Autonomous Vehicles: An Analysis of Implications and Implementation

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Date: April 21st, 2014

Acknowledgements

Throughout the Global Scholar process, many people have provided me support and help when I have needed it. I am grateful for the help that everyone has provided no matter how small, but I also would like to specifically thank some people who have gone above and beyond for me:

- My mentor: Dr. Nathanial Fairfield, who has been a great help in guiding and directing me, especially when I first started and had trouble deciding what to do.
- My panel members: Dr. Dario Untama, Mr. Ryan Ritz, Ms. Julie Liu, Mr. Peter Polit, and Ms. Alexa Petrucciani for their time and agreeing to be a part of my project.
- My friends for all their kindness and support through thick and thin, and also for always being there when I needed them.
- My family for provided all the love, support, and guidance I could ever want or need, and also for always pushing me to be the best I can be.
- Mr. Bryon Realey and Ms. Shirley Gaughan for setting up all the equipment necessary for my presentation.
- Dr. Jan Guffin for being an amazing Philosophies of Knowing teacher, and selflessly helping guide me through the Global Scholars process.

Abstract

In nearly 90% of all driving accidents, human error is a contributing factor, accounting for thousands of lost lives and billions in damages in the US alone. Autonomous automobiles can help ameliorate this problem by eliminating the most error prone element in driving, the human. Some studies suggest that if the 90% of cars in the US were autonomous, 4.2 million accidents could be avoided and $4.5 billion saved every year. With the promise of autonomous vehicles also comes the problem of a lack of literature. This paper aims to investigate the current state of autonomous vehicles and answer the question: how do we implement and what are the ramifications of an autonomous vehicle driving system in terms of single vehicle operation and vehicle-vehicle interaction?

The first section of this paper provides a comprehensive overview of the major developments and milestones of autonomous cars, beginning with radio controlled vehicles in the 1920s. This section covers the use of guidelines to control vehicles in the 1940s and 50s, and also the transition to computer vision in the 70s with the Eureka Prometheus Project. This section also defines the different levels of autonomy in accordance with the USDOT's classifications.

The next section of this paper provides an analysis of current technologies and techniques used to control autonomous cars by reviewing the results and data collected from the DARPA Urban Challenge, a government-sponsored autonomous vehicle competition. Sensing technologies that were analyzed include laser/radar systems, GPS, IMU, video cameras, and Odometry systems. This section also discusses the programming and logic techniques used in the vehicles for decision making.

The last section of this paper discusses the implications and future obstacles that autonomous vehicles will face, as well as benefits and drawbacks of implementing an autonomous automobile system. The ramifications of both single-vehicle operation and vehicle-vehicle interaction were discussed in this section as well. Finally, the paper ends on an overview of the current state of autonomous cars, predicting commercial availability by 2020.

Global Scholars Outline

Research Question: How do we implement and what are the ramifications of an autonomous vehicle driving system in terms of single vehicle operation and vehicle-vehicle interaction?

I. History
    A. 1920s: Radio Controlled Cars
    B. 1950s: Guideline Assisted Autonomous Cars
    C. 1980s: EUREKA Prometheus Project
II. Implementation
    A. Single Vehicle Operation (5 - 10 years away)
        1. Problems
            i. Vision / Data Collection
            ii. Object Identification
            iii. Determining Appropriate Response
        2. Solutions
            i. Hardware: cameras, radar, LIDAR, IFR VOR
            ii. Software
                a. Algorithms
    B. Vehicle-Vehicle Interactions (10 - 15 years away)
        1. Problems
            i. Low-Latency Communication
            ii. Data Interpretation
        2. Solutions
            i. Mobile Mesh Networks
III. Ramifications
    A. Benefits
        1. Greater Efficiency
        2. Less Traffic Congestion
        3. Increased Safety
    B. Drawbacks
        1. Car Enthusiasts
        2. Legal Implications
            i. Who is liable in accidents?
            ii. Who pays for insurance?
IV. Current State-of-the-art
    A. 3rd Party: Google X-Labs
    B. Big Car Brands: Mercedes, Audi, BMW, Volvo, Nissan
    C. Academia: VisLab

Introduction

In the past several decades, many new technologies have been implemented to prevent driving accidents, increase efficiency, and reduce traffic congestion. Seatbelts and airbags are now considered standard equipment on cars, while newer features like collision avoidance, blind spot monitoring, and lane departure warning are becoming ever more ubiquitous. A commonality found in all of these systems is that they are designed to help drivers make decisions and avoid accidents; however, current technologies fail to address the single largest source of error in driving, the human. A comprehensive study of road safety conducted by the United States Department of Transportation in 1977 – before the advent of smartphones, portable GPS devices, and in-car infotainment systems – found that 57% of all driving accidents were caused by human error, and that in 90% of the cases, human error was a contributing factor.[1] In contrast, the study determined that only 2.4% of accidents were caused by mechanical issues, while 4.7% were due to environmental factors. Multiple other studies conducted by private

[1] Treat, J. R., Tumbas, N. S., McDonald, S. T., Shinar, D., Hume, R. D., Mayer, R. E., Stanisfer, R. L. and Castellan, N. J. (1977) Tri-level study of the causes of traffic accidents. Report No. DOT-HS-034-3-535-77 (TAC)

organizations and government agencies have reported similar findings.[2, 3] The newest wave of technologies made to combat the dangers of driving aim to eliminate or at least greatly reduce the human element from driving. These next-generation safety systems are one part of a growing movement towards autonomous vehicles, more generally called self-driving car.[4] The advantages of this new technology can be seen in many places, the first and foremost being increased safety. Other benefits, among many, include vastly improved efficiency and traffic congestion. Current studies indicate that 4.2 million accidents could be avoided, saving 21,700 lives and $450 billion in damages every year if 90% of vehicles in the US were autonomous.[5] Additionally, it is estimated that up to 75% of traffic congestion could be alleviated with autonomous vehicles. Previously, the implementation of self-driving cars was limited due to the inadequate state of computers, a lack of funding, and weak demand. While opposition still exists today, many of the impracticalities and problems of self-driving cars have been resolved, pushing the dream the closest it has ever been to reality. This paper aims to answer the question: how do we implement and what are the ramification of an autonomous vehicle driving system in terms of single vehicle operation and vehicle-vehicle interaction, by first examining autonomous automobile history and then providing an in-depth review of current implementation techniques. Finally, this paper will finish with the ramifications of autonomous vehicles and the current state of the art.

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[2] USDOT. "Research and Innovative Technology Administration (RITA) - United States Department of Transportation (USDOT, US DOT or DOT)." Research and Innovative Technology Administration (USDOT). USDOT, n.d. Web. 24 Jan. 2014.

[3] USDOT. "Distracted Driving 2011." TRAFFIC SAFETY FACTS. USDOT, n.d. Web. 2014.

[4] NHTSA. "U.S. Department of Transportation Releases Policy on Automated Vehicle Development ." U.S. Department of Transportation Releases Policy on Automated Vehicle Development. N.p., n.d. Web. 24 Jan. 2014.

[5] Mearian, Lucas. "Self-driving Cars Could save More than 21,700 Lives, $450B a Year."Computerworld. N.p., n.d. Web. 24 Jan. 2014.

