustments to these changes on its own, upon initial detection (Clark 2015). In addition, Google's autonomous vehicles include a high-resolution video camera inside the car, which helps detect pedestrians, bicyclists, traffic signals, as well as any other moving obstacles. Along with its GPS system, it tracks any object's position with an inertial motion sensor (Brown 2011). This is extremely helpful for the vehicle when it is driving, since it will need to know the speed and placement of other objects and vehicles within its vicinity.

The software behind autonomous vehicles is both unique and sophisticated enough to allow the vehicle to continuously learn and process countless situations that it encounters while driving. Google has programmed its autonomous vehicle to obey simple driving etiquettes such as stopping at red lights, slowing down at yellow lights, and signaling if it wants to turn either right or left (Clark 2015). However, each time the vehicle is driven, all the miles are logged, and all the information from any incidents that were picked up while driving are all stored so that the vehicle is able to learn and adapt to any similar incidents in the future. Not only does the software allow the autonomous vehicle to process and store data from its own driving encounters, but it also is programmed to monitor and process the behavior of other driving vehicles surrounding it. The software uses a technique called behavioral dynamics, which is a descriptive analysis of the behavioral patterns that cause certain external behavior ("What is Behavioral Dynamics?"). In other words, Google's sophisticated software has the ability to learn and recognize the behavior of other vehicles while driving, and it can process all of that data in order to quickly recognize and find the most appropriate response to each of the problems that the vehicle encounters. According to Clark, the cars are able to recognize and acclimate to the following situations: a pot hole or any type of foreign object in the street that would cause a driver to swerve, a slow-moving car in the right lane suggesting that the vehicle behind it will speed up to try to pass this car in the left lane, or if a vehicle suddenly signals that they want to turn right and brakes immediately, there is a high probability that the vehicle behind would try to swerve into the other lane so that it would not have to slam on its brakes or reduce its speed (Clark 2015). This software is basically allowing the vehicle to establish its own memory, therefore, relying on only itself and its experiences, to properly navigate autonomously.

The technology behind self-driven vehicles must be so precise and accurate since it is substituting the physical presence of a human behind the steering wheel. In normal vehicles, humans are the ones with the "cameras" in their eyes, watching the road and reacting accordingly. The human brain processes the information from previous and current scenarios, and decides how to react to the different environmental conditions. Humans decide which direction to take and they use their hands and legs to control their vehicle. A car is essentially a machine that does not work unless someone physically turns it on and directs its every move. The purpose of an autonomous vehicle is to eliminate the human operation side, by simply allowing the vehicle to act just as a human would and ultimately operate by itself. This further supports the idea that both the software and technology behind autonomous vehicles must be very intelligent and reliable in order to prove to the public just how safe this technology is.

Each manufacturer of autonomous cars may have some differences when it comes to the type of software and technology that they want to use. By examining how Google is currently developing software for their cars, one can see that the most crucial pieces of technology in self-driven cars is the use of LIDAR, radar and sonar technology. This next section will further investigate what another manufacturer, Autonomous Vehicle Systems, is creating in their version of this vehicle.

A Look into Autonomous Vehicle System's Autonomous Technology

Autonomous Vehicle Systems (AVS) is a team of industry professionals and scientific researchers with expertise in advanced sensor development, unmanned aerial vehicle (UAV) development, autonomous navigation and control, software development, and high performance vehicle modifications (Autonomous Vehicle Systems). They are primarily a research company located in San Diego, California. When it comes to their work on autonomous vehicles, their technology is very similar to Google; however, they have their unique differences. In addition to LIDAR, radar, cameras, and sensors, AVS uses its own unique computation, actuation, and navigation systems (Autonomous Vehicle Systems). The computation system, or the "brain," is referred to as the Vehicle Autonomous Management Processors In Real-time Environments (VAMPIRE), and it consists of "9 high-speed processors interconnected by the fastest network system available today" (Autonomous Vehicle Systems). These nine processors each focus on a different task; for example, making the vehicle move a certain direction, processing sensor data and determining how to respond, or even mapping out directions for the vehicle to follow. AVS also developed a Base Autonomous Test System (BATS), which is used to monitor the vehicle while it's in operation. BATS monitors the health of any component of the vehicle, and the system sensors provide live feedback to the vehicle, making it aware of any issues. BATS along with the VAMPIRE system both work together in order to ensure safe and smooth driving. "The VAMPIRE system manipulates a series of actuators and relays that can control the vehicle" (Autonomous Vehicle Systems). Just like in a normal vehicle, the driver would control the steering wheel, brakes, and gas pedal; however, the actuation system in AVS self-driven cars would control everything all by itself, eliminating the need for a human driver. Finally, for their navigation systems, AVS, like Google, uses Global Positioning System (GPS) in order to determine the precise position of each vehicle using the constellation of satellites currently orbiting the Earth. In addition to GPS, they also use Inertial Navigation Systems (INS), in order to determine the exact vehicle position, proving to be extremely helpful in times where the GPS coverage is lost due to environmental factors (Autonomous Vehicle Systems). According to the AVS website, there have been recent developments to mm-wave Radar scanning, which will help to avoid collisions due to obscured weather such as dust, smoke, fog, snow, etc. Environmental factors play a huge role in autonomous driving. For the vehicle to have the ability to sense certain weather or environmental conditions, and not have them negatively affect driving is a huge benefit to both the automakers and the consumers of these vehicles. For the most part, the technology and software behind autonomous vehicles is primarily the same, however, depending on each manufacturer, there will be slight differences, and it is important for drivers and the public to be aware of these differences to see how and what is being done to transform normal vehicles into autonomous vehicles. In this next section, we will explore one last manufacturer, Delphi Automotive, and see how their autonomous technology compares to both Autonomous Vehicle Systems and Google.

