Autonomous Driving - A Practical Roadmap

2010-01-2335
Published
10/19/2010

Jeffrey D. Rupp and Anthony G. King
Ford Motor Company

ABSTRACT

Successful demonstrations of fully autonomous vehicle operation in controlled situations are leading to increased research investment and activity. This has already resulted in significant advancements in the underlying technologies necessary to make it a practical reality someday. Not only are these idealized events sparking imaginations with the potential benefits for safety, convenience, fuel economy and emissions, they also embolden some to make somewhat surprising and sometimes astonishing projections for their appearance on public roads in the near future.

Are we now ready for a giant leap forward to the self-driving car with all its complexity and inter-dependencies? Humans will need to grow with and adapt to the technological advancements of the machine and we'll deeply challenge our social and political paradigms before we're done. Even if we as engineers are ready, is the driving public ready?

Putting a man on the moon was achieved through a series of logical extensions of what mankind knew, with necessity driving a search for technical solutions in the usual as well as unusual places, much as the Defense Advanced Research Projects Agency did with their Grand Challenges. This paper addresses the autonomous vehicle vision in terms of the current state and some of the practical obstacles to be overcome, and proposes a possible roadmap for the major technology developments, new collaborative relationships, and feature implementation progression for achieving those ambitions.

1.0. INTRODUCTION

The desire for the ultimate personalized, on-demand, door-to-door transportation may be motivated by improved personal convenience, emissions and fuel economy; yet there are also potential safety benefits from the pursuit of autonomous vehicles. This paper describes some of the practical obstacles in achieving those goals, and explores the use of near term applications of technologies that will be by-products of pursuing them. This includes a partial history of autonomous vehicle development (Section 2), potential consumer acceptability issues (Section 3), followed by a development roadmap and discussion of some variables to be addressed before autonomous vehicles become viable (Sections 4 and 5), and ends with a consideration of collaborative relationships that could assist in acceleration of development and issue resolution (Section 6).

2.0. THE CURRENT STATE - PUTTING THE HYPE INTO PERSPECTIVE

There has been escalating excitement about fully autonomous vehicles in the robotics community for some time and the excitement has now spilled over to the automotive industry. The idea of a self-driving, road-ready vehicle sparks the imagination, and is a familiar concept due to repeated exposures in popular culture; be it movies, cartoons, television, magazines, books or games.

An exhibit at the 1939 World's Fair in New York[1] presented a vision where cars would use “automatic radio control” to maintain safe distances, a depiction of transportation as it would be in 1960, then only 21 years into the future. One of the earliest attempts at developing an actual vehicle was led by Dr. Robert E. Fenton who joined the faculty at Ohio State University in 1960 and was elected to the National Academy of Engineering in 2003[2]. It is believed that his pioneering research and experimentation in automatic steering, lane changing, and car following resulted in the first demonstration of a vehicle that could drive itself. Since then, OEMs, universities, and governmental agencies worldwide have engineered or sponsored autonomous vehicle projects with different operating concepts and varying degrees of success.

Most recently, the Defense Advanced Research Projects Agency (DARPA), an agency of the United States Department of Defense, sponsored three autonomous vehicle challenges. While a number of media friendly successes resulted in good ‘photo ops’, those in technical fields and many others readily appreciate the magnitude of work required to mature these vehicles into a viable, real world, design.

2.1. Contemporary Error Rates -- We're Way Off

In the months preceding the inaugural DARPA Grand Challenge in 2004, William “Red” Whittaker of Carnegie Mellon's Robotics Institute, with over 65 robots to his credit, stated “We don't have the Henry Ford, or the Model T, of robotics”, “Robotics is not yet mainstream; it's not yet a national conversation.”[3] His contributions and those of his students over the next few years would move the needle significantly, but his comments suggest the true nature of the challenge.

The error rates of robotically piloted vehicles today are still very high compared to human-piloted vehicles. At the 2005 DARPA Grand Challenge (DGC2) 5 of the 23 finalists successfully finished the 132 mile course, while two years later, at the 2007 DARPA Urban Challenge Event (UCE), 6 of the 11 finalists finished a 60 mile course. The mean mileage between significant errors (failure) at these events was 120 miles for DGC2 and 100 miles for UCE[4]. The errors cannot be attributed to a single primary cause, rather, multiple simultaneous causes and interactions including sensing, interpretation of the scene and simplification of its full complexity, simplifying assumptions and non-representative tradeoffs built into the algorithms, as well as unintended software bugs and hardware durability. Compare robotically piloted vehicle errors to that of human drivers, who averaged 500,000 miles driven between crashes in 2008[5].

Despite humans being 3-4 orders of magnitude better at driving than robots, crashes of varying severity occur regularly. In 2008 in the United States alone, there were 34,000 fatal crashes and 1.6 million injury crashes. Autonomous vehicles may need to be better drivers than humans, exhibiting fewer errors, to gain acceptance. The error rates inherent in today's autonomous vehicles are unacceptable for real world deployment in the present and will be for some time to come.

2.2. Progress Has Been Slow

Recalling the many predictions of a self-driving car over the last four decades, it is obvious that autonomous vehicles have taken and will take far longer than expected, especially when it comes to operational safety. Fully autonomous vehicles today are the product of laboratories, test tracks, and prize winning competitions, mainly conducted under favorable conditions with minimal and controlled uncertainties and no penalty for error. With limited success even in ideal situations, industry has little choice but to methodically split the problem into attainable steps, learning and developing the necessary enabling technologies along the way.

The combination of radio detection and ranging (RADAR) functionalities was patented by Christian Hülsmeyer in 1904[6], building on work from the mid-1800s by physicists James Maxwell and Heinrich Hertz. The majority of the development since then has been driven by maritime collision avoidance and military defense applications, including important signal processing extensions such as target velocity estimation based on frequency shift as proposed by physicist Christian Doppler. Despite this early start, it wasn't until 1999, with seven years of focused target tracking and controls development as well as electronics miniaturization, that Ford Motor Company launched the world's first-to-market radar-based ACC system with braking for an automotive application, on a Jaguar XKR.[7]

More than a decade later, advances in sensing technology critical for autonomous vehicle applications are just now accelerating significantly. Functionality of automotive forward-looking radars is increasing, even while prices are decreasing, with a drop of 75% over two generations expected in one case.[8] The progression to today's state of the art dual mode electronically scanned systems has allowed industry to use the resulting increased accuracy and availability to expand to new customer functions.

Digital camera systems have similarly been in existence for quite some time, with a patent application for “All Solid State Radiation Imagers” filed in 1968[9], and are now progressing more rapidly too. CMOS imagers have demonstrated increasing sensitivity, dynamic range, and pixel count, while costs have decreased due to the large volumes of consumer electronics applications. More recently, advancements in machine vision algorithms have enabled the evolution from lane tracking to significantly more complex vehicle and pedestrian detection and tracking functions.

Fusion sensing systems are also starting to see more automotive applications as well. Combining multiple sensing modalities, fusion leverages the orthogonality that can be established where the strength of one complements the weakness of another. This can create a sensing system with robustness and reliability greater than the sum of its parts. Ford developed and launched a radar-camera fusion system for Collision Avoidance Driver Support (CADS) functionality on the Volvo S80 in 2007. This was further expanded on the 2011 S60, overlaying a fused camera / forward looking multi-mode radar, with a multi-beam infrared and ultrasonic sensors, enabling collision warning and full auto braking for vehicles and pedestrians for collision avoidance, a world first, in addition to ACC, Lane Departure Warning, and Driver Alert (driver impairment monitoring) functionality.[10]

Other sensing technologies are also under development to better describe and interpret the external environment. Although automotive lidars, especially for ACC, have fallen out of favor, the development of 360° scanning and flash designs may bring about their resurgence. Detailed on-board maps are now available to help predict the road attributes ahead. Even as the number of radars and cameras in the vehicle proliferate, the industry also recognizes that on-board sensing could be significantly augmented through direct communication with other vehicles and the infrastructure. Research in the area of vehicle-to-vehicle and vehicle-to-infrastructure communications will be critical to any future cooperative transportation network. Despite these advancements, the verdict is still out as to the form of the ultimate sensing solution.

The majority of today's situation assessment algorithms enable only advisory and warning systems, as these systems are more easily implemented than fully autonomous control; using sensor data, the algorithms interpret the environment, predict the future, and provide some related driver support. With this limited approach, most performance errors merely result in annoyance. The environmental sensing system and control algorithm requirements are not as stringent as needed for autonomous operation, where the machine makes a decision and takes control of the vehicle. In the latter case, an incorrect decision may possibly result in a wrong action, possibly causing a collision when one may not have occurred otherwise. While designing a system that reacts positively (e.g. automatically applies the brakes prior to a collision) is readily achievable, the more difficult part of the task is to design the system to seldom make a mistake, and have the reliability and robustness necessary to appropriately respond to real world noise factors. The autonomous systems that exist today in controlled laboratories and test tracks are just not ready for the uncontrolled uncertainties of real world conditions. Automotive engineers are proceeding slowly to help ensure that appropriate level of performance exists before introduction.

2.3. Reluctant Consumer Acceptance of Autonomous Control

One need read only a few blogs in order to appreciate that consumers are uncomfortable with a machine making decisions for them and you can easily conclude that some drivers do not trust their vehicle taking even limited autonomous control. An independent analysis is available that describes the phenomenon of decision trust and the attributes affecting safety feature purchase.[11] Furthermore, the lack of third party endorsements for more than the most basic CADS functions (i.e. Forward Collision Warning; further enumerated in Section 4.2, Use Cases) has created little feedback for these technologies and therefore little customer enthusiasm and 'pull', and the lack of government mandates has created no 'push'.

Governmental and public domain agency action may help accelerate acceptance and adoption, or at least access and usage, of autonomous technologies, and several organizations around the world are considering regulation. Anti-lock braking systems were introduced in 1971, and reached 86% market penetration only after 37 years, in 2008. Compare that to Electronic Stability Control (ESC), introduced in 1995. Although the industry already had an implementation plan, the U.S. National Highway Traffic Safety Administration (NHTSA) accelerated penetration by mandating standard ESC in all new vehicles by 2012, less than 20 years later. NHTSA has included Forward Collision Warning and Lane Departure Warning in the ratings for the Active Safety New Car Assessment Program. The European Commission is considering mandates for Collision Mitigation Systems on light commercial vehicles. Non-governmental organizations such as the Insurance Institute for Highway Safety and the Consumers Union (publishers of Consumers Report magazine) have started to address CADS technologies, raising consumer awareness. Insurance companies are considering lower rates for vehicles with CADS features.