Classification of Vehicular Autonomy

The origins of the true *auto*mobile trace back to the mid-1920s, when Francis P. Houdina built the first physically "driver-less" car, dubbed the Linrrican Wonder.[6] Houdina outfitted a 1926 Chandler with a radio receiver and electric motors so he could control the vehicle from a distance. He demonstrated the capabilities of his car by driving on congested streets in New York. While not truly autonomous, Houdina's creation was one of the first documented cases in which a human did not directly drive a car. Today, the Linrrican Wonder is classified as having level 0 autonomy by the National Highway Traffic Safety Administration (NHTSA) because Houdina's vehicle required his control at all times. The NHTSA created a classification system in 2013 to better define autonomy and standardize the term. The different levels of classification of autonomy are as follows:[7]

> **No-Automation (Level 0):** The driver is in complete and sole control of the primary vehicle controls – brake, steering, throttle, and motive power – at all times.
>
> **Function-specific Automation (Level 1):** Automation at this level involves one or more specific control functions. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.
>
> **Combined Function Automation (Level 2):** This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.
>
> **Limited Self-Driving Automation (Level 3):** Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.

[6] "Science: Radio Auto." TIME 10 Aug. 1925: n. pag. Web.

[7] NHTSA. "U.S. Department of Transportation Releases Policy on Automated Vehicle Development ." U.S. Department of Transportation Releases Policy on Automated Vehicle Development. N.p., n.d. Web. 24 Jan. 2014.

> **Full Self-Driving Automation (Level 4):** The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

Within the classification, level 1 and 2 autonomy aim to aid the driver with information and warnings rather than taking control, while level 3 and 4 autonomy aim to reduce or completely eliminate driver intervention.

For most of automobile history, level 1 autonomy features have helped drivers control vehicles. Modern cruise control, for example, was first implemented in 1948 by a mechanical engineer named Ralph Teetor, while the concept of the speed governor was first created to control steam engines in the 18th century. Level 2 autonomy followed with the release of the 2001 Nissan Cima, which featured the first lane-departure warning system that could run in parallel with the cruise control. The highest level of autonomy available today is still level 2 autonomy. Many car manufactures today are working to develop and release level 3 and 4 autonomous vehicles by 2020, with some even claiming to have basic level 3 autonomy within the next five years.[8, 9, 10, 11, 12]

Research and Development of Level 3 Autonomous Vehicles

Beginning in the 1950s, the first real level 3 autonomous cars began development. One of the first documented demonstrations of a level 3 self-driving car appeared in 1958.[13] Having

[8] Cheng, Roger. "General Motors President Sees Self-driving Cars by 2020." CNET. N.p., n.d. Web. 07 Apr. 2014.

[9] Elmer, Stephen. "BMW Targets 2020 for Self-Driving Cars." AutoGuide.com. N.p., n.d. Web. 07 Apr. 2014.

[10] Garvin, Glenn. "Automakers Say Self-driving Cars Are on the Horizon." Tampa Bay Times. N.p., n.d. Web. 2014.

[11] Johnson, Drew. "Audi Predicts Self-driving Cars by 2020." LeftLane News RSS. N.p., n.d. Web. 07 Apr. 2014.

[12] Preisinger, Irene. "Daimler Aims to Launch Self-driving Car by 2020." Reuters. Thomson Reuters, 08 Sept. 2013. Web. 07 Apr. 2014.

[13] Quigg, Doc. "The Press-Courier - Google News Archive Search." Editorial. Press Courier[Oxnard, CA] 1960: 4. The Press-Courier - Google News Archive Search. Web. 24 Jan. 2014.

previously built a miniature model in 1953, RCA labs designed and constructed a full size system that used electrodes embedded in the road to guide the car. The cars were able to successfully navigate a 400 foot stretch of private highway in Nebraska, fully and independently automating acceleration, braking, and steering.[13] Two years later in 1960, RCA Labs in collaboration with General Motors opened demonstration to journalists, and incorrectly predicted widespread availability by 1975. In the 60s, national government organizations began taking notice of autonomous driving technology. The United Kingdom's Transport and Road Research Laboratory began testing a driverless Citroen DS that tracked a magnetic strip buried beneath the road. The car was able to reach speeds of 80 mph with little deviation in speed or direction.[14] At the time, this study was one of the first to display the benefits of autonomous vehicles. These early studies suggested 50% increases in road capacity and 40% reductions in accidents; however funding was withdrawn in the mid-1970s despite finding that the cost of upgrading Britain's highway infrastructure would be repaid by the end of the century.[15]

Beginning in the late 60s, autonomous vehicle development seemed to slow, only to pick up again in the 80s. From this point, the advancements of self-driving cars can be broken up into several milestones that will be discussed in further detail in the coming sections.

Computer Vision

While many of the autonomous vehicle designs of the 60s and 70s incorporated embedded magnetic or electronic guidelines in roads, the designs of the late 80s began to shift focus from this old technology to the newer computer vision. The impracticalities of the 60s' techniques are obvious; every road that an autonomous car would travel on would be required to be rebuilt with

[14] Waugh, Rob. "How the First "driverless Car" Was Invented in Britain in 1960." Yahoo News UK. N.p., n.d. Web.

[15] Reynolds, John. "Cruising into the Future." *The Telegraph*. Telegraph Media Group, 26 May 2001. Web. 2014.

guidelines. Massive new sets of standards would have had to be put in place so that cars of different makes and models could all use the same roads, and maintenance costs would increase significantly. Additionally, cars would not be able to travel off-road or on smaller streets that did not have the system installed.

Computer vision was the approach used to solve this issue.[16] Of its many applications, computer vision implemented in autonomous cars aim to combine the standards already in place today of traffic lights, lane markings, signs, etc. with the computational power and accuracy of computers. Humans drive mainly by vision, and calculate how to proceed and react to adverse situations with input from one source. With computer vision technology, processers in the car take in visual data and then decide how to proceed like humans do. The Eureka Prometheus Project that began in the 80s had some of the first documented examples of vision-guided cars.[17] The Mercedes-Benz van developed under this project was able to travel at 39 mph on empty streets using radar sensors to detect objects near the vehicle. In the same decade, the Defense Advanced Research Projects Agency (DARPA) funded a project to develop off-road capable vision-guided vehicles called the ALV or autonomous land vehicle. These vehicles moved at speeds of three miles per hour, and travel over complex terrain that included steep inclines, ravines, rocks, and vegetation.[18]

Research and Development of Autonomous Vehicles in the 1990s

In 1991, the United States Congress passed the Intermodal Surface Transportation Efficiency Act (ISTEA) Transportation Authorization bill, which instructed the United States

[16] Turk, Matthew A., David G. Morgenthaler, Keith D. Gremban, and Martin Marra. VITS - A Vision System for Autonomous Land Vehicle Navigation. IEEE, May 1988. Web. Mar. 2013.

[17] Albanesius, Chloe. "Google Car: Not the First Self-Driving Vehicle." PCMAG. N.p., n.d. Web. 24 Jan. 2014.

[18] "Driving Forces: Lockheed Martin's Autonomous Land Vehicles." Lockheed Martin, n.d. Web. 07 Apr. 2014.