A Look into Delphi Automotive's Autonomous Technology

Delphi Automotive PLC is a high-technology automotive supplier that integrates safer, greener, and more connected solutions for the automotive sector. Currently, Delphi only creates the technology and partners with software companies in developing the entire autonomous operating system, so that they can eventually sell to automakers, as the company will not be selling autonomous vehicles under their own name (Krok 2016). Being the 12th largest global OEM automotive supplier, and a world leader in automated driving software, sensors, and systems integration, Delphi has more than half-century's worth of experience with the unique technology that is used in autonomous driving. They are also the world's first supplier to have a fully autonomous vehicle to have completed a coast-to-coast trip across the United States, in the summer of 2016. Needless to say, Delphi is certainly on the verge to success in the automotive industry. When examining the software and technology that Delphi uses on its autonomous vehicle system, it has some similarities to the software and technology of both Google and Autonomous Vehicle Systems. Delphi's CEO, Kevin Clark, states in an interview that Delphi defines the words "active safety" by their current radar and vision systems, used on normal vehicles, but not yet LIDAR—which will however be ready in 2019 (Sedgwick 2016). He also mentions that those same three sensors, vision, radar, and LIDAR, are the main components needed for an autonomous vehicle to operate on its own, and will be added to Delphi's autonomous vehicle system. Clark adds that Delphi's "sweet spot" is in vehicle-to-vehicle (V2V), and vehicle-to-infrastructure (V2I), and this has already given the company a slight advantage when it comes to developing the high-technology behind these self-operating cars (Sedgwick 2016). The way that Delphi's current wireless vehicle communication technology works is that it "extends the range of existing advanced driver-assistance-system functionality, using radio signals to transmit traffic data from vehicle to vehicle to alert drivers of potential road hazards (Amend 2014). The software behind the vehicle would be able to detect and alert the passengers of any danger ahead. Delphi also provides both radar and vision systems, such as adaptive cruise control and lane-keeping (Amend 2014). However, the major attribute that is lacking with Delphi's current technology for normal vehicles, is of course the autonomous vehicle technology, as they cannot fully engineer it by themselves. This is why Delphi has partnered up with software companies, in order to help them fully create a safe and effective autonomous vehicle system.

Back in November 2016, Delphi announced that it was going to partner with Mobileye, a technology company specializing in advanced driver assistance systems, along with Intel, in order to build an advanced autonomous car system that they could sell to automakers within the next few years. According to Boudette's article, Intel is supplying Delphi with highly-powered processors for their autonomous efforts, and it is expected that they will be using the Core i7 Intel chip, which is capable of computing about 20 trillion mathematical operations per second (Boudette 2016). Autonomous cars need to be able to process an extremely large amount of data, all in real time, therefore ensuring that the vehicle is constantly aware of its situation and can react to any given scenario. This process will require increasingly complex computer brains that will magnify the technology that is currently being used in normal automobiles today. For this reason, all three of these companies will be contributing something unique to their autonomous vehicle program, helping to ensure that they will create the strongest autonomous vehicle system to eventually sell to automakers. Delphi will primarily focus on creating sensors, software, and system integration, while also integrating algorithms from their Ottomatika acquisition, which includes Path and Motion Planning features, and Delphi's own Multi-Domain Controller with radar, LIDAR, and a camera ("Delphi and Mobileye to Conduct…"). Mobileye will concentrate on refining their mapping, computer vision, and machine learning, and Intel will be providing specialized computer chips that will be able to process the entire driving process all in real time (Krok 2016). The work from all three companies will be put together to form a very strong and unique type of autonomous driving. An article published by The New York Times in November 2016 states that Intel, among other technology and chip-making companies, isn't the first to collaborate with automotive companies in creating the autonomous vehicle technology (Boudette 2016). There have been other companies like Intel, such as Nvidia and Qualcomm, that have already obtained their means of access in the world of autonomous driving. Of course, before deciding on who to collaborate with, an automaker must explore what other companies could potentially offer, and most importantly, see if they are aligned with their overall company strategies and ideas. In this case, both Delphi and Mobileye could have chosen to partner with any other technologic company, especially one that has already began working with other automotive companies. According to Boudette's article, Delphi's CTO, Glen De Vos, mentioned that the reason Delphi chose to partner with Intel in the first place is because "Intel had a plan to produce increasingly powerful automotive processors, and the scale to make the system affordable for mainstream cars" (Boudette 2016). This statement from Intel aligned with Delphi's strategies for autonomous vehicle technology, and thus, is the reason why Delphi and Mobileye chose to partner with them.

There is no doubt in saying that Delphi's partnership with both Mobileye and Intel will put them at a slight advantage in the autonomous world, due in part to the complexity and distinctiveness of the technology behind their self-driving software. They are surely making themselves well-known to automakers and further proving to society that they have created extraordinary autonomous technology. According to a recent article published on Delphi's website, Delphi and Mobileye are scheduled to conduct "the most complex automated drive ever publicly demonstrated on an urban and highway combined route in Las Vegas for the 2017 Consumer Electronics Show ("Delphi and Mobileye to Conduct…"). The article mentions how Delphi and Mobileye will be able to showcase their Centralized Sensing Localization Planning (CSLP) automated driving system through a 6.3-mile drive that will tackle all types of everyday driving challenges such as crowded streets, unexpected vehicle merging, tunnels, bridges, pedestrian interference, etc. During the CES show, Delphi and Mobileye will have a chance to highlight the uniqueness of their technology which will include the following: localization capability—which will ensure that the vehicle knows its location within 10 cm without any connection to GPS, path and motion planning—which allows the car to behave more "human-like," free space detection—which helps the car navigate complex lane splits or areas that do not have any visible lane markings, 3D vehicle detection—which can detect vehicles at any angle by identifying their shapes and movements, and 360-degree pedestrian sensing ("Delphi and Mobileye to Conduct…"). With more and more companies partnering together to work on autonomous programming and design, companies like Delphi and Mobileye must differentiate themselves in order to prove to the actual automakers of these vehicles that their technology is the safest and most reliable to use. Overall, it is extremely beneficial to understand a company's unique technology behind self-driving cars, as it will provide more knowledge to the public. As time goes on, and as companies continue to develop their technology, there is no doubt in saying that the majority of roads all over the world will be filled with more “robots,” otherwise known as the self-driving vehicles.