It is interesting to note that market adoption rates may have some cultural influence. Take the ACC system for example, a fairly straightforward extension of traditional cruise control that provides longitudinal control of the vehicle using brake and throttle to maintain distance to a vehicle in front. Ten years after initial introduction, it is finally getting significant mass market recognition, but the penetration rate in North America is only a fraction of that in Japan where the market seems to have a greater percentage of early adopters, allowing for rapid technology evolution. An independent study detailing these differences is also available.[12,13]

2.4. Today's Feature Implementation Progression

Although the adoption of CADS functions in private vehicles has been slow to date, the world is on the cusp of more widespread implementation of limited autonomous control. Technology will continue its rapid advance and as consumer acceptance expands, the industry will see systems that warn the driver of hazardous conditions, support driver actions, provide limited autonomous control with driver command, and even take some fully autonomous action to avoid a potential collision. The nature, direction, and pace of CADS feature introduction and progression can be inferred from the following list:

• Longitudinal support:

1958	Cruise Control (non-adaptive)
1971	Anti-lock Braking System (ABS)
1991	Ultrasonic Park Assist
1999	Adaptive Cruise Control (ACC)
2003	Forward Collision Warning (FCW)
2003	Collision Mitigation by Braking (CMbB),
2006	Stop & Go ACC (S&G)
2006	Full speed range ACC
2008	Low Speed CMbB (collision avoidance, City Safety™)
2010	Full Autobraking CMbB
2013 (*est.*)	Curve Overspeed Warning (electronic horizon-based)
2015 (*est.*)	Curve Overspeed Control (electronic horizon-based)

• Lateral support:

1971	ABS
1990	Variable steering assist, cross wind compensation, etc. (electrical)
1995	Electronic Stability Control
2001 (*Japan*)	Lane Departure Warning (LDW)
2001 (*Japan*)	Lane Keep Assist (LKA)
2002	Roll Stability Control (RSC)
2003 (*Japan*)	Lane Centering Aid (LCA)
2004 (*Japan*)	Intelligent Parking Assist System (IPAS)
2005	Blind Spot Information System (BLIS)
2006	Active Parking Assist
2007	Driver Alert, Driver Impairment Monitoring
2012 (*est.*)	Lane Change Merge Aid (LCMA)
2013 (*est.*)	Emergency Lane Assist (ELA)

• Integrated lateral and longitudinal support:

2010	Curvature Control (stability control-based)
2014 (*est.*)	Traffic Jam Assist (TJA) - S&G ACC + LCA

With the continuous evolution and improvement suggested by this feature progression, it is clear that many benefits from warnings and limited autonomous control are being realized, and more soon will be. Beyond this, incremental benefits can be reasonably attained only by advancing to a more complex and potentially intrusive level of functionality, one more closely associated with fully autonomous driver-support features. As suggested previously, consumer paradigms may need to shift again, and the governmental and social infrastructure may need to adapt. The key factor in establishing consumer comfort with these technologies may be empowerment of the driver in making the final control decision, say, overriding the function of the CADS feature.

3.0. A LOOK TOWARD THE FUTURE

3.1. Uncertainty, Unpredictability and Human Error

According to a World Heath Organization study from 2004, traffic accidents result in approximately 3,300 deaths every day, equaling over 1.2 million fatalities each year worldwide. By 2020, annual fatalities due to vehicular accidents are projected to increase to 2.34 million, assuming continuation of current trends. Already the leading cause of injury mortality, road crash injury is likely to become the third leading cause of disability-adjusted life years (DALYs) in the same time frame, trailing only heart disease and unipolar depression.[14]

The pursuit of autonomous vehicles, where drivers are supported in the driving decision making process, has a positive correlation with the pursuit of fatality-free, and even collision-free, transportation. Humans are fallible; driver error is the primary cause of about 90% of reported crashes involving passenger vehicles, trucks, and buses.[15] A misconception links these human errors solely as "… evidence of lack of skill, vigilance, or conscientiousness"[16] or insufficient training, since highly trained and skilled experts, such as doctors and pilots, are also susceptible to making errors, some with serious consequences. Frequently, errors result from poor reactions to unpredictable events and incomplete information as factors in the decision making processes. These probabilistic external factors typically form complex interactions creating random non-repeatable events. One study of airline pilots found that"… small random variations in the presence and timing of these factors substantially affect the probability of pilots making errors leading to an accident."[17]

Given these uncertainties, it seems unrealistic to assume that a decision making process, be it human or machine, will make the appropriate decision 100% of the time. Moreover, we must be cognizant of the fact that drivers are not machines and contemporary machines were shown previously to have not attained any where near the levels of holistic human cognition. Further, human reaction to the same exact external input will vary from individual to individual, and will therefore continue to be subject to unpredictable outcomes.

These external and internal uncertainties characterize the system inadequacies in which errors occurred, where the driver and the vehicle are only a portion of the overall transportation system. Rothe describes how the concept of a living system, one that adapts to change and achieves a new balance, can be applied to a driving scenario.[18] He suggests that an interactive relationship exists among the various system factors - biological (health/illness), psychological (doubt), social (seclusion), societal (norms), economic (lost wages), legal/political (arrest), other drivers and vehicles, the road infrastructure, and information regarding their status (weather and road conditions). Each of these factors set the stage for the other with recursive feedback between them. Focusing on a single factor merely distorts the situation without resolving it.

The implication from this is that a better understood and more tightly coordinated overall system will result in reduced levels of unexpected future events, and thereby a reduced likelihood of collisions. Nearly error free decision making is a very hard problem but it needs to be solved before an autonomous vehicle system that provides 'Full Driver Assist' is ready. Predicting when it will be feasible is merely guess work, but a roadmap would still be useful in approaching it in a comprehensive and systematic fashion.

3.2. Autonomy in Other Transportation Modes

The Shinkansen railway system in Japan provides an example of a positive attempt and outcome. Running on separate track from conventional rail, the lines are built without crossings, use long rails that are continuously welded or joined with expansion joints that minimize gaps due to thermal conditions, employ Automatic Train Control for on-board signaling, have early warning earthquake detection so trains can safely stop, and enforce strict regulation with stiff fines to prevent trespassing on the tracks. From the train sets, to the tracks, the operators, the information availability, and the governmental regulations, this tightly controlled system is designed to reduce the amount of uncertainty and enable a high reliability of safe decision making. The result: no injuries or fatalities due to derailment or collision in 46 years of operation, and only one derailment (with no injury) caused by an earthquake in 2004, while carrying over 150 million passengers a year (in 2008).[19]

The Shinkansen system demonstrates that fatalities may not be an inevitable consequence of transportation after all. A major difference lies in the train operators themselves - besides being highly trained, their number is but a mere fraction of the billions of personal-vehicle drivers in the world today. Thus, tight control over the system includes control over this uncertainty: the variance of individual driver (operator) reactions to external inputs. In the quest for further reductions in collisions in private vehicles it is inevitable to eventually seek to replace human unpredictability with something a bit more predictable. The result may not be purely an electronic substitution, but rather a driver 'subsystem' that involves both the human and the electronic system. The electronic system informs and aids the human in the ways it is better suited, by leveraging its strength (e.g. estimating range and closing velocity), and leaving higher level tasks for the human 'driver' to perform. It's an orthogonal decision making mode, similar to fusion of multiple modalities of sensing (e.g. radar and vision). Each has its strengths and weaknesses, but when properly combined results in a more reliable and robust solution.

Consider another self-driving (autonomous) vehicle, one that has existed for centuries. A ship's captain is on board, but may never touch the wheel; he is in command but not necessarily in direct control. He has a surrogate system, in this case human, that is 'programmed' to carry out 'lower level' control functions, whether that human be a helmsman, quartermaster, or engine room operator, relieving the captain of the burden of continuous interaction. Similarly, you hire and 'command' a taxi as a system (car + driver) by requesting a destination, but there is no direct control.

Beyond those analogies, there are many 'self driving vehicle' applications in existence today. These are autonomous vehicles in a very real sense, some having greater autonomy than others. Commercial airplane pilots engage the autopilot and monitor the systems until direct intervention is needed, whether induced by tower commands or an emergency. Automated train systems, such as those within an airport terminal network, ferry people without an onboard pilot, but are still controlled by humans at a central station. The military has significant autonomous vehicle assets in operation today including Unmanned Air and Ground Vehicles (UAV and UGV respectively), which can be directly controlled by a remote operator, or programmed for autonomous operation to patrol a certain area for a set number of hours, for example. In the past few decades, modern sailing vessels have replaced mundane operator tasks with computer control; an autopilot can now navigate from waypoint to waypoint and seamlessly control throttle, rudder, and roll stabilizers.

All these are examples of vehicles with autonomous control, but still not completely without human oversight. If a pilot is not directly on board, then there is an operator monitoring remotely. There is no vehicle or transportation or mobility system that doesn't have human oversight of some sort. And we should expect the human operator to be 'in-the-loop' for a very long time.

Moreover, these semi-autonomous systems rely on operators trained specifically for driving. To become a commercial airline pilot, for example, one must first obtain a commercial pilot license after 250 hours of flight time, with allocations dedicated to specific conditions and maneuvers. Additionally, a commercial pilot needs an up-to-date first- or second-class medical certificate, an instrument rating and a multi-engine rating. Thousands of additional flight hours are needed to even be considered for hire at a commercial airline. Once hired, additional training begins. Typically a 10 week course ensues, followed by a few weeks in the simulator, where the trainee experiences just about every emergency and anomaly imaginable. Once this training is done, initial operating experience is gained by flying some 25 hours with a special instructor pilot, followed by another flight test. Now the pilot can become a crew member. In order to become the captain of a major commercial airliner, a pilot must then obtain an airline transport pilot certificate which requires passing a written test, and logging 1,500 flight hours including 250 hours as the pilot in command. Similar levels of training are required to pilot a ship, control military UAVs, or control NASA's unmanned vehicles. Current driver training for operating an automobile is not nearly so stringent.

3.3. Do We Want a Driverless Car?

When people talk about fully autonomous vehicles, a common image is that of a driverless car, like the autonomous trains in an airport or DARPA challenge robots. Do consumers want a car without a driver, a car that can go somewhere without you like a military mission, whether delivering a package or picking up the kids after school with no one in control on board? There may be a few cases where a consumer wants someone or something else to do these tasks, but we already have services in place for that - package delivery services, buses, carpools, taxis, etc.

Instead, consumers of private autonomous vehicles may not want a driverless car, but rather a car that drives itself. You are in the car, and the car transports you, your belongings and your family, but you don't necessarily want to directly pilot it. You don't want to be locked into the detailed, sometimes tedious, moment to moment tasks of driving, but instead merely want and need to direct where it goes and how it gets there. You want command, but are willing to relinquish the detailed control to automation so that you can do something else; listening to music, placing a phone call, watching a movie, or just enjoying the scenery. What the consumer really wants is not a self-driving car, but an autonomous vehicle system that provides Full Driver Assist.

Recall the first mainframe computer, first PCs, the first PDA, and then the first cell phones. These devices were going to make our jobs and lives easier. And they have - not by doing work for us as originally thought, but by helping us work more efficiently. At first they were all clumsy devices, difficult to use, and not well accepted. Eventually they are integrated into the connected world in which we live and evolved into productivity tools that enable us to work in more places, more of the time. Similarly, the advent of autonomous technologies in vehicles will result in drivers that are more engaged in some aspects of the driving process rather than further removed, providing them with greater capability in managing the overall process. The driver would now be much more akin to the captain of the ship, biased toward the tactical, strategic, interactive, and predictive roles while leaving the role of the helmsman, lookout, navigator, and even quartermaster to the vehicle systems. Handling this type of automation in everyday life, however, requires that the consumer paradigm change.