Department of Transportation (USDOT) to demonstrate an automated vehicle system by 1997.[19] The Federal Highway Administration took on this task, and split the total funding cost of $90 million with several partners including General Motors, Caltrans, Delco, Parsons Brinkerhoff, Bechtel, UC-Berkeley, Carnegie Mellon University, and Lockheed Martin.[20] The engineering work and research culminated in a demo in 1997 on interstate-15 in San Diego, CA. A fleet of twenty autonomous cars, buses, trucks, etc. demonstrated close-headway platooning and well as individual vehicle maneuvers. While the program aimed to promote widespread commercialization of this technology, research was halted in the late 1990s due to tightening research budgets of the USDOT.[21]

Other notable milestones of the 90s include the twin vehicles VaMP and Vita-2.[22] These two vehicles were developed under the still ongoing Eureka Prometheus Project that started in the late 1980s. The twin cars built by Daimler-Benz and Ernst Dickmanns traveled more than 620 miles on a three-lane highway in Paris at up to 80 mph, albeit with occasional human intervention.[22] The aim of this demonstration was to improve driving safety. The cars implemented early forms of adaptive cruise control found in many modern day cars, slowing down automatically when the car in front slowed. These advancements allowed the cars to drive in convoys as well as free-agents. The next year in 1995, a reengineered Mercedes-Benz S-Class sedan equipped with similar technology from the Prometheus Project drove 990 miles on the German Autobahn, reaching speeds of up to 109 mph. The vehicle was able to drive autonomously 95% of the time.[22]

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[19] "Intermodal Surface Transportation Efficiency Act of 1991." National Transportation Library. USDOT, n.d. Web. 07 Apr. 2014.

[20] "Intermodal Surface Transportation Efficiency Act of 1991." National Transportation Library. USDOT, n.d. Web. 07 Apr. 2014.

[21] Bishop, Richard, MD. Intelligent Vehicle Technology And Trends. N.p.: n.p., 2005. Print.

[22] Dickmanns, Ernst D. *Dynamic Vision for Perception and Control of Motion*. London: Springer, 2007. Print.

Finally, in 1996, Alberto Broggi launched the ARGO Project, which aimed to develop autonomous cars that could follow lane markings using low cost video cameras and efficient stereoscopic vision algorithms. The culmination of Broggi's project was a 1200 mile journey through the highways of northern Italy in a modified car that only had two black and white off-the-shelf video cameras as hardware. Averaging 56 mph, the car was able to successfully operate autonomously for 94% of the time, demonstrating that autonomy could be achieved with software programming like stereoscopic vision algorithms without the need for advanced hardware like ultrasound, radar, and high frame rate video cameras.[23, 24]

Research and Development of Autonomous Vehicles in the 2000s

In the first decade of the new millennium, government-sponsored research and development of autonomous vehicles increased rapidly, mirroring the development that occurred in the 60s.[25] The US government funded three military development projects known as Demo I, Demo II, and Demo III. In 2001, Demo III demonstrated autonomous off-road capabilities in which steering, acceleration, and braking were all controlled by a computer in the vehicle. The project was able to achieve not only autonomous driving in difficult terrain, but also coordinated driving for higher level goals. In other areas like public transportation and industrial mining, autonomous vehicles also began testing for deployment.[26, 27] In the early 2000s, Advanced Netherlands Transport (ANT) designed a small-capacity autonomous people mover called Park Shuttle to transport passengers between a business park and a metro station in Rotterdam. The

[23] Albanesius, Chloe. "Google Car: Not the First Self-Driving Vehicle." PCMAG. N.p., n.d. Web. 24 Jan. 2014.

[24] University of Parma. "The Argo Project." ARGO Home Page. N.p., n.d. Web. 2014.

[25] Self-driving Cars: The next Revolution. Rep. Kpmg.com | Cargroup.org, n.d. Web. 07 Apr. 2014.

[26] "Park Shuttle Automated Driverless Vehicle Pilot Project - Netherlands." Park Shuttle Automated Driverless Vehicle Pilot Project - Netherlands. University of Washington, 2009. Web. 24 Jan. 2014.

[27] Rio Tinto Boosts Driverless Truck Fleet to 150 under Mine of the Future Programme. Rep. Rio Tinto, 2011. Web.

Park Shuttle system continually follows a defined path, so it is more akin to a light tram than an autonomous vehicle. Nonetheless, ANT's Park Shuttle system is valuable as a proof of concept system demonstrating the current commercial state of autonomous vehicles.[26] Since December 2008, Rio Tinto Alcan, a mining corporation based in Montreal, Canada, began testing an autonomous hauling fleet designed by Komatsu Limited, a Japanese corporation that specializes in mining and construction equipment. The company has since reported health, safety, and productivity benefits, so much so that in 2011, Rio Tinto Alcan signed a deal to greatly expand its fleet. Other companies also are beginning to produce autonomous hauling vehicles for mining like Sandvik Automine and Caterpillar Inc.[28]

Many automotive manufacturers also began testing in the mid-2000s like General Motors, Ford, Mercedes Benz, Volkswagen, Audi, Nissan, Toyota, BMW, and Volvo.[29, 30, 31] BMW has been testing autonomous driving systems since 2005, and in 2010, Audi sent an autonomous Audi TTS up Pike's Peak, a steep and twisty highway along a ridge of the Rocky Mountains known to be notoriously hard to navigate, at near race speeds. Google's X Labs have also been very active with autonomous vehicle development. Headed by Sebastian Thrun, a former professor at Stanford and winner of the 2005 DARPA Grand Challenge, Google's autonomous vehicle fleet of 12 vehicles has logged over half a million miles with no accidents due to the autonomous car its self.[32]

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[28] "Sandvik Mining to Supply World's Largest Underground Mine Automation System to Argyle Diamond Mine." Sandvik, n.d. Web. 07 Apr. 2014.

[29] Schmidhube, Prof. "Prof. Schmidhuber's Highlights of Robot Car History." Robot Cars. Cogbot Lab, n.d. Web. 07 Apr. 2014.

[30] "Toyota Sneak Previews Self-drive Car Ahead of Tech Show." BBC News - Technology. BBC, n.d. Web. 2014.

[31] "Nissan Car Drives and Parks Itself at Ceatec." BBC News - Technology. BBC, n.d. Web. 07 Apr. 2014.

[32] Simonite, Tom. "A Battery for Renewable Energy Storage." MIT Technology Review. N.p., 2013. Web. 2014.

Autonomy in terms of Single Vehicle Operation

There are many technologies currently in development to achieve vehicle autonomy. Nearly all modern techniques incorporate camera-based visual guidance systems, radar, GPS, and accelerometer sensors.[33] The systems architecture for several competing autonomous vehicles is highlighted in a report released in 2010 detailing the 2007 DARPA Urban Challenge. Speaking at a high level, most autonomous vehicle systems break driving into four smaller structures: sensing, perception, planning, and control, outlined in more detail in Figure 3 on the next page.[33]

The sensing subsystem is responsible for gathering raw data from the available instruments. In the vehicle in Figure 3, these instruments include a GPS system, inertial measurement units (IMU: a device that uses accelerometers and gyroscopes to measure acceleration, orientation, and velocity), and Odometry systems (process of estimating position from velocity and acceleration data).[33] These instruments were supplemented with video cameras to help identify traffic signs, stop lines, and lane markings. Lasers (LIDAR) and radar range-finders were also used to measure and map out static and dynamic objects and obstacles surrounding the near vicinity of the vehicle. Data from cameras and laser / radar systems were also combined to produce smaller and less computationally-intensive maps of the surroundings rather than individual input streams.[33]

[33] Campbell, Mark, Magnus Egerstedt, Johnathan How, and Richard Murray. Autonomous Driving in Urban Environments: Approaches, Lessons and Challenges. Cornell University, Georgia Institute of Technology, MIT, Caltech, 2010. Print. 2014.