Current Testing of Autonomous Vehicles at University of Michigan’s “Mcity”

Upon exploring the autonomous technology from Google, Delphi, and Autonomous Vehicle Systems, one can see many similarities and differences that are associated in the creation of self-driving cars overall. However, before these automakers will allow their vehicles on the market and let your average driver use them, they must perform extensive tests on their vehicles, to see how they will react in the most dangerous and problematic driving scenarios. With that being said, there is a new project, originating from Michigan, specifically for the automakers of these autonomous vehicles to test-drive their cars in very unique driving environments. This project is called Mcity, and it is a “32-acre microcosm of motoring complete with faded stop signs, roundabouts, lousy weather and out-of-date traffic signals” (Shankland 2015). The director of the University of Michigan’s Transportation Research Institute, Peter Sweatman, is the founder of this project. Mcity is located in Ann Arbor, Michigan, 30 miles west of Detroit, which is the motor city of the world. Mcity’s location is also perfect since the big three automakers, as well as other automotive companies, are all nearby and can work with Mcity to test their autonomous vehicles (Shankland 2015). The main purpose of the Mcity project is to provide a real-world setting where autonomous vehicles can be tested in the safest, controlled, and realistic driving conditions, since after all, every driving experience is different, and it can be unexpected what one can experience while driving. Sweatman describes Mcity as “an environment for advancing connected and automated technologies,” and he explains how the public desperately needs a space like this, in order to test autonomous driving (Shankland 2015). This 32-acre area is fully designed to have freeways, ramps, bridges, roundabouts, suburban streets, traffic circles, complex skewed intersections, mechanized pedestrians/cyclists, different weather conditions, a variety of traffic signals, and even different roadway surfaces, such as brick, concrete, asphalt, etc. Figure 2 below illustrates the current layout of Mcity.

Figure 2: *A View of University of Michigan's "Mcity" Project*

Source: *University of Michigan Mobility Transformation Center Website: "U-M opens Mcity test environment for connected and driverless vehicles"*

Mcity focuses on enhancing their connected technology, such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). They also believe that safety is the most important part of driving, and for this reason, the vehicle must be able to detect its surroundings and react accordingly. This is where Mcity is extremely useful. In a hypothetical situation, where for instance, five cars ahead of a non-autonomous vehicle suddenly start braking, the driver in that vehicle is not fully able to see the taillights of those vehicles far ahead of them starting to break.

This situation would most likely result in that driver to unexpectedly slam on their brakes, possibly not even in time to avoid the vehicles around it, and therefore causing an accident. With the environmental technology that Mcity is creating to enhance autonomous vehicles, Sweatman explains how Mcity's radio communication ability will be able to detect the braking of the vehicles ahead. This detection will then cause the autonomous vehicle to slow itself down safely, simply by sensing the electronic brake lights that were ahead of the autonomous vehicle, and thus, preventing an accident (Shankland 2015). This example further proves that the technology and unique environmental situations currently being applied at Mcity are an extremely helpful tool for automakers to further improve their autonomous systems before they enter the market.

When asked in an interview how Mcity is compared to other companies' approaches to testing in the real-world, Sweatman explains how Mcity, unlike Google, is actually producing the most unusual and challenging situations, and continuously changing them so that they are able to strengthen their facility and technology overall (Shankland 2015). Another difference is that Mcity is testing out their vehicles with the public. In other words, they are allowing volunteers, with little to no experience about autonomous vehicle technology, to experience riding in an autonomous vehicle, while of course providing feedback to Mcity. This is a great advantage for Mcity because not only do they get to receive feedback from outsiders, but they also get a chance to expose their extraordinary technology to a small section of the public, and further demonstrate how autonomous driving will work.

With that being said, there is currently no other institution in the world that is similar to what Mcity has created, and this is why they have a huge advantage and exclusivity in what they have accomplished thus far. Located in the motor city of the world, they have helped and will continue to help the automakers in Michigan advance in the race towards autonomous driving.

Mcity, which is funded by the Mobility Transformation Center at the University of Michigan, is currently working closely with 15 other companies, who are investing in their project and working together to improve autonomous driving. Some of those companies include Delphi Automotive PLC, Ford Motor Co., General Motors, Robert Bosch LLC, Iteris Inc., and Qualcomm Technologies, Inc. ("U-M Opens Mcity…"). As time progresses, additional companies have also started to invest in Mcity, since it truly is a one-of-a-kind driving assessment for self-driving cars. Overall, the earlier these companies start to test and improve their technologies with the help of Mcity, the earlier the public may start to see autonomous vehicles in operation.

Statistical Analysis of Google's Autonomous Vehicle Disengagement Report

This next section will explore the progress of autonomous vehicles test-driving in real-life driving scenarios. Two companies, Google and Delphi, have already begun testing their vehicles on the roads and they have shared their results with the public. Reviewing a disengagement report will be extremely beneficial to the automakers of the autonomous vehicles. Google and Delphi can understand their issues in more detail and further implement changes to improve their vehicle's operating system. Google's disengagement report will be examined first.

Because autonomous driving is a fairly new concept, it is not necessarily allowed in every state. The California Department of Motor Vehicles (DMV) has allowed Google to practice autonomous driving, agreeing that the company must submit a report listing out all of the vehicle's disengagements that have occurred on any public roads in California. The DMV defines the word disengagement as "when a failure of the autonomous technology is detected," and also "when the safe operation of the vehicle requires that the autonomous vehicle test driver disengage the autonomous mode and take immediate manual control of the vehicle" ("Google

Self-Driving Car Testing Report…”). This disengagement report, provided by Google, is an extremely valuable tool because it captures everything that occurs in the vehicle when it is driving autonomously. This report is a very valuable tool that can help the creators of the technology learn more about what works and doesn’t work well, and more importantly how they can continue to improve details of the vehicle so that it can be more effective and safer. The results in Table 1 below show both the number of miles driven on public roads, and the number of disengagements that occurred during Google’s testing period.