3.3.1. Driving to a Seamless Experience

Smartphone owners can buy a special application (app) for just about anything, from checking the weather to checking your bank accounts and paying bills, from playing games to updating your social network and checking sports scores, and so on. There are dozens of apps just for social networking - one for each online site - plus apps for email, contacts, text messaging, and instant messaging. In today's smartphone implementation, the entire task of staying in touch with a social network is an exercise in opening and closing apps, which is a clumsy and overly complicated interface at best. Soon there will be a single app where you can see all your friend's updates on the social networking sites, while tying it seamlessly together with the contacts, photos, email, and text messages on your smartphone.

Like consumer electronics, the automotive industry is now tackling these issues; focusing on improving the in-vehicle experience by combining these apps into seamless experiences. MyFord Touch™, Ford's new driver-connectivity technology, complementing SYNC®, Ford's device and off-board service connectivity technology, is an example of integrating and simplifying the experience of entertainment and connectivity in the vehicle. Through the digital cluster displays, large touch-screen interface and voice interaction, the system allows the driver to naturally command the vehicle to play new music, seek traffic, direction and journey-related information, answer calls, make calls, and even listen to text messages through multi-modal interfaces. Software application programming interfaces (APIs) will soon be available to allow apps like Pandora and Stitcher to be controlled through the voice-controlled SYNC® system to stream audio to build a consistent, user-friendly interface within the vehicle itself.

This development progression repeats a trend that has occurred time and time again. Compare these steps for starting a Ford Model T[20] with today's 'turn the key' or 'push the button' ignitions:

1. Pull the choke adjacent to the right fender while engaging the crank lever under the radiator at the front of the car, slowly turning it a quarter-turn clockwise to prime the carburetor with fuel.

2. Get into the car. Insert the ignition key, turning the setting to either magneto or battery. Adjust the timing stalk upward to retard the timing, move the throttle stalk downward slightly for an idle setting, and pull back on the hand brake, which also places the car in neutral.

3. Return to the front of the car. Use your left hand to crank the lever (if the engine backfires and the lever swings counterclockwise, the left arm is less likely to be broken). Give it a vigorous half-crank, and the engine should start.

Development focuses on the task the consumer is trying to perform, and works to improve the overall user experience associated with that task. Through integration, the functional evolution simplifies the operation and significantly enhances the efficiency in performing that task. Historically, the movement towards a simplified, seamless experience to improve operating efficiency has been a key to widespread adoption of new technology, stimulating a series of consumer paradigm shifts. Similar to a smart phone, the technologies discussed in Section 2.4, Today's Feature Implementation Progression, may be considered standalone apps as well, but in a vehicle environment. Many of the highest technology features have had limited take rates possibly due to perception of cost, complexity and uncertainty of performance, but we expect this will benefit from development into a more seamless experience. Traffic Jam Assist is a technology that operates the distance control of ACC S&G in conjunction with the lateral control of LCA at low speeds. A later step will be to integrate all CADS functions into a comprehensive Full Driver Assist functionality, simplifying the web of complex CADS functions into a coordinated holistic system - user-friendly, easy to understand, and available to all consumers.

When done well, this advanced development can result in recommendations by opinion leaders at many levels, improving the familiarity and comfort level with the technology, further speeding adoption and penetration into everyday life. But what does Full Driver Assist really mean to consumers? What tasks do automotive consumers wish were more efficient?

3.3.2. Of Desires, Expectations, and Values

America has always been a country where motoring nostalgia is heavily intertwined with the freedom of exploration. This explains American's love affair with the car; with hands on the steering wheel, foot on the accelerator, and hair blowing in the breeze while cruising down Route 66. Americans are in their cars a lot - an average of 87 minutes per day according to an ABC News survey.[21] Some automakers have recently focused on remaking car interiors like a comfortable and luxurious living room, but driving is not all for fun.[22] Commuting to and from work comprises over 27% of vehicle miles traveled, more than any other category. The next highest category was social/recreational travel, including going to the gym, vacations, movies or theater, parks and museums, and visiting friends or relatives; i.e. using the vehicle as a means to get to a destination. These two categories alone comprise over 50% of all vehicle miles traveled. A recent study by Northeastern University indicated that, given past history, one can predict anyone's travel route and location with 93% accuracy.[23] These studies imply that people are repeatedly visiting, or commuting to, the same locales with significant regularity.

So do people enjoy the daily driving routine? The study by ABC News indicates that nearly 60% of people like their commute, but only if the trip is relatively easy. Nearly 4 out of 10 state the primary reason they like their commute is that it gives them quiet or alone time, and nearly a quarter identified that their commute is easy and has little congestion or traffic. For city dwellers with more than a 30-minute commute or experience traffic congestion, the percentage who likes their commute drops into the 40's. To further understand consumer behavior, it's necessary to understand the human emotion and values. A great majority of drivers, according to this study, at least occasionally feel very negative emotions while driving, with 62% feeling frustrated, 56% feeling nervous about safety, and 43% even feeling angry. But the same survey also says that 74% often feel independent, while 48% often feel relaxed while driving. Interestingly, independent and relaxed are not really emotions, but relate to core human values. The Rokeach Value Survey (RVS) identifies 18 terminal values, which are values every human strives to experience at least once in their life (and more often if possible), and 18 instrumental values, which are the preferred means of achieving those terminal values.[24] Independence is an instrumental value, and relaxed can correlate to inner harmony, a world at peace, or comfortable life terminal values.

These values seem to at least partially explain, if not directly motivate, people's desire to drive. They explain the high consumer demand for infotainment in the car -- drivers want to enhance relaxation through music or conversation. Infotainment systems, as a relaxing agent, will become even more important as traffic congestion worsens. Hours spent in traffic delays have increased 50% from the last decade and continue to increase[25], so it is expected that the number of people feeling relaxed while driving might actually decrease, even with infotainment systems in the vehicle. On the other hand, Ford and MIT's AgeLab, in conjunction with the U.S. Department of Transportation's New England University Transportation Center, have been working since 2004 to develop vehicle systems that detect the stress level of the driver at key points in time.[26] A recent extension of that project intended to identify specific stress-inducing driving situations, apply biometrics to monitor driver reactions and evaluate methods to incorporate new stress-reducing or even stress-optimizing features.[27] These features include the Blind Spot Information System with Cross Traffic Alert, Adaptive Cruise Control and Collision Warning with Brake Support, MyKey, Voice-Activated Navigation, and SYNC®.

Additionally, the RVS values discussed previously explain why only 5% of trips are on public transportation. Although one can just as easily feel relaxed on a commuter train as in a vehicle, 93% find traveling by car more convenient. It is this convenience that keeps drawing drivers back to the road; the freedom to leave whenever you want; the convenience of getting you from exactly point A to point B without changing modes of transportation. Having your own personal vehicle translates to independence, eliminating the need to rely on someone else to accomplish your own tasks or pursue your goals.

What do drivers want? They want a utilitarian appliance that moves them from door-to-door on their terms; they want to be more effective in the driving process, and they want luxury comforts. They use descriptors such as ‘productive’, ‘efficient’, ‘relaxing’ and ‘personalized’. An autonomous transportation device with independent supervisory control would fit the bill, but they also want the ability to drive the enjoyable drives which may add excitement and enhance a sense of freedom. A successful vehicle will likely need to seamlessly blend full assist and fully manual modes of operation and probably everything in between to satisfy consumer needs, expectations, desires, and values.

3.3.3. Consumer Paradigms

In order to build the future of personal transportation that people want, the associated consumer paradigms must change. There is precedence for the shift necessary for adoption of new technological innovations. When Nicolas Joseph Cugnot introduced one of the first self-powered vehicles in 1769 (which was commissioned by the French army), not many imagined that this curiosity would spawn a technological gold rush for the next century and a half in a race to provide ‘auto-mobile’ vehicles to the masses. Instead there were concerns about their safety and usefulness, as this early vehicle could only travel at 2.5 mph for 10 minutes at a time, and crashed in its first demonstration. Technology progressed, and by the first half of the 1800s there existed a small market for steam-powered auto-mobile vehicles. However, in 1861, the British Parliament was sufficiently concerned about public safety to enact The Locomotive Act that severely limited operation of motorized vehicles on-road. Although this stopped most motorized vehicle development in Britain, innovation continued elsewhere, especially in Germany, France and the United States. As the automobile moved into the mainstream and garnered ever more press coverage, consumers became more comfortable with and confident in the technology. This Act was partially repealed in 1896, and automobile development accelerated at the turn of the century with the advent of electric and internal combustion propulsion. By 1913, Henry Ford was building Model T's that every working man could afford, the result of standardized manufacturing and internal combustion engine technology.

The evolution from the driver-guided to the autonomous personal vehicle will parallel the evolution from the horse-drawn to the auto-mobile carriage: a period of initial caution and low acceptance, initial innovation and invention, use by early adopters, followed finally by rapid innovation and expansion, mass market penetration, and standardization. New technology will deeply challenge the social and political paradigms of the day, but now, as always, humans will adapt. As before, full consumer acceptance will not occur until consumers observe early adopters for a sufficient amount of time to trust that the system can operate safely and has a mature level of robustness and functional tuning. The wall of resistance to limited autonomous control is just starting to fall. With consumers showing signs of increasing comfort with automation, expect acceleration in the implementation and penetration of vehicle CADS technologies. Each generation of CADS implementation builds consumer confidence in the technology, and eventually consumers will accept autonomous control as naturally as they accept a self-powered (auto-mobile) vehicle.

4.0. DEFINITION AND ROADMAP FOR A FULLY AUTONOMOUS VEHICLE

Successful development of something as complex as a fully autonomous vehicle will be most readily achieved by those taking careful evolutionary steps, rather than one revolutionary leap. The DARPA Challenges served to jump start work on autonomous vehicles in the commercial sector, and fed new learning back to the military-industrial complex that has been working on the same problem for decades. These competitions and demonstrations provide glamour and some important lessons, but the technologies developed will not be directly applicable to the consumer market for quite some time, if ever. They just are not the practical next steps to putting something into production for public sale; these solutions leap right past more fundamental problems.

However, there's a place for the revolutionary vision, partly to show the world the march towards autonomous control, but mostly to motivate the effort and the long-term investment required. Industry and society both need high visibility demonstrations to sustain enthusiasm through the arduous hours of detailed engineering and analysis necessary to turn a dream into reality. We need to take time to understand true consumer values, and then engineer the technology and infrastructure for the reliability and robustness necessary to enact a safe and secure driving experience, one that inspires consumer confidence.

An on-demand, door-to-door, personalized automated transportation system may very well be achieved some day, but there are many lesser autonomous functionalities that customers will value that can be implemented much more quickly. As the industry researches and engineers towards Full Driver Assist it needs to follow a spiral development model, spinning off technologies and capabilities as they mature, bringing the consumer along step-by-step, little by little. These spin-offs cannot be limited to only the latest and greatest technology implementations. They must also include low cost solutions that can be implemented on lower cost vehicles for global implementation.

What follows is one promising roadmap for realizing a fully autonomous vehicle, or more precisely a Full Driver Assist-capable vehicle. It begins with an overarching design philosophy followed by customer-valued Use Cases that build upon existing collision avoidance and driver support features, which should be sequentially achieved, with appropriate operational reliability and robustness before proceeding to successive levels.