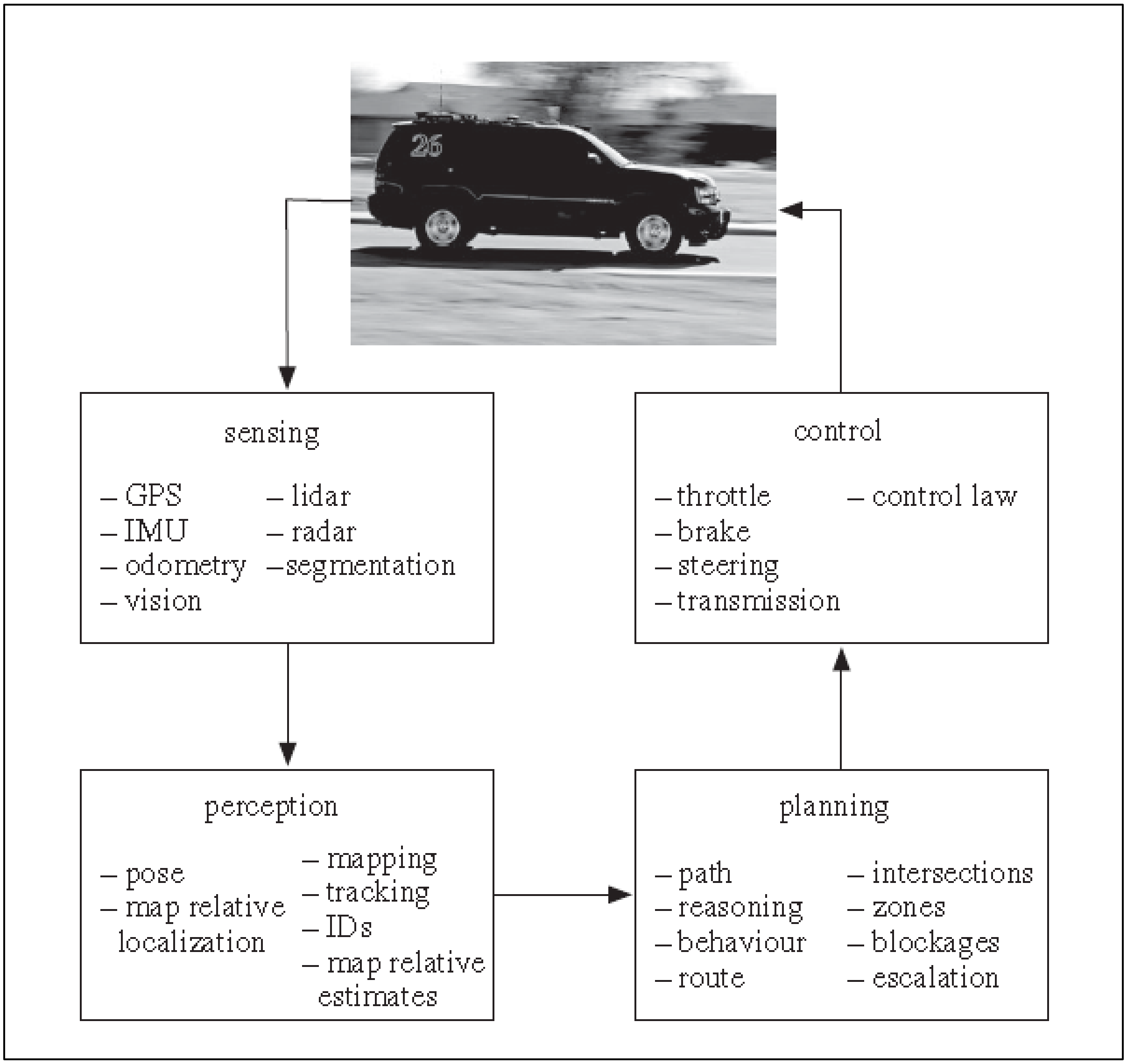

Figure 3: Shown above is the basic sub-system components of an autonomous driving system used in the 2007 DARPA Urban Challenge. The four segments each contain a header, which represents a stage in the approach process. Below each header contains examples of the acting components in that sub-system.[33]

The perception sub-system generates useful data from all of the raw data from the sensors to be fed into the planning sub-system. The perception segment handles vehicle estimation, including pose (inertial position, velocity, attitude, rates) as well as navigation relevant information, like position on a map or inside a lane. Because of the variety of sensors that can be used, and the multitude of ways the sensors can be positioned, many variations of the perception sub-system exist. Most vehicles in the DARPA Urban Challenge had sensors placed around the vehicles so the space surrounding the vehicle could be properly mapped.[33]

The planning sub-system varies substantially between developers and is highly dependent on the type of approach the developers plan on taking. Planning sub-systems usually contain path, map, and behavioral planners that determine the actions of the vehicle. In the 2007 DARPA Urban Challenge, MIT chose to use “a combination of a navigator that specifies a goal point and a motion planner that finds a feasible path to the goal using a unique sampled-based approach called closed-loop rapidly exploring random tree (Kuwata *et al*. 2009), while the Cornell and Caltech teams used optimization based path planners (Hardy *et al*. 2008).”[33] Other approaches included that of Georgia Tech’s system, which combined high-level decision-making algorithms with lower-level “voting” systems.[33] A key element present in all planners is the ability to reason probabilistically, which typically requires the use of a finite-state machine (computers that specialize in probabilistic calculations). Finally, “escalation planners” were created to handle unexpected situations such as large perception errors and sudden environmental changes. These escalation planners act by removing restrictions on other planners so the vehicle can avoid collisions and other accidents.[33]

The control sub-system contains the physical motors, pneumatic pistons, and other driving systems. Like the planning sub-system, the control sub-system contains significant variance because of the sheer number of ways the vehicle can be controlled. Some vehicles had drive-by-wire systems, while others installed physical actuators to turn the steering wheel and depress the accelerator. The control sub-system takes in data from the planning sub-system like calculated paths, and also occasionally from the perception sub-system when faster response times are required (eg. emergency braking to avoid a collision). In consumer grade autonomous vehicles, control systems will most likely be drive-by-wire because it is space saving.[33]

Vehicle-Vehicle and Vehicle-Infrastructure Communication

Many of the benefits of autonomous vehicles arise from their ability to communicate with other vehicles and traffic centers. For example, at the recent 2014 International Consumer Electronics Show (CES) in Las Vegas, Audi unveiled its newest autonomous technology. While the system is classified as Level 2 autonomy, the technology demonstrates a key component of future autonomous vehicles: communication. Audi's new technology connected their cars to the traffic light control infrastructure, allowing cars to predict changing lights while also providing them with more accurate traffic congestion data.[34] This simple feature allows drivers to greatly reduce the number of times they have to stop at traffic lights because Audi's cars can calculate how fast the vehicle must travel to reach a given traffic light exactly when the light turns green. Audi's new autonomous vehicle technology is categorized as vehicle to infrastructure communication (V2I) rather than vehicle to vehicle communication (V2V) because it relies on