Month	Number of Disengages	Autonomous Miles Driven on Public Roads	Average Number of Disengagements per Mile Driven
2014/09	0	4,207.20	-
2014/10	14	23,971.10	1,712.22
2014/11	14	15,836.60	1,131.19
2014/12	40	9,413.10	235.33
2015/01	48	18,192.10	379
2015/02	12	18,745.10	1,562.09
2015/03	26	22,204.20	854
2015/04	47	31,927.30	679.30
2015/05	9	38,016.80	4,224.09
2015/06	7	42,046.60	6,006.66
2015/07	19	34,805.10	1,831.85
2015/08	4	38,219.80	9,554.95
2015/09	15	36,326.60	2,421.77
2015/10	11	47,143.50	4,285.77
2015/11	6	43,275.90	7,212.65
Total	**272**	**424,331**	**1,560.04**

Table 1: *Comparison of Number of Disengagements and Average Miles Driven per month on Public Roads*

According to Table 1, there was a total of 272 disengagements recorded. The maximum number of disengagements per month occurred in January 2015, with a total of 48 total incidents reported. The second highest number of recorded disengagements was in April 2015, with a total of 47 incidents reported. The minimum number of disengagements per month was recorded in

September 2014, with no record of disengagements of any sort. The average number of disengagements was 18, and the overall standard deviation is 15 disengagements.

Table 1 also shows the number of miles that were driven per month. Google had operated its autonomous car for over 1.3 million miles, and according to Table 1, 424,331 of those miles occurred on public roads in California ("Google Self-Driving Car Testing Report…"). The maximum number of miles that was driven by Google's autonomous car was in October 2015, where Table 1 shows the vehicle drove a total of 47,143.50 miles. The minimum number of miles driven was in September 2014, with a total of 4,207.20 miles. The average number of miles driven over the 14-month period was 28,288.70 miles. The standard deviation was 13,155.40 miles. Overall, these results show the number of driver-initiated actions that resulted in a disengagement of the vehicle, in order to prevent it from an accident. Table 1 also shows the average number of disengagements per mile driven for all 14 months. The highest average number of disengagements per mile driven was in August 2015, at 9,554.95 miles. This means that a disengagement occurred at an average of around 9,554.95 miles during this month. The lowest number of disengagements per mile driven was in September 2014, as there were no disengagements reported during that month. In addition, the autonomous miles driven by Google's vehicle had steadily been increasing over time. Part of Google's testing procedures includes switching their vehicle in and out of autonomous mode several times a day, in order to allow for more technological improvements to be made to the vehicle. Table 1 shows that there are some months where their vehicle drove more miles than other months. Because safety is Google's highest priority, they ultimately want to invest more time improving their operating system so that it is able to drive more miles with less disengagements reported. During months where there weren't many technological changes being done to the vehicle, Google's self-driving car was able to drive more miles by itself, thus resulting in the steady increase of miles reported over the 14-month period.

In Google's ongoing stage of testing, test drivers sit in the vehicle while it drives by itself, and they are directed to manually take control of the vehicle as often as they feel possible, in cases that they are seeing an issue or if they believe that the vehicle cannot handle a certain situation by itself. As they are doing that, the vehicle automatically records this instance and captures the situation even before the driver manually takes charge, so that when the software team reviews all these incidents, they can fully see the reasoning behind the driver taking manual control. They can also determine how they can further improve this incident so that when it happens again, the vehicle will be intelligent enough to direct itself, therefore preventing a disengagement from occurring in the first place.

Figure 3 below illustrates a better visualization of the significant reduction of disengagements over a span of a year, from the fall of 2014 to 2015. Again, the graph is showing that the highest record of disengagement incidents were in the months of January and April of 2015. The number of disengagements suddenly decreased in February 2015 and then increased again in April and then steadily decreased over time, all the way until November 2015. This further supports the fact that the more testing and monitoring that's being done, the more the creators of these self-driving vehicles can continue to learn and improve upon them, and eventually start reducing the amount of disengagements that occur.