4.1. Design Philosophy

Until we have proven sufficiently reliable machine automation in a highly complex, continuously varying, unpredictable environment, one filled with both human and autonomous agents, the approach should be to keep the driver in the loop, as well as in the driver's seat. The driver should have the responsibility to engage the Full Driver Assist feature in a manner similar to how Adaptive Cruise Control (ACC) is currently engaged; by selecting certain operating parameters such as headway and vehicle speed.

During hand-off transitions, the driver will be expected to maintain vigilance and readiness to take control of the vehicle and will need to be supported in doing so. To accomplish this, the Human Machine Interface (HMI) must evolve from the current set of least/latest credible/imminent hazard warnings intended to minimize nuisance alarms, to providing more immersive situational awareness throughout the driving experience. Experience with automated aircraft cockpits[28] reveals that operators are often uncertain about its 'behavior'. What is it doing now? What will it do next? How did I get into this mode? I know there is a way to get it to do what I want, but how? The potential for automation success increases when several situations are created:

• Timely, specific feedback is given about the activities and future behavior of the agent relative to the state of the world,

• The user has a thorough mental model of how their machine partner works in different situations,

• Automated systems take action and act consistently with prior direction from the human operator.

The driver has legal responsibility for control of the vehicle and must have the ability to override the system by adding or subtracting steering input, applying the brake or adding throttle. He will have the ability to request or make certain maneuvers (e.g. initiate a lane change), and may be requested to confirm appropriateness and acceptance of a system recommended maneuver.

4.2. Use Cases

Although potentially interpreted as a simple roadmap or a checklist of sequential developments, each step may very well require extraordinary advancement in order to attain the necessary operational reliability and robustness in increasingly complex operating scenarios. As discussed in Section 2.1, Contemporary Error Rates - We're Way Off, autonomous vehicles will likely need to be better drivers than humans, exhibiting even fewer errors and more favorable error modes before they gain initial acceptance, let alone widespread implementation.

Use Case 0.0 - Status Quo

This case exists in the majority of vehicles on the road today. There are no on-board radars or cameras to measure the external environment, and no algorithms to provide information, advice, warning, or control.

In this case, the vehicle operator is left to his own preferred behaviors, behaviors that can change from day to day or moment to moment based on many and various external and internal factors, varying from relaxed to assertive and even unaware driving. Opportunities exist to provide timely advice or assistance to the driver in making the most appropriate decision in the given situation. Such decision making would require vehicle systems that are equipped with algorithms that can learn from the past driver's experience, identify hazard situations, and accordingly implement the corresponding emergency maneuvers.[29] We can expect more on-board algorithms for driver and situation learning, anomaly detection, probabilistic decision making, and more intensive interaction between the driver and the electronic vehicle control systems in the future, resulting in an increased level of intelligence of the electronic vehicle control systems.[30,31]

The addition of external environment-sensing capabilities to vehicles enables the following use cases:

Use Case 1.0 - Information, Advisory and Warning

This set of use cases comprises advisory and warning CADS functions that help the driver make better decisions. The CADS function provides information and advisories to the driver about the road environment as well as warnings about potentially hazardous conditions, such as the possibility of an impending collision, without any autonomous vehicle control actions being taken.

Use Case 1.1

In this use case, the CADS functions address the road environment. The information is not critical to the driving task, but will help the driver make informed decisions in the near future. These advisory functions could include speed limits, sharp curve ahead, blind spot information, ultrasonic park aid, etc.

Use Case 1.2

In this use case, the CADS functions address potentially hazardous conditions, such as the possibility of an impending collision or low mu conditions ahead. These warning functions include Forward Collision Warning, Lane Departure Warning, Lane Change Merge Aid, etc.

Use Case 2.0 - Emergency Control

This set of use cases comprises autonomous emergency countermeasures that help the driver mitigate or avoid a potential collision. It is useful to separate autonomous emergency action from normal steady-state vehicle control because the control logic tends to be considerably different. Whereas emergency action is taken with the focus on collision avoidance, normal driving focuses more on passenger comfort and smoothness. This emergency action is only taken when there is an error in the normal driving state, whether internally or externally imposed; an autonomous emergency action could be taken, regardless of whether the car is under driver control or fully-automated control. Many functions that are a part of this use case have been deployed in vehicles around the world, albeit at fairly low take rates.

Use Case 2.1

In this use case, the CADS functions support driver actions to avoid a potential collision. These functions include brake assist, brake pre-charge, and limited autonomous braking to reduce the collision speed.

Use Case 2.2

In this use case, the CADS functions autonomously take corrective action to avoid an otherwise unavoidable collision, only acting at the last possible moment. These autonomous collision avoidance functions include ESC, RSC, LKA, and autonomous braking such as that introduced on Volvo vehicles as City Safety™ (launched in CY2008) and Collision Warning with Full Auto-Brake (with up to 25kph speed reduction, launched in CY2010).

Use Case 3.0 - Steady State Control

This set of use cases comprises the first stage of Full Driver Assist in normal steady state driving. CADS functions in this family comprise limited autonomous control for a short interval at the driver's command, allowing the driver to focus on other aspects of driving. These functions are designed typically for a specific driving scenario, and the driver will need to take over once the expected scenario is compromised.

Use Case 3.1

In this use case, the CADS functions take limited autonomous control in a single axis when activated by the driver. Functions in this use case, many of which are in production today, include ACC (longitudinal control, freeway driving), LCA (lateral control, freeway driving), S&G (longitudinal control, traffic queue), etc.

Use Case 3.2

In this use case, the CADS functions take limited autonomous control in multiple control axes when activated by the driver. Functions in this use case include Traffic Jam Assist (a pre-emptive assistance during traffic jams, i.e. S&G ACC plus low-speed LCA), combined with autonomous driving from expressway entrance ramp to exit ramp, where the driver gets onto the freeway and enables the system to drive to, but not exit at, the desired ramp.

Even this use case can have phased introduction, starting with short intervals, i.e. ‘take the wheel’ until circumstances change appreciably. This would be ‘on demand’ by the driver, but with system concurrence that would take into account traffic density and road geometry, with the vehicle driving in automatic mode at posted speeds without lane changes.

The short interval can be extended further to full entrance-to-exit ramp driving, lane changes and even passing, but which might be limited to roadways that the vehicle has already successfully driven passively and analyzed as 'self-drivable' to verify road markings, GPS availability, number of lanes, etc. The system may still ask the driver for confirmation, possibly having started a conversation with the driver via SYNC®, "Of the standard options (provide list) which would you like?", and extend to "I recommend changing lanes, shall I go ahead and do that for you?" or "Do you concur that it's ok to change lanes now?"

Additional extensions of this use case can include auto-park, latch, and platooning functionality.

Autopark is where the driver and passenger depart the vehicle and engage an autonomous valet parking routine in a known infrastructure space with administratively restricted access for pedestrians, etc. Latch is where a vehicle strictly follows a selected forward vehicle at a standard following distance, initially at a low speed (e.g. TJA), then gradually at higher speeds. Platooning, the automatic following of a 'certified' lead vehicle, such as a commercial bus or truck, is further enabled by V2V communication with and between the lead and following vehicles, characterized by latch functionality and close quarters/shortened following distance for fuel economy benefits.

<u>Use Case 4.0 - Transitional Control</u>

This use case is highlighted by new functionality that helps the driver negotiate challenging traffic. This includes scenarios where vehicles come together in potentially conflicting intent and space. Support is provided either through information, advice, warning, or automatic control, both as late evasive actions as well as early smooth coordination and cooperation.

Use Cases 4.1 and 4.2 - Freeway and Intersection Blending

The first case aides the vehicle activity at a freeway on ramp and off ramp, extending the steady state control from freeway ramp-to-ramp to include merging and exiting. This includes anticipation of the exit and the pre-positioning of the vehicle in the appropriate lane, i.e. actively pursuing a lane change, as opposed to passively recognizing a lane change opportunity. This also includes a second case for turning and merging into similarly flowing traffic at an intersection.

Use Case 4.3

This use case is characterized by aiding the driver when traversing intersections with opposing flow traffic. The functions will inform, guide, or even control by assessing whether crossing traffic will collide, pass in front, or pass behind; thus determining the safe margin for a left turn across oncoming (head-on) traffic as well as the safe margin for entering into traffic from a branch intersection, such as turning left across oncoming traffic from the left or simultaneously merging with oncoming traffic from the right.

Use Case 4.4

This use case addresses convenience support at an intersection. More specifically, this includes the automated slowing and stopping for a stop sign, yield sign, traffic light, prioritized junction (e.g. driveway connection with roadway), or other traffic management system or protocol in a preplanned comfortable fashion when there is no preceding traffic that would otherwise govern free flow. This is in contrast to emergency-based intersection transition functionality.

Use Case 4.5

In simple terms, this use case involves the 'safe stop', appropriate as a bootstrap function in the event the driver becomes totally disengaged, unresponsive, or incapacitated with respect to performing further driving tasks. This function communicates an emergency situation to surrounding traffic followed by the slowing, stopping, and parking of the vehicle on the side of the road. This is a marginally preferred alternative to continuing non-stop without driver intervention or stopping in-lane.

<u>Use Case 5.0 - Revisiting Known Destinations and Routes</u>

This use case is highlighted by the extension to all roads, no longer biased to limited-access expressways. However it is still restricted to roadways that the vehicle has already visited and passively assessed; where the vehicle is familiar with these surroundings and only has to confirm, rather than recognize and analyze, the proper way to interact with this new environment.

Use Case 5.1

This use case is limited to areas frequently traveled, for example from home garage to work parking lot, and therefore has high confidence in familiarity and low likelihood of change in the nature and condition of the infrastructure, accompanying traffic flow, etc.

Use Case 5.2

The next increment could be related to a vacation or holiday destination, say a weekend or summer cottage or condominium; a place it has already been but with longer distances and less frequently visited, introducing the greater possibility of changes since the last time it drove there. The ability to recognize changes in infrastructure and nature of traffic flow is correspondingly increased.

Use case 5.3

A special use case would be the local shuttle scenario. The uniquely tailored character of this scenario would provide the first opportunity for full drive-for-me functionality. This use case would be a limited pre-implementation feasibility demonstration and learning opportunity only, where the new HMI and situational awareness and autonomous controls can be further developed for reliability and robustness. Besides the driver being on board, there would also be a specially trained test co-pilot who is there only to intervene on the driver's behalf if warranted. The driver would be observed for tendency toward non-driving activities given this level of driving support and HMI. If the vehicle runs into a scenario it hasn't encountered before, or has not been designed to handle, or when sensing becomes blocked and the vehicle goes into 'limp home' mode, the driver can take over and continue the shuttle delivery manually, etc.

A shuttle such as this could be administratively managed by and wholly contained on a private road network, such as at the Ford Research & Engineering Center in Dearborn, Michigan. In this case it could build on the current Smart Intersection,[32] which would allow for greater adaptation of the vehicle and infrastructure for experimentation in terms of infrastructure communication, dedicated localization targets at road edges and intersections, etc.