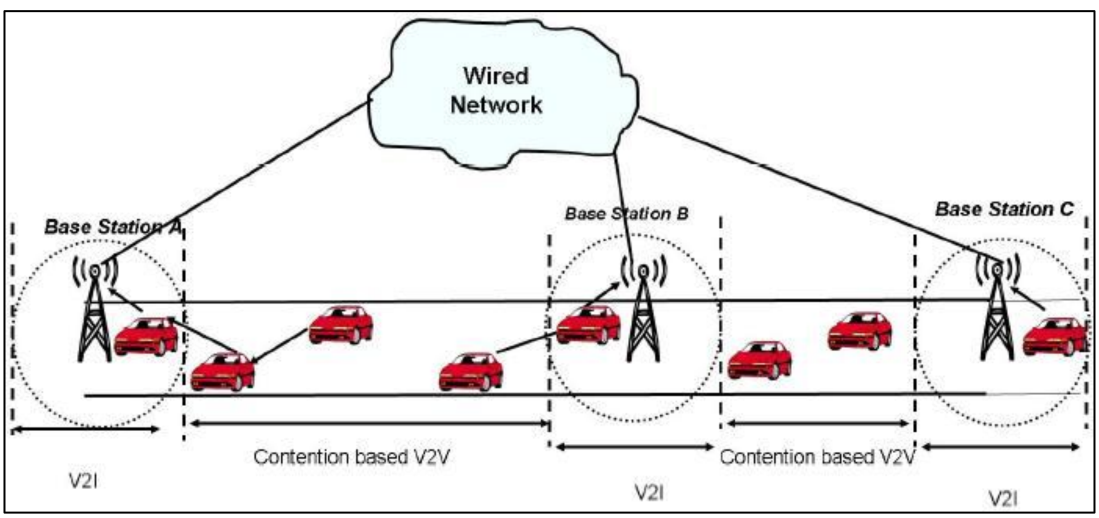

Figure 4: Shown above are multiple examples of V2V and V2I communication. Information about crashes, traffic congestion, hazardous road conditions, etc. can be relayed along this network to most of the vehicles. This system is relatively robust because of the V2V communication potential in addition to V2I communication potential.

[34] New York Daily News. "Audi shows off self-driving, self-parking A6 Avant and RS7 Sportback." Jan. 28, 2013. (Oct. 2, 2013) http://www.nydailynews.com/autos/audi-shows-self-driving-cars-article-1.1249419

traffic data from traffic light control centers. V2V communication networks can also significantly increase roadway safety; the USDOT claims that up to 74% of roadway accidents can be prevented with V2V communication safety standards in place.[35]

Vehicle to infrastructure and vehicle to vehicle communication systems operate in wireless spectrum as seen in Figure 4 on the previous page. V2V communication allows cars to communicate with each other directly, creating chains of vehicles that can relay information when V2I communication is not possible. These mesh networks provide a platform in which safety and traffic technologies can be layered to create a robust communication system.

Increased Safety

The benefits of automated self-driving cars come in all shapes and sizes, ranging from the smallest conveniences like a smoother ride to massive improvements in safety. Of all the benefits, the one that has the most implications by far is increased safety. According to the World Health Organization (WHO), “nearly 3400 people die on the world’s roads every day” with “tens of millions of people injured [sic] or disabled every year.”[36] As early as 1974, the World Health Assembly adopted resolution WHA27.59, which declared road traffic accidents a major public health issue. In a recent WHO report, the *risk* of experiencing a road traffic accident was categorized as a function of four elements, namely: (1) factors that influence exposure to driving, (2) factors that influence crash involvement, (3), factors that influence crash severity, and (4) factors that influence post-crash trauma.[37]

[35] USDOT. "Research and Innovative Technology Administration (RITA) - United States Department of Transportation (USDOT, US DOT or DOT)." Research and Innovative Technology Administration (USDOT). USDOT, n.d. Web. 24 Jan. 2014.

[36] WHO. "Road Traffic Injuries." WHO. N.p., n.d. Web. 24 Jan. 2014.

[37] WHO. "World Report on Road Traffic Injury Prevention." WHO. N.p., n.d. Web. 24 Jan. 2014.

These main factors for risk are summarized in detail in Figure 1. A single error can have life or death consequences, and a majority of the time errors arise from the human limitations such as altered mental states, poor vision, or unfamiliarity. With autonomous cars, humans can be taken out of the equation. The extremely fast response times of computers, and their consistent and reliable day-to-day performance provide the optimal platform for automotive safety technologies to be based off of. An example of this can be seen in many higher-end car safety systems, such as Mercedes Benz's Pre-Safe technology.[38] An onboard computer on all Pre-Safe equipped models constantly monitors the vehicle's speed and surroundings. If a possible collision is detected, the system will automatically alert the driver, prime the brakes so that the necessary maximum force can applied to try and avoid the collision, tighten the seatbelts, reduce the engine speed so the vehicle can stop quicker, prime the airbags for quicker deployment, and unlock the doors, among many other things.[38] All of this occurs behind the scenes even before the driver has time to put his foot on the brake. The

FIGURE 3.1

The main risk factors for road traffic injuries

Factors influencing exposure to risk
- Economic factors, including social deprivation
- Demographic factors
- Land use planning practices which influence the length of a trip or travel mode choice
- Mixture of high-speed motorized traffic with vulnerable road users
- Insufficient attention to integration of road function with decisions about speed limits, road layout and design

Risk factors influencing crash involvement
- Inappropriate or excessive speed
- Presence of alcohol, medicinal or recreational drugs
- Fatigue
- Being a young male
- Being a vulnerable road user in urban and residential areas
- Travelling in darkness
- Vehicle factors – such as braking, handling and maintenance
- Defects in road design, layout and maintenance which can also lead to unsafe road user behaviour
- Inadequate visibility due to environmental factors (making it hard to detect vehicles and other road users)
- Poor road user eyesight

Risk factors influencing crash severity
- Human tolerance factors
- Inappropriate or excessive speed
- Seat-belts and child restraints not used
- Crash helmets not worn by users of two-wheeled vehicles
- Roadside objects not crash protective
- Insufficient vehicle crash protection for occupants and for those hit by vehicles
- Presence of alcohol and other drugs

Risk factors influencing severity of post-crash injuries
- Delay in detecting crash
- Presence of fire resulting from collision
- Leakage of hazardous materials
- Presence of alcohol and other drugs
- Difficulty rescuing and extracting people from vehicles
- Difficulty evacuating people from buses and coaches involved in crash
- Lack of appropriate pre-hospital care
- Lack of appropriate care in the hospital emergency rooms

Figure 1: Risk of driving injuries, as defined by the WHO is categorized into the four factors shown above.[34]

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[38] "Safety." *Mercedes-Benz USA*. N.p., n.d. Web. 07 Apr. 2014.

semi-autonomous technologies of today help drivers prevent accidents, but with fully automatic systems, road injuries could be nearly eliminated. The current wave of autonomous vehicles in development today also uses equipment that far outperforms the capabilities of human vision. Technologies like radar and infrared cameras allow computers to "see" in inclement weather, darkness, and other conditions when human eyesight fails.[38] Not only do many abilities of computers greatly outperform those of humans, but computers also are more reliable. Unaffected by fatigue, alcohol, or drugs, autonomous vehicles could ferry passengers around without the danger of them driving under the influence. Additionally, autonomous vehicles are programmed to react and drive predictably. In a recent *New York Times* piece, writer Henry Fountain describes riding in one of Google's autonomous vehicles, "the Lexus hybrid drove itself, following the curves of the freeway, speeding up to get out of another car's blind spot, moving over slightly to stay well clear of a truck in the next lane, slowing when a car cut in front." Autonomous cars are programmed and designed to behave like steady, alert humans, rather than an over-sensitive robot. The predictability of the car's behavior combined with the precision of its performance result in a system that greatly improves safety. Finally, in accordance with the WHO report, autonomous cars also reduce the risk of an accident by decreasing exposure time (decreased traffic congestion and higher speed limits) and aiding in post-crash rescue (current cars can already alert officials if the vehicle is in a crash). Sebastian Thrun, the lead developer and director of Google's autonomous vehicle program, stated that Google's current technology in development today "has the potential to cut that number [1.2 million lives], perhaps by as much as half"[39]

[39] Thrun, Sebastian. "What We're Driving at." Official Blog. Google, 2010. Web. 24 Jan. 2014.