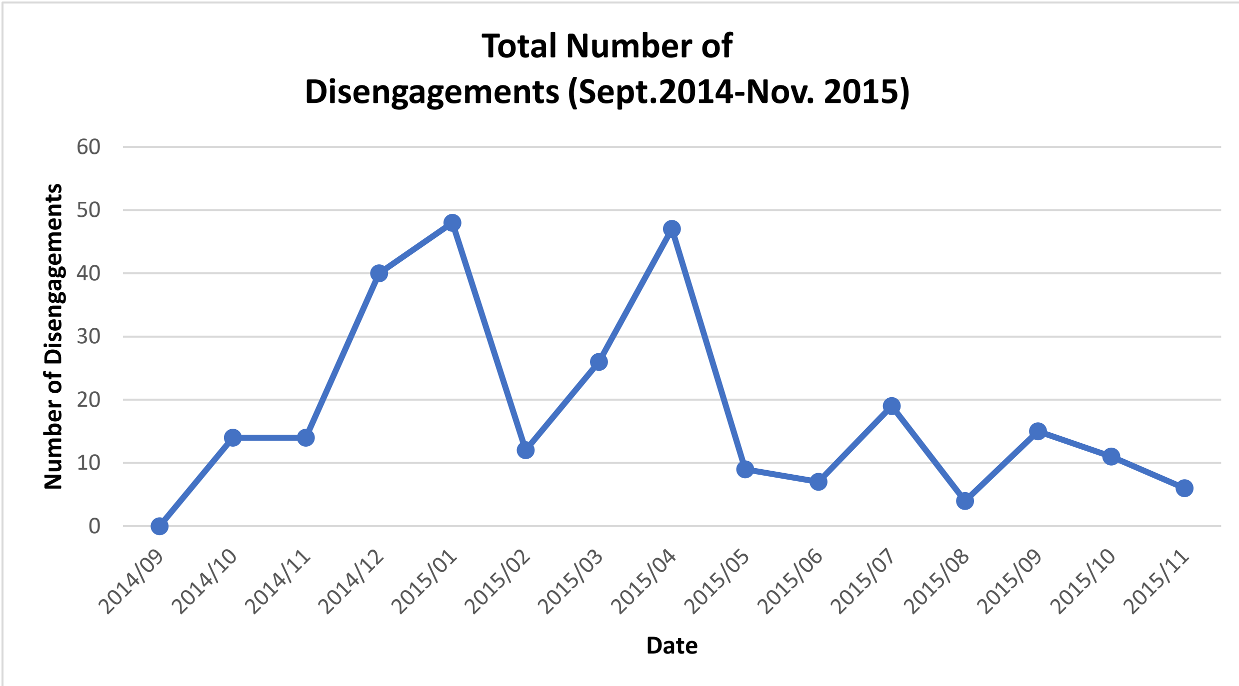

Figure 3: *Google's Number of Autonomous Car Disengagements from 2014-2015*

Looking deeper into the root cause of the disengagements, Google provides data showing the cause of each disengagement that prevented their autonomous vehicle from driving entirely by itself. A total of 341 disengagements were recorded in Google's disengagement report. The results shown in Figure 4 below illustrate that the most frequent disengagement was due to a perception discrepancy, which refers to a situation in which the vehicle's sensors are not correctly perceiving an object. Objects would include overhanging branches, large road signs, or even other large objects. In addition to perception discrepancies, the next two most common disengagement issues were caused by software discrepancies and from unwanted maneuvers of the vehicle. The software discrepancy refers to situations involving apparent software inadequacies that do not readily fall into other categories, such as map or calibration issues. The unwanted maneuver of the vehicle discrepancy refers to the vehicle moving in a way that is undesirable, for instance, when the vehicle would be coming extremely close to a parked car or object while either parking or driving ("Google Self-Driving Car Testing Report…"). These three types of disengagements accounted for 74% of the total issues reported. The two least frequent causes for disengagements occurred from an emergency vehicle in the way during

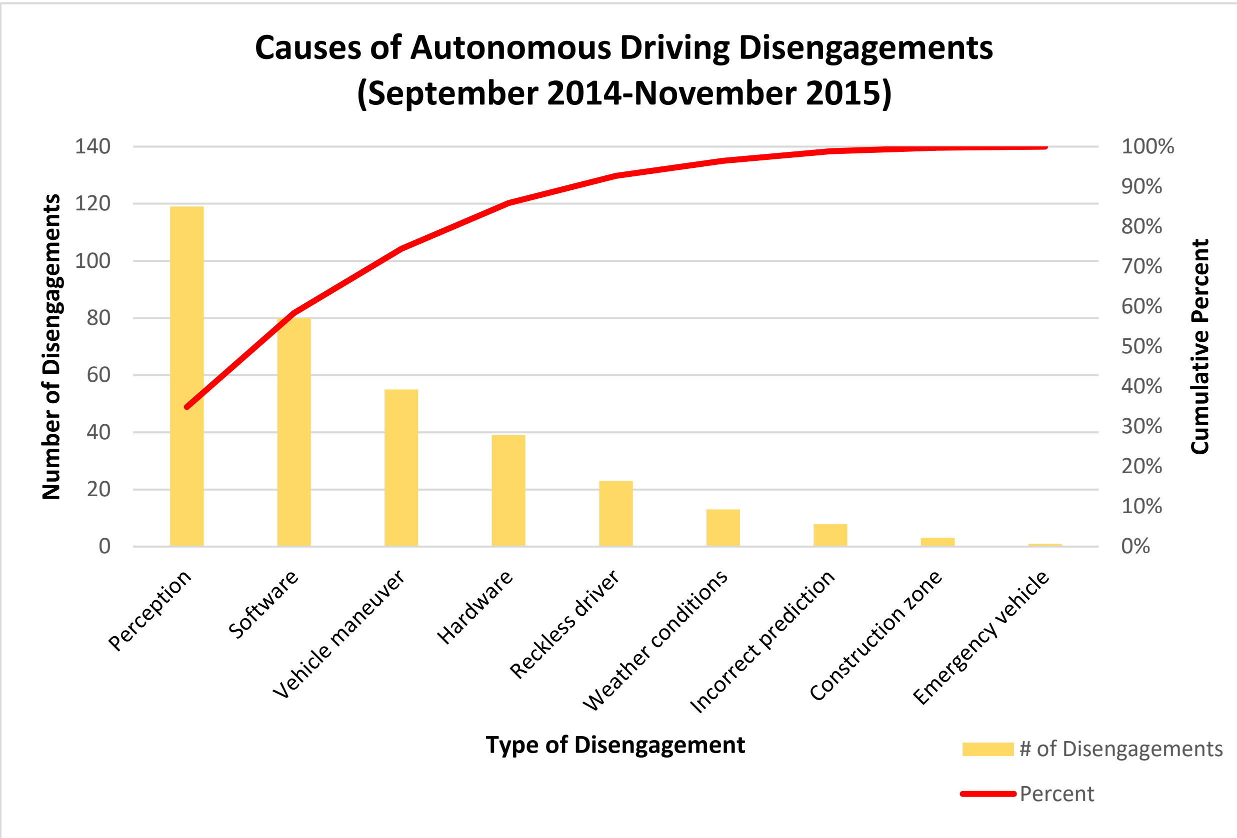

Figure 4: *The Causes of Google's Autonomous Driving Disengagements from 2014-2015*

autonomous driving testing, and from construction zone interfering with the autonomous driving that was being conducted. This information is extremely helpful to Google, as this information helps them focus their attention on reducing the top three most frequent disengagements, so that the car will be able to function in situations without any manual control.