Use Case X.0 - Traversing Unknown Routes and the General Case

Here is where we put it all together, pursuing the idealistic fully autonomous functionality. Autonomous, Full Driver Assist functionality is extended to situations that have not been sensed, analyzed, or hardcoded previously. The vehicle is capable of traveling anywhere; to places it has never been before, handling scenarios never encountered before -- it's ready for the all new experience.

In order to proceed to this level, the engineering staff will have learned through all preceding technology development cycles and use cases. The sensing hardware/software, as well as assessment software, will have been shown to be reliable and robust in the prior use cases, and are now stretched to modes where safe, real time learning is permitted, enabled, and successfully achieved using advanced machine learning algorithms. Fully autonomous functionality should achieve at least the same outcome as the human driver when encountering new situations, but with the greater diligence and situational awareness, as well as rapid recognition of subtle novelty that a machine can have.

Learning safely will depend on continuing development of HMI concepts through successive use cases. Cases that now merely communicate unlearned situations to the driver will be continuously succeeded by more complex, autonomous designs that further offload the driving task as a design ideal. The focus will be on the development of models and algorithms that are not only able to learn but also to summarize identified relationships and facts to a higher level of abstraction. The goal is to integrate this part of the multi-attribute decision-making mechanism under different conditions and situations which is a necessary condition for autonomous driving.

As previously discussed and shown in the market, CADS warning and emergency functions have been introduced in phases of gradually increasing effectiveness:

- CADS 1 - capability sufficient to warn only for moving cars/trucks/motorcycles,
- CADS 2 - capability to warn and provide relatively small autonomous braking action for stationary, as well as moving cars/trucks/motorcycles,
- CADS 2.1 - capability for large autonomous braking in reaction to vehicles ahead (special low speed case),
- CADS 2.2 - capability to both warn and initiate a large autonomous braking action when an alternative steering path is not available,
- CADS 2.3 - warning capability for unintended lane departure or potential impairment based on the driver's lateral control performance, and
- CADS3 - capability to both warn and initiate a large action in reaction to both moving and stationary cars/trucks/motorcycles and pedestrians.

In this use case, we build upon the level of effectiveness of the already available CADS functions and incremental use cases listed previously, and now extend them to the general case. The general case includes warnings and large autonomous actions (longitudinal and lateral) for hazards of all types including trees, poles, and other undefined or unexpected (e.g. debris in the driving lane) hazards, not just a smaller set of pre-classified types. The goal is to do this with early recognition and small actions for a smooth, seamless experience, vs. a panicked, last moment, large evasive emergency maneuver.

Intersection traversibility and cooperation, initially limited to conventional 3 or 4-way orthogonal configurations, is now extended to the n-way configuration. Scenarios may develop in such a way that the vehicle cannot brake to avoid a stopped car or large animal entering the lane, requiring an assessment whether it is safe to change lanes, e.g. whether there is parallel or oncoming traffic. Assessment of a 'safe alternative path' that may not be the designated driving surface, but which is suitable in emergency situations, such as the road shoulder, is also added. Implied in earlier use cases is the notion that late warnings of impending undesirable situations (a 'stop, don't do that' warning), will gradually be replaced with earlier advice, followed by increasingly stronger recommendations and requests for a positive desirable alternative action ('do this instead'), providing specifics the driver should focus on.

The CADS functions are also extended to the general case, including the full variety of weather and road conditions. Extreme weather conditions include snow where boundaries between driving and adjacent oncoming and non-driving surfaces are completely obscured. Road conditions include rural roads with painted lane markings only on the centerline, markings that may be faded, sporadic, or nonexistent, and gravel roads where the lane and road edge has no geometrically defined transitions whatsoever. Other extremes include off-road trails, stream fording, and open-spaces such as countryside, dunes, desert, tundra, etc.

5.0. SOME CONSIDERATIONS FOR BUILDING THE SYSTEM

Creating a system for autonomous personalized transportation involves more than just replacing one sub-system with another, replacing a driver function with an automated one, or completely replacing the human driver with a computer, let alone a robot. It will involve creating new subsystems, as well as new ways of integrating them; sub-systems that deal with interpretation of complex and cluttered driving environments, prediction of uncertain actions of other agents, and human-machine interaction ensuring sufficient situation awareness and engagement of the driver. The list of elements discussed here is by no means comprehensive, but highlights important areas of early development focus. As mentioned previously, the journey along the development roadmap will likely provide greater insights and uncover more proposals to be added to the list.

5.1. The Role of the Operator

Humans typically express the need for retaining control (beyond their fundamental legal responsibility), feeling that is safer and more secure than giving an unknown black box full authority over a highly complex task that, with an error, could seriously jeopardize their life or health. Since automation is classically described as better suited for dull, dirty, and dangerous activities, a driver in the autonomous personalized transportation mode will most benefit from Full Driver Assist functions. These functions offload moment-to-moment driving tasks, such as moving the driver from direct control of the throttle, brakes, transmission gear selector, and steering wheel, to predominantly a command mode. The driver then becomes an operator, who is still in charge, but in supervisory mode, like the orchestra conductor who commands all the instrumentalists (stop/start, faster/slower, louder/softer), but does not play the instruments himself. Even though the operator may be less involved in the moment-to-moment, direct control of actuators, the operator will need greater awareness of the situation, system status, and behavioral intent than is currently available to properly supervise the vehicle's actions. Through Full Driver Assist, the driver is provided additional time and can thereby have more confidence in performing a more appropriate role in the overall system, one that is partially tactical but becomes mostly strategic in nature.

Today, the automotive industry is providing driver support systems in private vehicles to help the driver in critical situations. Warnings, followed by preparation of actuators for operation, are used in sequence in an effort to guide the driver towards a collision avoidance response. Even with the best driver support systems, not all human responses will be ideal; some will inevitably be sub-optimal, not taking full advantage of the support system. The industry is therefore beginning to provide limited autonomous emergency actions in an effort to avoid or reduce the likelihood of an imminent collision. Many, if not all systems allow the driver some override capability versus the autonomous actuation, such as steering away to preempt, cancel or counteract an auto-braking function, if that is preferred. In a similar vein, limited autonomous driving support such as ACC has been introduced, with strict limits on control authority (longitudinal control only, limited deceleration levels, warns driver when control limits have been reached). On the other hand, allowing the driver to override the autonomous system would allow the driver to mistakenly override it as well; yet employing this method allows the earlier introduction and benefit of these autonomous systems.

When will we be ready to override human action with machine action? Flight control logic in modern aircraft already limits pilot input authority to a level which the plane's computers determine is within a safe operating regime. However, transportation modes that currently employ higher levels of autonomy vis-à-vis private road vehicles have one thing in common: very limited interaction with other operators. Airplanes are typically spaced a mile apart or more. The tightest train schedules place trains at least a few minutes apart, and the separation experienced on the ocean, without a harbor pilot aboard, can be even larger. This limited interaction significantly reduces the exposure to the unpredictability of the human reaction / interaction. On the other hand, consumers have an intuitive understanding of the complexity of interaction among vehicles sharing a road. This will likely slow their acceptance and adoption of fully autonomous vehicles.

Given that autonomous vehicles will change the very nature of driving, it is conceivable that the licensing of vehicle operators will need to change along with it. Today we have graduated driver's licenses with legal limitations, and as a driver fulfills certain requirements, more capability gets ‘turned on’. Driver training today is mostly limited to several hours of on-road instruction, followed by real-world driving practice to build experience.

More specialized training may become the future norm. This training could include education on advanced CADS systems so that drivers will be better equipped to use the more advanced autonomous driving systems, similar to the pilot training required to fly a significantly autonomous commercial airliner. At some point, we may transition the first autonomous systems to only those in the driving public who have undergone specialized training, earning a certification and a special license to operate an autonomous vehicle. Ultimately, as autonomous vehicle technology matures and becomes more common, an even higher level of training and certification may be required to drive a vehicle in the totally manual, autonomous-off mode.

5.2. Communicating with the Operator

The Human Machine Interface is critical to continued operator engagement, and human-centered design will be essential for ensuring the HMI is properly designed for two-way interaction. The system must communicate everything the human operator wants to know in order for them to be comfortable with the autopilot driving the vehicle. Its effectiveness would be enhanced by knowing something about the operator's state as well.

The ultimate HMI for the autonomous vehicle may be the Brain-Machine Interface (BMI), first demonstrated experimentally in 1999.[33] The Full Driver Assist BMI application would benefit from operational feedback, proprioceptive-like cues, but on a vehicle basis. Similar to the notion that an autonomous vehicle will be available in just a few years, recent public demonstrations have combined with the magnitude of BMI's potential resulting in an enthusiasm that outreaches its readiness. Then again, there are many valuable and arguably necessary intermediate steps before that is realized in common practice.

Today's HMI systems focus mainly on general warnings that only give limited directionality and context. Continued research will be required to understand the best warning methods given the technology of the day, typically audible and visual. A recent study showed that haptic indications work well too, acting almost as a subconscious indication to induce mode changing. When warned at a point that a mode change was not expected, i.e. when a warning was given well before a problem arose that would be difficult to respond to, the operator reacted well to the inducement. When warned at the point that a mode change was proper and expected, the operator continued appropriately without distraction.

To enhance the human response, the HMI must evolve from generating warnings to providing a more immersive, situation-aware, experience. Improved situational awareness is important even in today's limited automatic control features such as ACC, where automatic control in benign situations reverts back to human control when the situational requirements exceed the control authority of the system. Emergency handoff, especially without proper context, is ill-suited to human behaviors. Human attention could waver during autonomous control and the operator may not be prepared to take decisive corrective action.

To improve awareness, the HMI could provide continuous feedback. Steering responsiveness or resistance could be altered as the vehicle gets closer to the lane boundary in order to provide feedback on lane position. Sound could be piped in to the operator correlating to the traffic conditions. With more traffic, there could be greater subliminal presence of sound. If a threat is increasing, then perhaps a localized and directional high frequency sound could be provided, getting louder as the threat grows.

Augmented reality displays (e.g. full-windshield Head-Up Display or wearable display) might be employed to provide directionality and improved awareness by highlighting objects of interest or displaying other scenario information. To achieve the even grander levels of autonomy sought by some, insight into HMI designs that allow the driver to take on more tasks, yet still be engaged, would be required. For the dull driving task, the augmented reality display could be supplemented with driver gaze monitoring to provide pertinent information as the driving scenario becomes critical, when the operator needs to be focused back onto the road. Warnings would still have their role as the last resort, but given an immersive situational awareness the driver would be more involved, informed and active in his role, so when it is time to hand over from autonomous to human control it's not a surprise, the context is understood and it will be a mutual decision. The autonomous system could request confirmation of readiness or willingness for handover of control. This request could be orchestrated so as to preserve a fall-back option of transitioning the vehicle to a non-moving and safely-positioned state suitable for an indefinite period of time (e.g. park it at the side of the road) if the driver doesn't respond or chooses not to accept handover from the autonomous control.

Another goal for a more advanced HMI would be to ensure greater awareness of *evolving* threats such that multiple simultaneous threats can be understood and prioritized, minimizing the need to respond to more than one at the same time, by dealing with the most critical earlier than necessary. In the meantime, other threats could mature or diminish, but all would be strung out sequentially and dealt with before any become critical for response, much the way an air traffic controller would handle it.