Increased Efficiency and Reduced Traffic Congestion

While autonomous vehicles have the potential to greatly improve safety, they also can increase fuel efficiency, ease traffic congestion, and reduce travel times. The classic and logical approach to relieving traffic congestion is to build more lanes and highways; however, because of the increasing cost of construction and decreasing availability of land, this option is not feasible in many situations. Another approach is to explain traffic flow in terms of mathematics, which results in two main theories: the butterfly effect and kinematic waves.[40] The butterfly effect is a common term usually coined to mean that a small cause can result in a big effect. In terms of traffic, this theory postulates that one driver can have a significant effect on traffic congestion. Kinematic wave (the invisible wave) theory tries to explain a phenomenon commonly seen during rush hour: the phantom traffic jam. These phantom jams appear on stretches of road without warning and many times without reason. In a paper published in 1955, authors M. J. Lighthill and G. B. Whitham attribute these traffic jams to a "propagation of changes in traffic distribution along roads [sic],"[41] which causes waves or humps to form in the traffic. These waves are characterized by shockwaves that occur when "vehicles passing through it [the traffic jam] have to reduce speed rather suddenly on entering it, but increase speed again only very gradually as they leave it"[38] as seen in Figure 2. These phantom traffic jams create positive feedback loops that make the wave worse and worse until serious congestion results. Fortunately, these traffic jams are relatively easy to fix. In a recent NPR piece from November 2013, MIT computer science professor Joe Palca said that drivers "need cars that can do forward and backward monitoring on their own and make the necessary adjustments automatically" such

[40] Neff, John. "The Science Behind Traffic Jams." Autoblog. N.p., n.d. Web. 24 Jan. 2014.

[41] Whitham, G. B., and M. J. Lighthill. "On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads." On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads. N.p., n.d. Web. 24 Jan. 2014.

that there is ample space in front and behind each car.[42] Because of the processing power, speed, and accuracy of the computers and instruments used to determine speed, surrounding space, and location, autonomous cars are excellent at doing this exact thing. Today's adaptive cruise control systems automatically slow down the car if it is approaching too quickly, but with autonomous cars, one car could not only slow down, but also signal to other cars to begin slowing down, thereby preventing a shockwave from forming. Autonomous cars provide several other key advantages over their human-driven counterparts as well, namely synchronized platooning, increased speed limits, and improved driving efficiency.[43]

Synchronized platooning is a method of increasing the capacity of roads by organizing groups of vehicles into tightly spaced units. Autonomous vehicles are particularly suited for these types of maneuvers because their extremely precise movements, fast response times, and

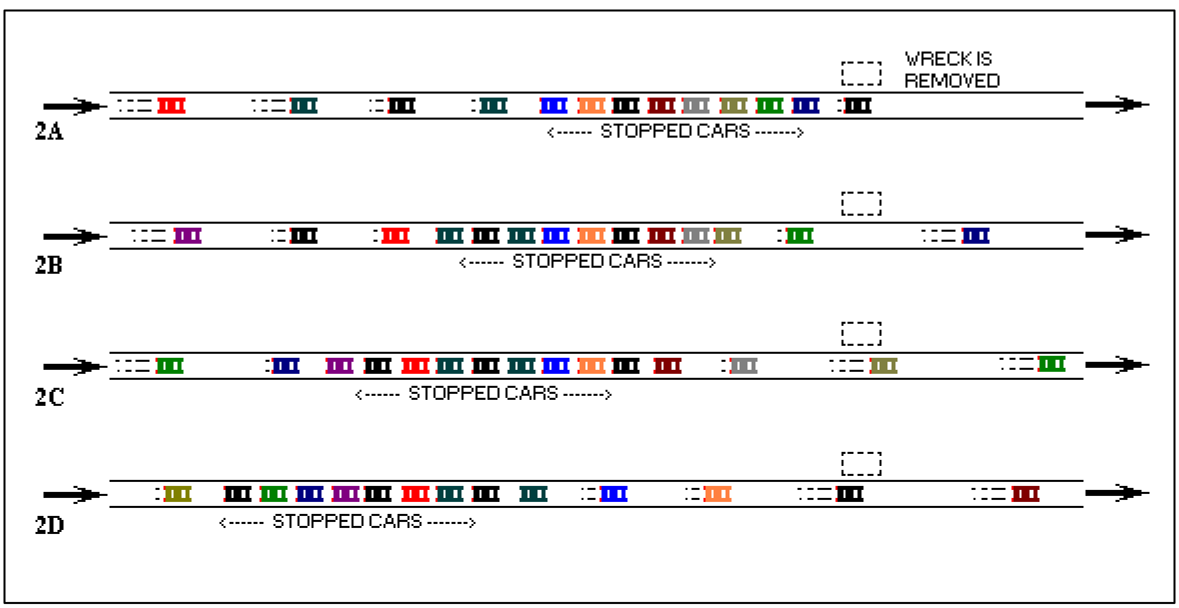

Figure 2: Shown above is a traffic wave that has formed because of a traffic accident. Notice the propagation of the wave in the opposite direction of the flow of traffic. This traffic hump can be described as having a string-stability of 1, meaning that the wave neither grows nor decreases. In systems with autonomous vehicles, string-stability values would be less than 1, meaning that that traffic waves would naturally self-dissipate.

[42] Palca, Joe. "Phantom Traffic Jams: What Causes Mysterious Highway Backups?" NPR. NPR, n.d. Web. 2014.

[43] "An in Depth Analysis of Autonomous Cars." *Autonomous Cars*. Robotic Magazine, n.d. Web. 07 Apr. 2014.

vehicle-vehicle communication abilities. When platoons are formed with human drivers, driving accidents and traffic waves can occur; however, autonomous cars can organize themselves into platoons at high speeds with string-stability. One study found that "to achieve string stability with constant inter-vehicle spacing, vehicle-to-vehicle communication was shown to be necessary."[44] That is, autonomous vehicles not only improve traffic flow, but also are necessary for cars to be able to operate in a fashion that ensures range errors do not propagate down the platoon, the main cause of phantom traffic jams. Another benefit of autonomous vehicles that is widely cited is increased speed limits. The stability of autonomous vehicle platoons allows the vehicles to drive much faster than is normally possible with human drivers.[44] As reported earlier, in the 60s, the British Transport and Road Research Laboratory demonstrated vehicles that could travel at 80 mph on test tracks in any weather condition without deviation in speed or direction. Additionally, Chris Urmson, an analyst involved in the development of Google's self-driving cars, presented preliminary data at the 2013 Robotic Conference in Santa Clara, CA that suggested that their autonomous cars were already both safer and smoother than human driven cars.[45] Finally, platoon driving also increases vehicle gas efficiency by reducing drag. A study conducted by the University of Southern California found that "vans experience substantial drag savings at spacings of a fraction of a car length."[46] The study also estimated that in 7-8 member platoons, each individual vehicle experiences average drag reductions of half. These drag reductions translate directly into fuel savings.

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[44] Sheikholeslam, S. and Desoer, C. A.: Longitudinal Control of a Platoon of Vehicles, Proc. of 1990 American Control Conference, San Diego, pp. 291-296 (1990).

[45] Simonite, Tom. "Data Shows Google's Robot Cars Are Smoother, Safer Drivers Than You or I." *MIT Technology Review*. MIT, 25 Oct. 2013. Web. 07 Apr. 2014.