Not only does the cause of disengagement make Google aware of potential issues, but the location of where the vehicle drove during that disengagement can also help Google focus specifically on strengthening the vehicle's knowledge in certain situations at a specific location. Figure 5 provides information on the specific location where the disengagement occurred. The 341 total disengagements reported all occurred either on the interstate, freeway, highway, or streets. We can clearly see from the bar chart in Figure 5 that the highest amount of disengagements occurred while the autonomous vehicle was driving on the streets, which is a more complex environment, when compared to highways, freeways, and interstates. There was a

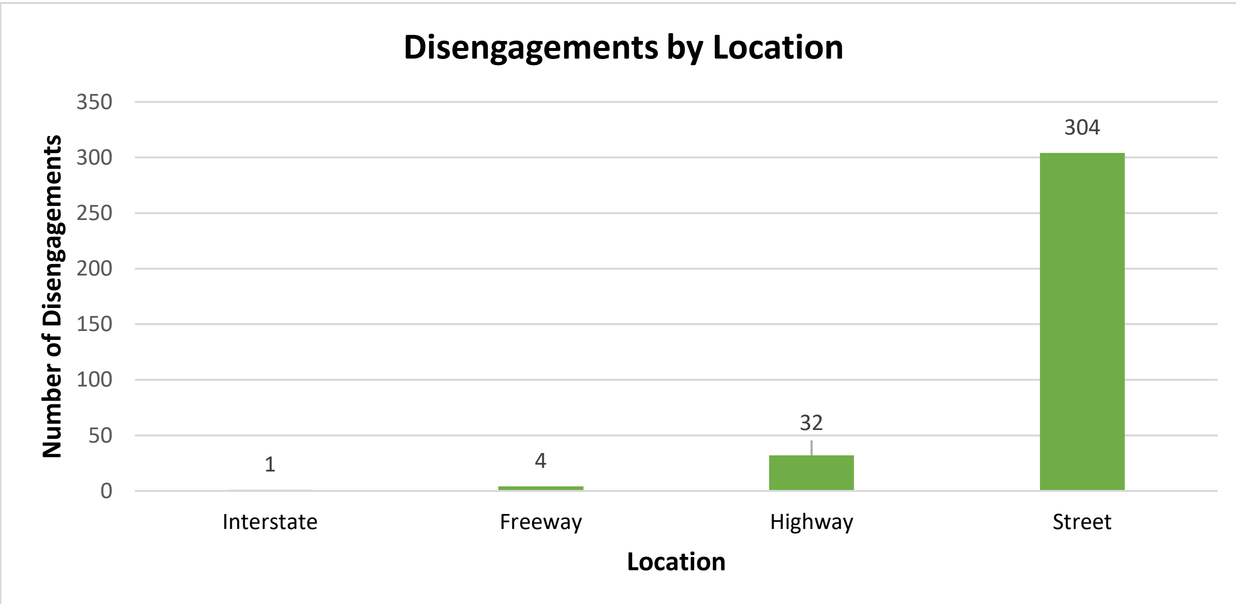

Figure 5: *Google Autonomous Car Disengagements by Location from 2014-2015*

total of 304 incidents of a disengagement that occurred on the streets from 2014-2015. The least recorded amount of disengagements occurred both on the interstate and freeway. By examining this data, it does make sense that the vehicle would incur the most problems in a typical street environment. A street is usually the busiest environment, which can include drivers, buses, trucks, parked cars, pedestrians crossing, drivers stopping to drop/pick passengers up, construction blockage of lanes, workers fixing stoplights, emergency vehicles passing by, and so on. An autonomous vehicle driving in this environment might not be as responsive to all this commotion, and could therefore be unable to react accordingly, causing a disengagement in the autonomous driving. Likewise, these observations should be a huge red flag to Google, as now they can focus their attention more on improving the vehicle's ability to drive on the streets, rather than on freeways and interstates. The more they improve the vehicle's ability to handle the most difficult situations, the better it will be when handling even the most complicated situations.

In addition to being aware of both the type and location of disengagements, Google's disengagement report provides information regarding the period of time elapsed from when the autonomous vehicle test driver was alerted of the technology failure and when the driver assumed manual control of the vehicle. In other words, this data was only recorded if the test driver had to take charge of the vehicle and disengage the autonomous driving entirely. The average time to manual driving for each cause of disengagements can be show in Table 2 below, as well as their standard deviations.

Type of Disengagement	Average Time to Manual (sec.)	Standard Deviation of Time to Manual (sec.)
Perception discrepancy	1.12	0.52
Recklessly behaving agent	0.89	0.59
Software discrepancy	0.64	0.29
Construction zone during testing	1.40	0.99
Emergency vehicle during testing	0.20	-
Hardware discrepancy	0.45	0.19
Incorrect behavior prediction of traffic participants	1.30	0.95
Unwanted maneuver of the vehicle	0.73	0.59
Weather conditions during testing	0.89	0.3
Grand Total	**0.85**	**0.53**

Table 2: *Google's Average Time to Manual for Different Types of Disengagements*

Table 2 shows that the maximum average time to manual was from a disengagement due to construction zone during testing, with an average time of 1.40 seconds, and a standard deviation of 0.99 seconds. The minimum average time to manual was from a disengagement due to emergency vehicle during autonomous testing, with an average time of 0.20 seconds. In the end, this data shows that the test driver was able to take manual control of the vehicle in under one second, since the overall average time to manual driving was 0.85 seconds. This analysis definitely illustrates the strength of Google's technology behind autonomous driving.

Statistical Analysis of Delphi's Autonomous Vehicle Disengagement Report

Looking at Delphi Automotive's disengagement report, one is able to see how well their vehicle performed under their testing period. The disengagement report occurred during the timeframe from October 2014 to the end of November 2015. The vehicles used were a 2014 Black Audi SQ5-1 and a White Audi SQ5-2. Like Google, Delphi tested their vehicles in the state of California. According to their disengagement report, both of Delphi's autonomous vehicles are designed to automatically trigger a buzzer if any of their hardware failed during a drive, alerting test drivers to take manual control of the vehicle ("Summary of Autonomous Vehicle Disengagements"). One of the vehicles that was tested, the 2014 Black Audi SQ5-1, drove a total of 7,157 miles over the span of a year, and the other vehicle, the 2014 White Audi SQ5-2, drove a total of 9,504 miles over that same timeframe. A total of 16,661 miles were driven over a 13-month period. Table 3 below summarizes the number of miles driven per month for both Delphi vehicles.