As mentioned previously, the autopilot may also need to determine whether or not to rely upon the interruption and guidance of the on-board human. For example, if the driver is in a sub-optimal awareness state (e.g. intoxicated), the computer may need to pursue a completely different task, such as preventing the operator from starting the car. The machine should also protect for the situation where the driver is in perfect operating condition, but misjudges the situation, such as when estimating the closing velocity of a vehicle (something that humans have difficulty doing), not seeing the 2nd car in the line of traffic, missing the car approaching from the right when looking to the left, etc. As the capability is developed, the HMI should include both direct and indirect driver monitoring and interpretation of operator state to ensure properly coordinated driver assist.

The transition from 'driver' to 'operator' will likely take decades, but it has already begun as previously discussed. Tomorrow's HMI designs should help guide and nurture this transition, but large step changes in HMI design may slow consumer acceptance. Therefore designs should evolve smoothly and gradually. Before the autonomous personalized transportation system is realized, the semi-autonomous systems (e.g. CADS) must gradually raise driver familiarity and comfort level for the warning, control, support and interventions of partial automation.

5.3. Deriving Situational Awareness

Real-time, up-to-date information is another critical element of the system. This includes information about the dynamic states and intended action of other vehicles; road hazards, environmental information (including weather, road conditions, natural disasters, etc), or road infrastructure information (e.g. traffic lights are not functioning ahead). The types and amount of information available to road vehicles today lack the reliability and comprehensiveness required to meet the demands of an autonomous personalized transportation system. It is improbable to think that these systems alone could predict other non-autonomous vehicle intentions or their likely future state, and little help is currently available from infrastructure-based information flows.

The radars, cameras, GPS/INS, and map data implemented in today's vehicles are key building blocks for the future; and many more advances are in the foreseeable future. Monocular vision systems may lead to stereo. Lidars may reappear in earnest with scanning multi-beam designs. Flash lidars or 3D cameras may mature enough to enable low cost long-range sensing providing dense range and intensity maps with integrated night vision capability. The numbers and coverage of these sensors will expand to encompass 360 degrees around the vehicle, with longer range and improved positioning and classification.

Additionally, sensors are needed to determine vehicle position relative to proper path. Current localization methods, however, are not precise at all times. For example, GPS positioning accuracy may fall below necessary levels due to atmospheric inconsistencies, drop out zones (due to a tunnel, tree canopy, etc.) or multi-path (urban canyons) failure modes. Alternatively, localization through a comparison of geographic and infrastructure artifacts detected by an on-board sensor to self-generated or publicly available 3D maps may also become important. This technology was demonstrated during the DARPA Grand Challenge 2 and improved in the Urban Challenge Event; subsequent study suggests capability with a single beam scanning lidar within centimeter levels of accuracy. Moreover, 3D maps are on their way, with a number of companies recently discussing their development publicly.

Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) network communications can be considered a sensing element that will significantly improve the accuracy and timeliness of information when fused with other on-board environmental sensing. V2V and/or V2I communication (V2X) will enable visibility of other vehicles when direct line of sight is blocked. It will also enable new information to be passed to vehicles, including traffic, weather, and road conditions, and information about the states of other vehicles. Infrastructure information may include environmental sensing of the road network through sensors on the roads, such as placing lidar localization targets in areas with GPS blackouts, or through compilation of the on-board sensing data available from other vehicles connected to a V2V network. If the detection or prediction of low mu conditions prior to encountering them is not yet possible, communicating the experience of a preceding vehicle to others approaching the hazardous area by V2X is a good alternative. The information update and flow would need to be seamless, not only from vehicle-to-vehicle, but also to/from the government, industry, and private sources. New invention and coordination is necessary to make sure the data is the most recent and relevant to autonomous personalized transportation vehicles.

Ultimately, sensing will need to evolve to 'general case' detection, tracking, and classification. Sensors today interpret the world by looking for patterns that match known objects, some of which use a training set and classifiers. Automotive radars are designed to look for a vehicle, which is why they initially worked only on faster moving objects in the driving scene. On the other hand, when humans see the world, they

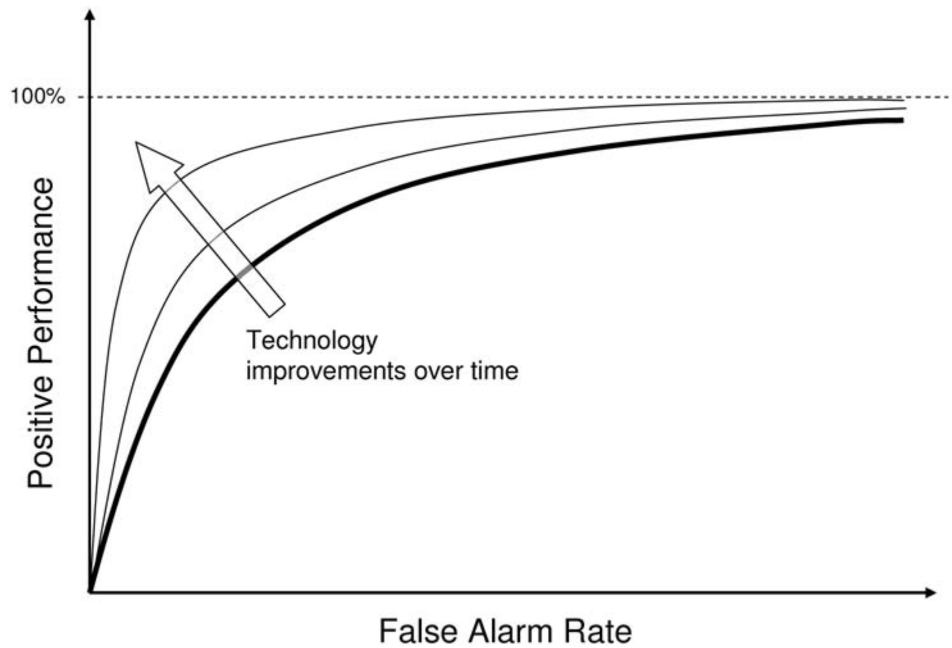

Figure 1.

also look for other cues that help determine whether or not the object ahead is of interest, or if the road is safe to traverse. Beyond just a measurement, there is a level of interpretation and judgment that must be implemented with the sensing system. This would allow estimation of lane and road boundaries when they are not really visible, due to faded, snow covered, glare-obscured conditions or judgment that an object in front, be it a vehicle, bicycle, pedestrian, tree, or moose, may be of interest; or even the gut feeling humans get that the scenario ahead may become a threat and the system should be wary. Knowing that sensors can physically measure much more accurately than humans, we should strive not only to replicate the human sensory perception capabilities, but also to exceed them. An important aspect of this is the use of multiple modalities of sensing in order to address the important problems of sensor reliability and validation of the sensor readings. The common sense verification mechanism that naturally accompanies human perception should be replicated in autonomous vehicles as algorithmic preprocessing validation of the measured data and capability for inferring and predicting new events through associative and case-base reasoning.

5.4. Limits of Situational Awareness

Sensors for situational assessment or awareness (SA) are statistical in nature, merely returning a digital representation of the external environment that must be interpreted for accuracy. Not only do the accuracies of the target characteristics have to be interpreted (e.g. relative range, range rate, and azimuth as well as classification, etc.), but whether the detection itself is valid also needs verification. Both radar and vision systems provide ample targets for interpretation. So it becomes a matter of trading off the true vs. false detection rate (i.e. positive performance vs. false alarms for a collision warning system) for a given modality and specific hardware capability, and then tuning along the curve for an appropriate level of reliability and robustness as shown in Figure 1. As SA technology improves, the tradeoff relationship improves, thereby shifting the curve. This is not much different from when the human acts as a SA system, with cognitive systems that include inductive reasoning, which by their nature, occasionally reach erroneous conclusions even when the basis for it is true.

Humans will never attain perfection, yet we allow them to perform challenging activities, tacitly accepting the consequences. How much better does a machine have to be than the human it would replace, before society allows that replacement to happen? Without knowing the answer, we can still utilize the machine as a situational awareness tool, not feeding an autonomous decision and control system, but in a limited capacity as a driver's aid. Machines are less susceptible to distraction so can provide a benefit given their greater diligence alone. Perhaps it is not a matter of how good an SA or decision-making machine is, but more a matter of how well it learns. Maybe it will be sufficient to allow replacement when it performs *and* learns at least as well as a human, i.e. without making the same mistake twice. Perhaps to break through into a truly autonomous decision making machine, it must be required to, even designed to, learn from and not repeat the mistake of other machines that previously made such an error? The industry has much development ahead before making that determination, but future SA systems should be conceived with consideration of these limitations in mind.

Perhaps the single greatest challenge to effective situational awareness is the speed at which the vehicle must travel to be considered a valued mode of transportation. Initial robotic successes were characterized by the very slow, seemingly deliberate, pace at which the sensing platform traversed the environment. With increasing velocity comes a need for increased sensing range, speed of situational interpretation, hazard detection, classification, and path planning, as well as reliable dynamic control.

5.5. The Vehicle and Artificial Intelligence

The artificial intelligence (AI) that commands the autonomous control system must also evolve, but the evolutionary path is still unclear. Should it be nondeterministic, implementing stochastic type algorithms of learning, optimization, decision making, planning, and goal formation under different situations and states that are not generally known in advance? We don't really know how useful that will be in the long run, but that may be a function of how strong the match must be between the pre-programmed and actual event. Does it need to be more human-like to be self-sufficient, being intuitive, adaptable, and strategic in its functionality? On the other hand, it is important to remember human fallibility; we're not even sure yet how much involvement the operator should have in the system.

We can say that whatever the AI, it needs to handle some level of unexpected environmental perturbations, because chaos exists even in a tightly controlled system. The AI needs to handle any intentional system compromise, for example, dealing with external hacker attacks and false signals. It needs to handle unknown objects in the external environment, like a new type of vehicle on the road that doesn't communicate. It needs to handle unexpected internal failures such as electronics and software faults. The AI really needs to make use of information whenever and wherever it's available, making judgment as to which information to use and when.

Moreover, the AI needs to be able to make decisions spanning both physical safety and societal norms, accounting for the social, political, and cultural complexities inherent in human decision making. Even in a task as simple as a lane change, the decision making logic is complex. When is it safe to make a lane change? When is it appropriate to make a lane change? When is it socially acceptable for an autonomobile to make a lane change? Is it ever acceptable for one autonomobile to cut in front of another, say in an emergency? And in mixed mode operation, one driver may feel comfortable handing control over to his autonomobile, but are other drivers in the adjacent lane ready? All this presumes learning specific driver's actions and preferences in the operation of the vehicle. The models are later used by the intelligent control system to invert the mapped relationships and advise the driver for the most appropriate actions under specific circumstances. All these questions impose requirements on the AI system that are well beyond the capability boundaries of the existing decision making systems and suggest a wide range of challenging research problems.