[46] Hong, Patrick, Bogdan Marcu, Fred Browand, and Aaron Tucker. "Drag Forces." Drag Forces. N.p., n.d. Web. 24 Jan. 2014.

Potential Obstacles and Problems

It seems that with every solution, another problem arises; this proposition holds true with autonomous vehicles. This paper will focus on four main problematic aspects of autonomous vehicles, namely:

1. Unauthorized use of autonomous vehicles
2. Regulations and legal implications
3. Accident liability
4. Impact of driving economy
5. Resistance from enthusiast drivers

Autonomous vehicles will be connected to the internet like many high end cars today. This feature allows cars to communicate to gather information, but also makes the vehicle susceptible to cyber-attacks.[47] Electronics based car theft has been recorded in many states, and police forces are known to possess technology that can unlock any car.

Additionally, regulations and standards need to be put in place to ensure that autonomous cars of different makes, years, and models are compatible with each other. While research and development is moving at a brisk pace, only four states as of 2013 have ratified laws that permit autonomous vehicles to drive on public roads.[48, 49] Many automotive manufactures and companies predict autonomous vehicles on the road by 2020. If autonomous vehicles are to have a successful adoption rate, regulation needs begin to match the pace of development. Another area that will also have to modify procedures and guidelines is the automotive insurance sector. With the liability of an accident taken away from the driver, the question arises: who is responsible for the liability of damage and injury? Car manufactures, insurance companies, and

[47] Kurczewski, Nick. "Report Finds That Cyber-terrorists and Hackers Could Break into Your Vehicle's Electronics, Even While You're Driving." *NY Daily News*. N.p., 19 June 2013. Web. 07 Apr. 2014.

[48] Muller, Joann. "With Driverless Cars, Once Again It Is California Leading The Way." *Forbes*. Forbes Magazine, 26 Sept. 2012. Web. 07 Apr. 2014.

[49] "Green Car Congress: Nevada Enacts Law Authorizing Autonomous (driverless) Vehicles."*Green Car Congress: Nevada Enacts Law Authorizing Autonomous (driverless) Vehicles*. N.p., n.d. Web. 07 Apr. 2014.

government agencies will need to discuss possible solutions before autonomous vehicles can enter a widespread market. However, progress has already been made in California and Nevada, where state laws have been modified to place damage liability on the company that designs the autonomous vehicles.[50] Chris Urmson, a lead developer of Google’s autonomous vehicle program, “dismisses claims that legal and regulatory problems pose a major barrier to cars that are completely autonomous”, citing that “when the inevitable accidents do occur, the data autonomous cars collect in order to navigate will provide a powerful and accurate picture of exactly who was responsible.”[51] While not all corporations and states have ratified the laws Nevada and California have, a precedent is certainly being set by Google and their state government partners.

A less predictable result of autonomous automobiles is their effect on jobs based off of chauffeur services and also the transportation and insurance industries as a whole. According to the American Trucking Association, over-the-road transportation of goods in 2011 accounted for $604 billion in revenue or approximately 81% of all total domestic transportation revenue.[52] Additionally, in New York City there are more than 13,000 operating taxis, gathering more than one billion dollars in taxi fares each year, in addition to 40,000 other for-hire vehicles.[53] The impact of autonomous vehicles on this sector is unclear, but it is possible that trucking and taxi associations could pose resistance to the adoption of autonomous vehicles. In the insurance sector, Celent, a consulting firm based in Boston, released a study that predicted insurance premiums were to fall 12 percent by the year 2022 due solely to increased road safety. While the

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[50] Gurney, Jeffery K. "Sue My Car Not Me: Products Liability and Accidents Involving Autonomous Vehicles." By Jeffrey K. Gurney. University of South Carolina, 2013. Web. 24 Jan. 2014.

[51] Simonite, Tom. "Data Shows Google’s Robot Cars Are Smoother, Safer Drivers Than You or I." *MIT Technology Review*. MIT, 25 Oct. 2013. Web. 07 Apr. 2014.

[52] "SelectUSA." The Logistics and Transportation Industry in the United States. N.p., n.d. Web. 24 Jan. 2014.

[53] "Taxi History." PBS. PBS, n.d. Web. 24 Jan. 2014.

introduction of autonomous vehicles could have negative impacts in these sectors, the overall gain in safety, convenience, and speed will likely outweigh the negative side effects.[54]

The last drawback of autonomous vehicles comes from a specific niche of people who enjoy driving and who don't trust autonomous vehicles. While some might argue that fully-autonomous automobiles will promote the freedom of movement, others might argue that it restricts the freedom to drive. This suggests that an autonomous system must be developed that accounts for human drivers on the road. Autonomous vehicles must be robust and able to not only function with other autonomous cars, but also human drivers. In 2011, an online survey of people in the US and UK found that 49% of people felt comfortable using a driverless car.[55] Nearly half of the market is not yet ready to embrace autonomous vehicles, and while this will likely reduce the efficiency of autonomous systems because of the added human error, the gains of implementing an autonomous vehicle system will still be significant. For most of the general population, however, day-to-day use of autonomous cars will provide a great new platform for transportation that combines safety, convenience, and speed, especially once autonomous vehicles reach affordable consumer-level prices.

The Current State of the Art

For the past decade, autonomous research and development has been exploding. Car manufacturers like Mercedes-Benz, General Motors, Nissan, Volvo, BMW, Toyota, and Audi plan to release semi-autonomous (level 3) cars on the market by 2020, while other companies and organizations continue to make groundbreaking progress. In 2010, Italy's VisLab test ran

[54] "Advantages and Disadvantages - Autonomous Systems." *Advantages and Disadvantages - Autonomous Systems*. N.p., n.d. Web. 07 Apr. 2014.

[55] "Consumers in US and UK Frustrated with Intelligent Devices That Frequently Crash or Freeze, New Accenture Survey Finds." *Accenture News Room*. N.p., n.d. Web. 07 Apr. 2014.

two autonomous vans in a 9900 mile inter-continental trek from Italy to Shanghai, China.[56] Three years later in 2013, VisLab conducted another pioneering test, in which an autonomous vehicle drove through downtown Parma, Italy without any human control.[57] The vehicle was able to successfully navigate roundabouts, traffic lights, and many other sophisticated traffic conditions. Also in 2013, Mercedes-Benz and Infiniti released the 2014 S-Class and 2014 Q50 Sedan respectively, both featuring lane-keeping and adaptive cruise control. The Mercedes S-Class sedan is also capable of autonomously steering, accelerating, and braking at speeds of up to 124 miles per hour. In 2014, Induct Technology's Navia shuttle became the first fully autonomous self-driving car available for commercial use and sale.[58]

[56] "8,000-mile Driverless Test Drive Begins." *MNN*. N.p., n.d. Web. 07 Apr. 2014.

[57] "PROUD-Car Test 2013." *PROUD Car Test 2013 – Description*. N.p., n.d. Web. 07 Apr. 2014.

[58] "Navia - The 100% Electric Automated Transport - InductInduct." *Induct Navia The 100 Electric Automated Transport Comments*. N.p., n.d. Web. 07 Apr. 2014.