	2014 Black Audi SQ5 "SQ5-1"	**2014 White Audi SQ5 "SQ5-2"**
Oct-14	397	894
Nov-14	586	578
Dec-14	577	559
Jan-15	242	214
Feb-15	381	3,560
Mar-15	3,837	2,767
Apr-15	48	16
May-15	32	48
Jun-15	95	147
Jul-15	244	227
Aug-15	566	66
Sep-15	91	400
Oct-15	41	0
Nov-15	20	28
Total Miles	**7,157**	**9,504**

Table 3: *Summary of Delphi's Total Autonomous Miles Driven*

Compared to Google's 424,331 total miles driven over a 14-month period, Delphi's vehicles drove 407,670 miles less than Google did. This could possibly result from Delphi focusing more on correcting certain aspects of their operating system, rather than having the vehicle being constantly disrupted from its autonomous state, due to a disengagement.

When looking at Delphi's disengagement report, a total of 405 disengagements were recorded from October 2014 to November 2015. Figure 6 shows the most frequent causes of disengagements that the vehicles encountered while driving. We can see from the chart that the most popular disengagements were due to poor lane markings, traffic light detection, and system tuning and calibration. The poor lane markings disengagement could have resulted from the vehicle not identifying the lane markings on the street, and would therefore not be familiar with the overall area it should drive in. The traffic light detection disengagement resulted from the vehicle misreading a traffic light and either not stopping in time for a yellow or red light, or even mistaking a different lane's stoplight for the lane that the vehicle is currently in. The third highest disengagement reported was due to system tuning and calibration, which means that the test drivers had to disengage the vehicle from autonomous mode, so that they were able to fine tune the technology during their testing. These three disengagements accounted for 67.65% of the total issues reported. The least frequent causes of disengagements shown in Figure 6, were from stock vehicle failures, emergency vehicles, and precautionary intervention to give extra space for a cyclist. By examining this data, Delphi should focus their attention more on reducing their top three issues, and therefore working to strengthen the vehicle's technology so that it can be able to detect these situations more carefully and properly adjust driving if needed.

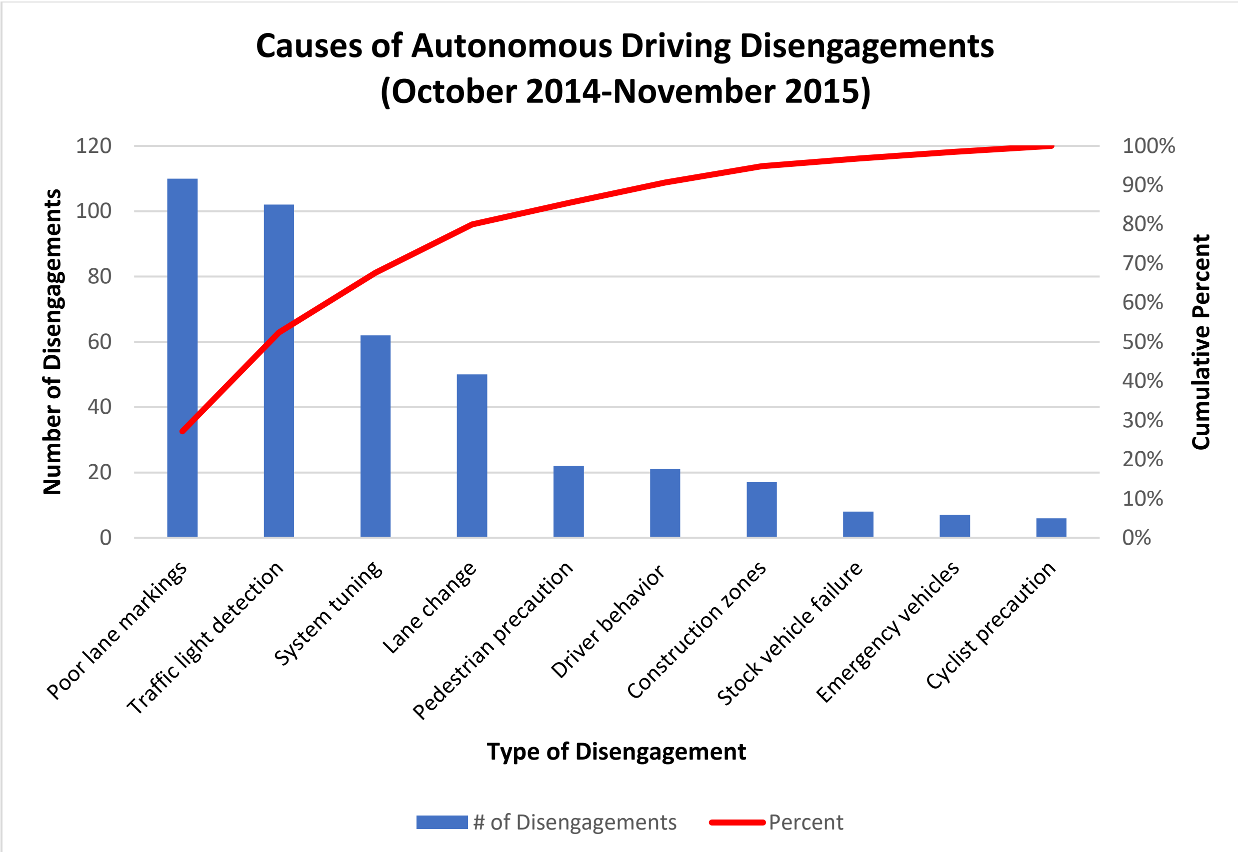

***Figure 6**: The Causes of Delphi's Autonomous Driving Disengagements from 2014-2015*

The comparison of Delphi's autonomous vehicles' disengagement data in both 2014 and 2015 has revealed the major improvements in Delphi's technology, as the amount of disengagements have been significantly reduced. Figure 7 below shows the disengagement data comparing October 2014, which was the start of testing, until November 2015, which was the end of the testing period. It includes results for both types of vehicles, the Audi SQ5-1 and the Audi SQ5-2. This data compares the type of disengagements by location, occurring either on the highway or on the streets. From this data, we can see that the number of disengagements have significantly decreased by the end of 2015, when compared to the amount in 2014. The most frequent type of disengagement in 2014 was under typical road conditions and occurred on the streets. The least frequent types of disengagements in 2014 were due to freshly paved