5.6. The Road Infrastructure

Infrastructure may also require modification to support future autonomous operational modes. As we transition towards full autonomy, we must accept that mixed mode operation may be the norm for a long time, with both human and computer pilots interacting on the road. Some thought needs to be given to this transition - given the uncertainty of human reaction and the interactions that result in random events, we may look to minimize this uncertainty by some day providing special autonomous-only traffic lanes, much like the High Occupancy Vehicle carpool lanes demarked <HOV> today. These lanes could have very limited access, with known access locations, allowing only autonomous pilot-enabled vehicles to enter.

When enough vehicles on the road have autopilot capabilities, we may progress to having some roads, such as limited access highways, be autonomous only; while human drivers could still operate on secondary roads. Eventually, we may transition to virtually all roadways being autonomous only, with only a few exceptions, such as scenic Route 66, preserved for nostalgia's sake.

5.7. The Regulatory Environment and Beyond

While government and regulatory environments will need to adapt to enable the autonomous future, and will likely play a key role in their success, non-regulatory ratings can drive OEM strategies with the same rigor. These latter ratings include government ratings such as NHTSA's New Car Assessment Program (NCAP), as well as third party ratings such as the Insurance Institute for Highway Safety's Top Safety Pick. Many vehicle manufacturers emphasize their performance on these ratings as a communication strategy for vehicle safety; hence these ratings have considerable clout and could even be considered defacto regulations.

Collision avoidance technologies are the fundamental building blocks for autonomous vehicle operation and have been subject to 3rd party influence since NHTSA's NCAP action in 2002 (which applied the fish-hook performance test criteria to ESC systems) which was followed by EuroNCAP braking requirements in 2006. These actions have reverberated around the globe, with Korean, Japan, and China NCAPs all enacting dynamic rollover requirements.

Based on recent history, some NCAPs evolve into regulations. In the preceding example, the US began mandatory phase-in of requirements for ESC by the 2009 model year, a 14 year lag from introduction to regulation. In contrast, regulatory phase-in of passive restraints, a combination of automatic seatbelts and airbags, began in 1986, while a full phase in of airbags began in 1996. A shorter delay is not necessarily preferred even though it can create an earlier ‘pull’. A longer delay provides more time to evaluate different technologies and let them mature.

This path is not universal with respect to steps or timing either. In 2010, the US launched a new NCAP Assessment for collision avoidance, with the addition of a FCW and LDW protocol and test methodology. Just prior to that, Japan elected to proceed directly down a regulatory path for collision avoidance, kicking off “if fitted” requirements for CMbB systems, as well as convenience based technology like ACC and Reverse Parking Aid systems. EuroNCAP also just announced the “Advanced Award” (formerly referred to as Beyond NCAP) to supplement the overall safety star rating of the vehicle if the vehicle has Blind Spot, Driver Distraction, or Lane Departure Warning capabilities or Advanced Emergency Braking Systems (AEBS). This can result in near-instantaneous rating assessment of the newest technologies.

These are likely just the first stages of many more requirements to come. Industry is closely watching the US and the EU for regulatory movement in collision avoidance beyond stability control. The US Crash Avoidance Metrics Partnership is a collaboration between several OEMs and NHTSA, researching crash imminent braking system test methods and requirements, among other things, which may result in new NCAP or regulatory requirements. The European Union has already begun to shape commercial vehicle regulations for AEBS and LDW systems, with the United Nations Economic Commission for Europe planning to develop technology requirements in the near future.

Many in the automotive industry are looking for harmonization of these new requirements, with the hope that ISO standards, which exist in either a released or draft form for many of these new features, become the foundation. If harmonization attempts are unsuccessful, the OEM base will face a substantial challenge as it drives toward global technology platforms. Regionally unique requirements could result in key enabling technologies that are unique at a fundamental level. Considering the preceding SA tradeoff discussion (Section 5.4, Limits of Situational Awareness), this could result in one market having a stringent false positive reliability requirement, while another elects to have a high degree of positive function capability, and a third market implements a more simplistic feature presence-based rating or regulation.

Make no mistake, governmental action can stimulate and encourage development of technologies, especially in infrastructure intensive areas, but it should also be careful to not regulate in ways that are restrictive to innovations with societal benefit. All things considered, however, CADS and autonomous vehicle research and development could greatly benefit from the inclusion of governmental agency and legislative partnerships.

6.0. NEW COLLABORATIVE RELATIONSHIPS

Several key factors affecting the pace and extent of innovation are the generation of new concepts, available investment levels, and available time to mature them to a meaningful implementable level.

The solution to complex problems such as Full Driver Assist can only come from the synthesis of many diverse inputs, from diverse sources, and through cooperative relationships. The large investment that will be required presents its own challenge, and that burden is well suited to collaboration as well. Achieving new goals typically requires new skills, developed on the job or gained through additional education, yet both require significant time. Alternatively, skills can be immediately brought into the team by partnering outside your own enterprise.

The traditional supply base is focused primarily on solving today's problems; that is where the majority of demand is, where their expertise is, and where they can be profitable. Yet suppliers also earmark a portion of their budget for R&D to solve future problems. How to spend that investment is a challenging question, with some suppliers extending today's knowledge and others branching out in new directions. Maintaining a regular dialogue with suppliers on trends and new directions ensures alignment and efficiency, but gaps can arise when there is a discontinuity, such as that presented by Full Driver Assist. Sometimes disruptive (i.e. beyond evolutionary) technologies, whether they're from traditional or non-traditional sources, are required.

Disruptive technologies may come from traditional suppliers, but also from other industries, percolating from advanced engineering, fundamental university research, or wherever inspiration may arise, even nature. This opens the door to new entrants in the technology supply base and all should be considered. Looking in non-traditional areas can be like early gold prospecting; you eventually find what you were looking for, but you would probably dig a number of empty holes first.

The following is a partial outline of collaborative relationships that have been or are being explored, but they are presented in a generic and partially fictionalized way. For the purposes of this paper, it is less important to discuss a specific set of corporate relationships, and more relevant to illustrate the breadth and variety of partnerships and technologies, both traditional and non-traditional.

6.1. Traditional partnerships

6.1.1. Tier 1 and 2 suppliers

Long standing chassis and body electronics suppliers are essential contributors to the rapid development and proliferation of new collision avoidance and driver support system technologies. They have proven their capability through the years, but now their out-of-the box creativity is being tested. An opportunistically timed new feature or functional capability breakthrough has the potential to extend their market share overnight in a highly competitive and otherwise mature market.

6.1.2. Pre-Competitive OEM Partnerships

Most notable in this category is the Crash Avoidance Metrics Partnership (CAMP), a research consortium of automobile manufacturers and suppliers engaged with the United States Department of Transportation for the advancement of promising new active safety technologies. This has been a highly effective and productive relationship, having generated numerous concepts, requirements, specifications, and field operational test results on track for eventual implementation.

CAMP's role in the development of V2V and V2I safety communications could serve as a model for Full Driver Assist. Since 2002, CAMP has organized multiple OEMs to work cooperatively on this technology with NHTSA and other parts of the US DOT. The work has ranged from basic testing and analyses to building applications to developing necessary standards and then working together to get these standards adopted. The OEMs currently working together at CAMP (Ford, GM, Honda, Hyundai/Kia, Mercedes, Nissan, Toyota and VW/Audi) are completing the standards necessary for a NHTSA deployment decision in 2013. To support this NHTSA decision, the OEMs working together at CAMP are also building vehicles with this technology for Driver Acceptance Clinics and for model deployment.

To support full commercial deployment of V2V and V2I safety communications, OEMs and the government needed to come together to define the enabling pre-competitive elements, such as infrastructure requirements, as well as message protocols, content, and security, etc. OEMs will need to be able to trust the wireless messages that their vehicle receives from vehicles manufactured by their competitors to provide warnings to the drivers of their vehicles. The level of cooperation and trust for Full Driver Assist applications will need to be examined and, if appropriate, mechanisms such as CAMP should be utilized.

6.1.3. Academia

Also common are relationships with colleges and universities ranging from a one-time grant to formal multi-year alliances. These can in turn leverage research funding from governmental science and military sources, industrial military sources, health care providers, etc. as well as collaborative relationships with other universities.

One quickly finds that university faculty, students, research staff, and affiliated technical institutes working in areas directly relevant to Full Driver Assist form a rather small community, yet draw upon knowledge, skills, and experience from non-automotive ground (construction, agricultural, industrial) and marine vehicles, general/commercial/military aviation, planetary exploration applications, medicine, and brain & cognitive science.

6.2. Non-Traditional Partnerships

Non-traditional partnerships are especially important in tough economic times. You can readily find a partner on a pay-to-play basis, but you easily exceed tight budgets with aggressive long term research when there is a priority on near term results. Non-traditional partnerships often arise when both partners have budget challenges and are motivated to find an equal equity partner, one that brings intellectual capital to move new concepts forward. These can be very strong relationships when they are born from mutual dependence, toward a shared ultimate goal/vision and well aligned with individual goals. The title for each of the following examples serves to capture the essence of these unique relationships.

6.2.1. The Mental Athlete

Formal contests, or any competitive context, can provide motivation and a means for a technical staff to perform at very high levels of creativity on a very short time scale. These contests are common in academic circles and range from toothpick bridges, baking soda cars, and science fairs for the younger set, to high performance and fuel-efficient ground vehicles, concrete canoes, and energy and space efficient homes for those more learned.

This approach to innovation is especially powerful when the team constituents are multi-disciplinary and blended from academics, OEM, suppliers, etc. This has likely driven the recent expansion to include competitions aimed at motivating professional participants as well. These competitions investigate topics ranging from human powered flight, to commercial space flight and space exploration, to ultra-high fuel efficiency, education, health care, and beyond.

Those well suited for this high energy, high stress, instant feedback, creative environment can find themselves supporting professional competition or time sensitive high-stakes consulting teams (e.g. Formula 1 racing, or oil rig fire control, mine collapse rescue, etc.). The downside is that this high level of energy is difficult to sustain for indefinite time periods, and can result in burn-out if continued for too long.

In the Full Driver Assist context, the most notable examples have been contests sponsored by the Defense Advanced Research Projects Administration (DARPA), namely their two Grand Challenges and their Urban Challenge for autonomous vehicle operation. These have drawn hundreds of teams from around the world and brought the notion of 'driverless cars' into mainstream media with widely publicized demonstration events, all while technical advancements (primarily software) are finding their way into further research activities behind the scenes.

6.2.2. The Start-up

Every once in a while a group of engineers has an idea that is ahead of its time, at least within their current context, which warrants a parting of the ways. This has happened several times in the robotics community, and in one case, the engineers decided to spin themselves off from their military contractor parent and start their own company, rather than bookshelf their ideas. Specializing in situation awareness, path planning, threat assessment, vision/image processing, proprioception, search/processing prioritization, and real-time computing, these individuals are highly regarded in the robotics community, regardless of their venue, and they have made good on their vision.

An OEM seeking to push the envelope can learn from such an organization, working together to explore different theories and rapidly prototype complex sensing and control systems with great utility. Their story ends with their former parent organization re-recognizing the value of their abilities, accomplishments, and vision, and ultimately reacquiring them.

Another form of the startup, graduating university students, is also common and possibly more predictable. Typically graduate and undergraduate work is extended into a focused product or services business model by those funding their research. This presents a ground floor opportunity and can be especially powerful if they're also building upon a Mental Athlete collaboration model - first hand knowledge and proven under fire.