Findings

The first step towards autonomous automobiles was with radio controlled cars like the Linrrican Wonder which was demonstrated on the streets of New York in the 20s. In the 40s through 60s level three autonomy was achieved by many separate institutions using magnetic strips embedded in the ground to guide cars. Most notably was the work of RCA Labs in conjunction with General Motors which resulted in cars that could travel 400 feet on private highways completely controlling their own throttle, braking, and steering. This technique is not as robust as more modern approaches which use computer vision to drive cars. This way, an entirely new infrastructure will not have to be built to simply accommodate self-driving cars because modern autonomous cars can leverage the current system of road lines and street signs. In the 80s, the Eureka Prometheus Project culminated in two vehicles VaMP and Vita-2 that were able to drive on a Paris highway for over 400 miles and at speeds up to 80 mph. Finally, in 1996 the ARGO Project developed a car that drove more than 1200 miles using only low-cost video camera and efficient algorithms to follow lane markings. The vehicle was able to drive autonomously 94% of the time, averaging 56 mph.

Many sectors are now involved in autonomous vehicle development, including big corporations, the federal government, and the world of academia. Traditional automotive companies like Mercedes, Nissan, and GM all have plans to roll out commercial autonomous vehicles by 2020, while technology giants like Google continue to push development of their own vehicles. Autonomous cars today leverage several technologies and techniques in combination like LIDAR, accelerometers, and optical video to build self-sufficient vehicles. While the technology needed to build autonomous cars exist today, many other legal and philosophical hurdles still lie in the way of widespread adoption. With the further digitization of automobiles, many ethical questions will arise, like who has access to these vehicles, who is responsible for compensation in car theft, and who can control these vehicles. Additionally, the use of autonomous vehicles to ferry substances and people provides a means for organizations to transport illegal things without traceability. Cybersecurity and privacy has become a topic of serious controversy and concern in the past decade, and there will definitely be risks and problems with autonomous vehicles concerning these issues. Additionally, reluctance to give up driving by a large percentage of the population also creates another obstacle for autonomous cars. But despite these issues, autonomous cars still show much promise.

By eliminating the greatest source of error in a car, the human, autonomous automobiles can dramatically improve safety and fuel economy while simultaneously improving traffic congestion. This is achieved by utilizing the power and accuracy of computers cars will be able to react quicker and more precisely, allowing vehicles to form platoons. Additionally, autonomous vehicles use robust networks of sensors to gather information about their surroundings, allowing them to see and react accordingly to objects and obstacles in unfavorable driving conditions, unlike their human counterparts. Current studies suggest that 4.2 million accidents could be avoided and $450 billion in damages could be avoided if 90% of all cars in the US were autonomous. In the near future, autonomous cars could render driving tests, daily hour-long commutes, and high insurance premiums obsolete.

However, as of today, few commercially available autonomous cars exist in the world, and no commercially available autonomous cars can be driven in the US due to both a lack of availability and regulation by the government. What does exist in the current US automotive market are semi-autonomous (level 2) cars with technologies like Adaptive Cruise Control and Lane Keeping Assist to help guide the driver. These current cars do not aim to replace the driver, but rather aim to act as a supplement to him/her. Last Spring, Mercedes-Benz demonstrated the autonomous capability of its new 2014 S-Class sedan, claiming that it could drive up to 124mph without human intervention on a highway in the right circumstances.

Today, public, private, and government sectors all have research and development dedicated to autonomous cars. Google for example has invested millions in its autonomous vehicles which have recently logged over half a million miles. Government sponsored programs like the DARPA Grand Challenge promote development, while research universities like VisLab in Italy also develop and refine autonomous automobile technology.

Questions Which Remain

The benefits of autonomous vehicles extend well beyond the realm of the consumer. Some of the first autonomous vehicles were created for scientific exploration purposes, like Unmanned Underwater Vehicles (UUV) used to gather data about ocean currents and temperature. Other possible outlets that were not explored in this paper are autonomous aerial vehicles and autonomous humanoids.

New computational techniques that leverage machine learning, neural networks, and artificial intelligence were also not studied in this project. While these new techniques definitely have the potential to benefit autonomous automobiles, the scope of this project is limited to more traditional sensing technology.

Implications and Recommendations

At the intersection of automotive engineering and technology are autonomous automobiles. They show great promise in creating safer, faster, and more robust transportation networks, and will no doubt revolutionize the way we travel. Previously, self-driving cars have only existed in science-fiction, but now in the midst of a technology revolution, they may finally become reality.

There are two areas in this study that would be benefit from additional research by peers. The first is in the area of vehicle-vehicle interaction, in which there is not very much development. Currently, most autonomous car developers focus on a single vehicle, but with the widespread availability of autonomous cars, efficient and robust vehicle-vehicle interaction could amplify the benefits of autonomous vehicles. One place this is already seeing traction is with autonomous vehicle platoons; however, more research is needed in developing effective systems of communication between cars. While connected autonomous cars are more than a decade away, research in connected vehicles would still greatly benefit current versions of autonomous vehicles. Another area of study that would benefit this field is in machine learning. These new techniques of processing large amounts of data in efficient manners would greatly benefit autonomous cars if implemented correctly. Artificial intelligence systems would allow cars to reason better and make more appropriate responses to unfamiliar or challenging situations. This process of receiving input from sensors and outputting a correct response is critical to the functioning of autonomous cars, making additional research in machine learning very valuable.

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Outcomes

While autonomous automobiles have been a prevalent facet of society and culture in the past century, only relatively recently have the technologies necessary autonomous vehicles become available making my research limited to more recent papers. Additionally, many major developments occur behind the closed curtains of large corporations and government agencies. Naturally, these organizations want to protect their research, so while literature that gave broader overviews of development was easy to find, in-depth articles that specifically explained how autonomous vehicle systems worked were much more difficult to obtain. My paper would benefit from more scholarly sources that detail exactly how their systems work.

Skills Learned

This project has taught me many things, and my favorite lesson so far has been the sense of accomplishment I feel when I look at my finished paper. Thinking about how all of the hard work, late nights, and stress that has gone into this project have finally culminated in this paper gives me the greatest sense of satisfaction and relief. I cannot be more proud of my work. In addition to showing me the fruits of hard work, this project has also helped me manage time better. I personally have seen the consequences of procrastination, and I know next time I will get an earlier start. Additionally, I have learned to write in a scholarly and academic way that I have previously had very little exposure with. Not only does this benefit me in terms of writing research papers, but I now understand professionalism in academia better now. Finally, I have learned how to deal with ambiguity better. I distinctly remember at the beginning of this project, I was confused, lazy, and scared. Looking back, I'm glad that I took the bull (or at least what I thought was the bull) by its horns. This project has taught me so many new skills that go well beyond the scope of academics and into my everyday life.

Personal Strengths

My greatest achievement in this project has been being able to manage my time well such that I didn't have to give up any of my other extracurricular activities. I'm glad that I was able to continue playing sports and violin, while simultaneously keeping up with school and working on my paper. There were times in junior and senior year where I felt that I could not make it, but I'm proud that I didn't give up and that I kept pushing until I crossed the finish line.

Personal Weaknesses

While I met most of my deadlines, I cannot say I did them with ease. Like many of my peers, time management was a big problem as well as a big lesson for me. I definitely procrastinated starting this project both out of dread and not knowing where to begin. While eventually I did get working, it took longer than I would like to admit. My procrastination and resulting cramming placed stress not only on myself, but also on my friends and family. I think that this is an area that has not only affected Global Scholars, but also my schoolwork and college applications. This is something that I can definitely improve on.

Another thing that I could have done better is maintaining consistent contact with my mentor, Dr. Nathanial Fairfield. At first, I contacted him by phone and email regularly, but as time passed I lost contact. Dr. Fairfield was an extremely qualified and knowledgeable asset that I did not properly utilize. Next time, I hope to maintain better contact with my mentors and better utilize the tools available to me.