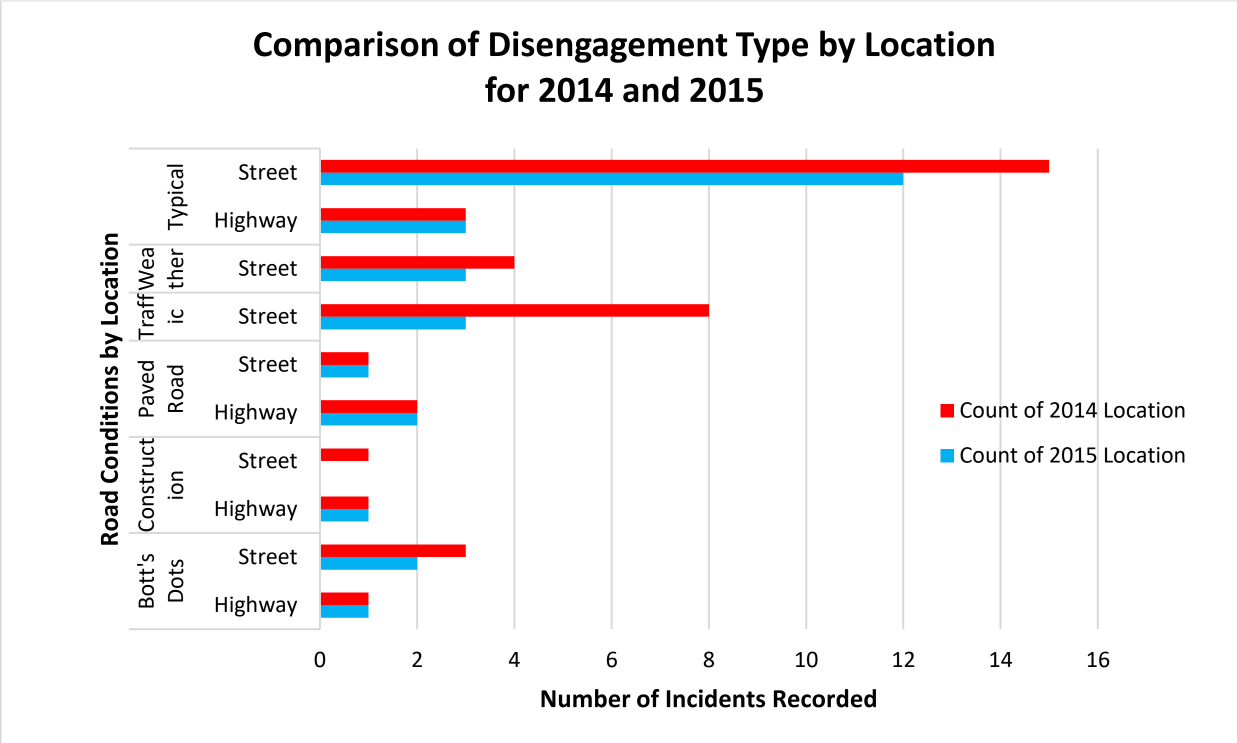

Figure 7: *Delphi's Comparison of Disengagement Type by Location (October 2014-November 2015)*

roadways occurring on the street, construction occurring on both the streets and highways, and Bott's Dots occurring on the highways. Bott's Dots refer to the round, non-reflective raised pavement markers located on many freeways in California. Their main purpose is to enhance the painted lines used to designate lanes on the freeway. Perhaps Delphi's autonomous vehicles weren't familiar with these objects, which therefore resulted in the test driver having to take manual control of the vehicle. Regardless, now looking at the data for 2015, still the most frequent type of disengagement resulted from typical road conditions on regular streets, although its occurrence has slightly reduced over the 13-month testing period. The disengagement due to construction occurring on normal street conditions was completely eliminated in 2015. Moreover, since the data shows that Delphi's vehicles are still encountering issues on the main roads, Delphi should work on improving their operating system, as well as continue to actively test their vehicles in the most unique and well-diversified situations on main roads, so that the vehicle can have more exposure to different situations and can eventually reduce the total number of disengagements.

Like Google, Delphi's disengagement report also provides information regarding the period of time when the test driver had to take manual control of the vehicle, due to a serious disengagement that the vehicle could not handle on its own. However, Delphi's report only illustrates that it took the test driver less than a second to assume manual control of the vehicle, and this included all types of disengagements that occurred while driving. Although there are no exact times recorded by Delphi, having a time to manual of less than one second, like Google, is very ideal for any company working on autonomous technology. This observation further illustrates the fast-thinking and intuitive computation of the vehicle's operation system.

Final Remarks:

The topic of autonomous driving will continue to be one of the most popular subjects discussed in the automotive industry during this day and age. Countless companies are at a race to complete their vehicles and offer them to the public within the next decade. The era of technology will continuously bring new improvements and changes to vehicles, and drivers are interested in knowing what these changes are. When it comes to self-driving vehicles, most people are not familiar with the engineering and technology behind these new machines. Understanding this can help keep the public informed regarding the development of these autonomous vehicles, as well as further emphasizing the safety factors for drivers.

This paper explores the unique software and technology that is being used in autonomous vehicles today. Additionally, it highlights how autonomous vehicles will most likely function from a combination of LIDAR, radar, camera sensors, and positioning software, all in which will be fully programmed into the vehicle in hopes of replicating the mind of a human driver.

Furthermore, this paper explores the current technology that Google, Delphi Automotive, and Autonomous Vehicle Systems are implementing in their operating systems. It informs the public on how soon these vehicles will be on the market, and highlights one of the main benefits autonomous driving will provide: a significant reduction in the amount of daily automobile accidents. The paper also helps in better understanding the environments that automakers are utilizing to test their autonomous vehicles. Finally, the use of descriptive statistics was utilized to summarize the performance of autonomous vehicle systems of two companies. This analysis can provide huge benefits to the companies working on these vehicles, as it can help them narrow their focus on the most significant factors that their vehicles are incurring. There is no telling exactly when autonomous driving will be utilized more than normal vehicles, but it is clear that the world of autonomous driving is progressing ahead at full speed, and will eventually become an everyday reality.

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