6.2.3. The Hobbyist

How often does it happen that someone turns their hobby into a new business and becomes a new entrant in a highly competitive field? It only has to happen once, in the right technology, and you have the makings of a potent collaboration - if you are in on the ground floor.

In one case, a hobbyist applied curiosity, a little inspiration, and a lot of perspiration to develop a new sensing device. This device wasn't entirely novel, but it was uniquely capable nonetheless. It solved a much larger portion of the general case SA problem than had previously been accomplished, addressing road departure and safe path detection, planning, advice, and control.

This sensor is currently being used as an instrument grade research tool and is being produced at low volume for architectural applications, among other things. It has put incumbent sensor suppliers on notice, illustrating that there is a disruptive technology opportunity. Perhaps with additional packaging, manufacturing, and robustness development, this technology will become suitable for automotive applications.

6.2.4. The Gamer

They may 'only' write software for video games, but a serious skill set may be overlooked without a little more investigation. The gamers are really solving an image-processing problem, in their own unique way in some cases, and it is that diversity of knowledge, concept, and approach that can be leveraged. If you find a connection and can draw out their best efforts focused on your problem, the progress could be quite amazing.

6.2.5. The Coach

If you want to teach someone (or an intelligent vehicle) to drive, you might start with someone who is a professional driver, or even better, a professional driving instructor or coach. You, or the intelligent vehicle, need to get that seat-of-the-pants/'been there done that' experience, but without repeating their entire driving history. You need someone to distill and convey it to you efficiently and effectively. Furthermore, advanced driving skills are perishable for humans, so coaching isn't necessarily a one time event.

You (the intelligent vehicle) need to learn the vehicle's nominal character, its limitations, and how it behaves beyond its limits. If this could be done online or in a virtual environment, it could be done in a repeatable way, without the peril of hazardous situations, and in a concentrated fashion. This leaves out the nominal driving mileage and focuses the time on key events and experiences. This might ultimately enable novice drivers to start out with the wisdom of a mature driver, and an intelligent vehicle might embody the natural understanding, presence, and anticipation of a professional.

6.2.6. The Improviser

You need a test method to characterize a collision scenario in a repeatable way, without harm to the test drivers or test vehicles, and you need to ultimately validate such a system. Enter the Improviser. You tell him/her your story and before you know it, something has been discovered in the barn, the hangar, or the tool crib that with a bit of blacksmithing, a few extra wires, and a handful of plastic wrap, perfectly fills the bill. You don't teach someone to do this; this type of person just happens.

6.2.7. The Biologist

The application of chaos and complexity theories in the field of biology is not new, but their application to the human driving condition is. There are inhabitants of planet earth that are wired differently than humans: insects can perform collision avoidance on a time scale, within physical proximities, and with innumerable distractions and clutter, that a professional athlete or intelligent vehicle would be envious of. To understand how to mimic and embed the instinctive as well as cognitive processes observed in nature in future intelligent vehicles, you would do well to diversify your automotive team with this atypical skill set.

7.0. SUMMARY/CONCLUSIONS

It is fanciful to consider practical Full Driver Assist capability achievable in the near or even midterm. Amazing capabilities have been achieved and demonstrated in the carefully controlled environment of the test track, even in the glare of the TV lights. But are we ready to turn this loose on the mainstream consumer? Ultimately the argument of when, or even if, we will ever be ready is moot, as the benefits from the journey itself is worth it regardless the answer.

Having provided a summary of the current challenges and a roadmap for future work, it is fitting to revert to history for some perspective. It has been said that we put mankind on the moon in one giant leap. President Kennedy set forward a visionary challenge and in less than a decade we were there. Why? “We set sail on this new sea because there is new knowledge to be gained … and used for the progress of all people.”

Necessity drove a search for solutions in all conceivable places, the usual and the unusual, but the first moon walk was achieved through a set of logical extensions of what mankind knew. Many challenges remain - more than forty-five years later we still don't have regular commercial service to the moon, earth orbit, or even the upper atmosphere. While our undertaking may not be as grand as putting a man on the moon, perhaps our task is more difficult - there is no road rage in space.

REFERENCES

1. Federal Highway Administration, “The Dream of an Automated Highway,” ttp://www.fhwa.dot.gov/publications/publicroads/07july/07.cfm, July/Aug 2007 Vol. 71 No. 1

2. Annual Report, Department of Electrical and Computer Engineering, Ohio State University, 2003.

3. The Great Robot Race, McGray, Douglas, Wired, December 2003.

4. A Perspective on Emerging Automotive Safety Applications, Derived from Lessons Learned through Participation in the DARPA Grand Challenges, McBride, J., Ivan, J., Rhode, D., Rupp, J., Rupp, M., October 2008. Journal of Field Robotics, Volume 25, Issue 10, pp. 808-840. ISSN 1556-4959.

5. NHTSA, “Traffic Safety Facts; 2008 Traffic Safety Annual Assessment----Highlights,” http://www-nrd.nhtsa.dot.gov/pubs/811172.pdf, June 2009

6. Reichspatent Nr. 169154, Verfahren zur Bestimmung der Entfernung von metallischen Gegenständen (Schiffen o. dgl.), deren Gegenwart durch das Verfahren nach Patent 16556 festgestellt wird, November 11, 1904. Translation: *Methods for determining the distance from metal objects (ships, or the like), whose presence from the procedure under 16556 patent is found*.

7. Delphi, “Manufacturer Products: Safety Electronics, Active Safety, Delphi Adaptive Cruise Control,” http://delphi.com/manufacturers/auto/safety/active/adaptive-cruise-control/, 2009.

8. Smyth, Louise, “Adapt to Survive,” Vision Zero International: 27-30, June 2010

9. Stupp, E. H., Cath, P. G., and Szilagyi, Z., “All Solid State Radiation Imagers,” U.S. Patent 3 540 011, Nov. 10, 1970.

10. Volvo Car Corporation, “Pedestrian Detection with full auto brake - unique technology in the all-new Volvo S60,” http://www.volvocars.com/en-CA/top/about/news-events/Pages/press-releases.aspx?itemid=17, March 2010

11. Frost & Sullivan, “Active and Passive Safety Systems in the US: Customer Desirability and Willingness to Pay (Passenger Vehicles),” Sept. 2005.

12. Frost & Sullivan, Analysis of North American Market for Advanced Driver Assistance Systems, December, 2009.

13. Frost & Sullivan, Strategic Analysis of Japanese Passenger Vehicle Safety Systems, June, 2010.

14. World Health Organization, “The Global Burden of Disease, 2004 update”, WHO Press, Geneva, Switzerland, ISBN 978 92 4 156371 0, 2004.

15. Research and Innovative Technology Administration, John A. Volpe National Transportation Systems Center, “Focus,” http://www.volpe.dot.gov/infosrc/highlts/02/mayjune/d_focus.html, May 2002.

16. Dekker, Sidney, The Bad Apple Theory pp. 1-14, The Field Guide to Human Error Investigations, 2002. TJ International, Padstow, Cornwall, Great Britain. ISBN 0-7546-4825-7.

17. Dismukes, R.K., Berman, B. A., Loukopoulos, L. D. “The Limits of Expertise”, Ashgate, United Kingdom, ISBN: 978-0-7546-4964-9, 2007.

18. Rothe, P. J., James, L., Nash, J., Freund, P., Martin, G., McGregor, D., Frascara, J., Redelmeir, D., “Driving Lessons, Exploring Systems that Make Traffic Safer” University of Alberta Press, Canada, ISBN-10:0888643705, 2002.

19. Central Japan Railway Company, "About the Shinkansen", http://english.jr-central.co.jp/about/index.htrnl, retrieved: Aug 2010.

20. Car and Driver, "How to Drive a Ford Model T," http://www.caranddriver.com/features/09q3/how_to_drive_a_ford_model_t-feature, July 2009

21. Langer, G., "Poll: Traffic in the United States; A Look Under the Hood of a Nation on Wheels", ABC News, Feb 2005.

22. NHTS, "Summary of Travel Trends: 2001 National Household Travel Survey," http://nhts.ornl.gov/2001/pub/STT.pdf, Dec. 2004.

23. Song, C., Qu, Z., Blumm, N., Barabási, A., "Limits of Predictability in Human Mobility", Science 327(5968): 1018-1021, Feb. 2010, DOI: 10.1126/science.1177170.

24. Rokeach, M., "The Nature of Human Values", Free Press, New York, ISBN 0029267501, 1973.

25. Shrank, D. and Lomax, T., "2009 Urban Mobility Report", Texas Transportation Institute: The Texas A&M University System, Jun 2009.

26. Massachusetts Institute of Technology, Center for Transportation & Logistics, "Driver Wellness, Safety & the Development of an AwareCar," http://agelab.mit.edu/system/files/file/Driver_Wellness.pdf, Dec. 2009.

27. Ford Motor Company, "Ford and MIT Team Up To Improve Safety by Reducing Driver Stress", http://media.ford.com/article_display.cfm?article_id=31682, Dec. 30 2009.

28. Joint Cognitive Systems: Patterns in Cognitive Systems Engineering, Woods, David D., Hollnagel, Erik. Published by CRC Press, Boca Raton, Florida, 2006. ISBN 978-0-8493-3933-2.

29. Cacciabue, P., Modeling Driver Behavior in Autonomous Environments, Springer-Verlag, London, 2007.

30. Lu, J., Filev, D., "Multi-loop Interactive Control Motivated by Driver-in-the-loop Vehicle Dynamics Controls: The Framework," Proc. of the IEEE Conference on Decision and Control, December 16-18, 2009, Shanghai, China.

31. Pentland, A., Liu, A. (1999) "Modeling and Prediction of Human Behavior", Neural Computation, Vol. 11, pp. 229-242.

32. Ford Motor Company, "Ford's new smart intersection 'talks' to cars to help reduce collision, fuel-wasting congestion", http://www.ford.com/about-ford/news-announcements/press-releases/press-releases-detail/pr-ford26rsquos-new-smart-28610, July 10, 2008.

33. Chapin, J.K. et al. (1999) Real-time control of a robot arm using simultaneously recorded neurons in the motor cortex. Nature Neuroscience, 2, 664-670.

CONTACT INFORMATION

Jeffrey D. Rupp
Ford Motor Company
Product Development Center - Safety Engineering
Room GB-A83, MD 129
20901 Oakwood Blvd
Dearborn, MI 48124-4077
jrupp@ford.com

ACKNOWLEDGMENTS

The authors would like to thank those who have provided invaluable input and critique for, as well as the investigation and advancement of the technologies which are the subject of this paper: Tom Pilutti, James McBride, Dimitar Filev, Louis Tijerina, Mike Shulman, Alex Miller, Dev Kochhar, Andy Sarkisian, Venkatesh Prasad, Stephen Rouhana, Doug Rhode and Roger Trombley. The authors also gratefully acknowledge those who have facilitated the process of creating this paper in innumerable ways: Nancy Burke, Haleh Ghalambor, Stephen Kozak, Randal Visintainer, and Loralee Rupp.

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

doi:10.4271/2010-01-2335

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper.

SAE Customer Service:
Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE Web Address: http://www.sae.org
Printed in USA

SAE International™