Large-scale deployment of autonomous vehicles: still a long road ahead.

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Abstract— **Since the advent of the so-called Google cars, which first appears at the end of the year 2000s, a large interest and fascination for autonomous vehicles (AV) or “driverless cars” was initiated in public and political arenas alike. This growing interest has translated into a major hype exhibiting nowadays an honest but somewhat over-optimistic view of the field near future. The aim of this survey paper is twofold: first to discuss several issues and challenges that we are still facing before a large-scale deployment of these driverless autonomous vehicles happen; second to clarify a few concepts already spreading through the literature that would require a more rigorous definition, which hopefully may help in better defining standards and processes, thus allowing the stakeholders to take better long-term decisions toward deployment of autonomous vehicles on our roads.**

We will first recall some basic knowledge on autonomous vehicles as well as their potential roles and expected benefits in road transportation, with a special care for more rigorous definitions of usual associated terms found in the literature. Then we will survey the current development status of the required technologies to achieve such driverless cars and examine the various challenges, be it technological, societal, legal or economy, that we are still facing for a successful and efficient deployment of those vehicles. Such a deployment hopefully will help improve human mobility and make future road transportation systems wiser and more efficient.

Index Terms— **Intelligent transportation systems, autonomous vehicles, automation, driverless cars, smart cars, intelligent vehicles, road transportation systems, traffic optimization.**

I. INTRODUCTION: HERE THEY ARE

The field of autonomous vehicles and driverless cars has been around to the public eyes for quite a while now. In fact some mentions of it date back in the early and mid-twentieth century. Several recent web articles are providing interesting details on the history of autonomous vehicles [1], [2], [3]. Some of the first experimentations on roads took place in the 70s and 80s like the European *Prometheus* project (1988-1995) [4] or the US Carnegie Mellon University’s Navlabs [5]: several 100s of km were driven in real traffic at that time. However, it is only since the successful campaign of Google publicizing its prototypes in the late 2000s that the general public, the politicians and automotive OEMs alike started to get a growing interest for those intelligent vehicles. But why is driving automation happening now? For one thing, this is the result of a long trend and we currently assist to a kind of transition. From the second half of the 20th century until now, sciences and technologies progressed at an astonishing pace. We have witnessed breakthroughs such as lasers, atomic clocks, GPS, microprocessors, MEMS, nanotechnologies, exponential increases in computing power and data storage capacity, wireless telecommunications and worldwide interconnectivity through Internet. These advances led to successful introduction over recent years of an ever-increasing number of intelligent functions in vehicles, which has also contributed to the growing interest toward autonomous driving. Some of these “intelligent” functions are totally transparent to the driver and are triggered automatically, such as the Antilock Braking System (ABS) and the Electronic Stability Control (ESC), whereas others support the driver in the form of advanced driver assistance systems (ADAS). Some examples of ADAS for specific automated maneuvers include [6], [7] :

Adaptive cruise control: automated control over longitudinal inter-vehicle speed and distance in dense traffic on highways;

Traffic jam assist: longitudinal control (stop and go) following the preceding low speed traffic flow in congestion conditions;

Parallel parking assist: automated control for parallel parking maneuvers (which is by the way a non-trivial maneuver, considering that a car is a non-holonomic system);

Lane keeping assist: automated lateral control to keep the vehicle in its current lane;

Frontal collision mitigation breaking systems: automatic emergency stop or evasive maneuvers in case of imminent frontal collision;

Automatic overpass assist: complete automated and secure overpass and lane change maneuvers;

Automated maintenance: self-diagnosis and automated scheduling allow vehicles to visit car dealer location for maintenance and repairs.

Thanks to those ADAS and other automated functions, the road ahead seems likely to have fewer traffic accidents, less congestion and less pollution. Data published over the recent years [8], [9], [10] suggests that those features are already

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helping to reduce crashes. The National Highway Traffic Safety Administration stated that “the critical reason was assigned to the driver in an estimated 94 percent of the crashes” [11], a figure that has led most experts to predict that autonomous driving will reduce the number of accidents on the road by a similar percentage [12]. The benefits to society would be huge if we assume those technologies to become ubiquitous and to have such an effect. Indeed, almost 1.2 million people still die on the road every year and this death toll cost trillions of dollars worldwide according to the World Health Organization [9]. Unfortunately, this is only the tip of the iceberg: “For every death on European roads, there are an estimated four persons with permanently disabling injuries, such as damage to the brain or spinal cord, eight persons with serious injuries and 50 one with minor injuries” [10]. Some other studies also suggested that the deployment of autonomous vehicles in platooning scenarios may optimize traffic flow and increase vehicle density on highways, thus reducing congestion [13], [14].

In short, by removing humans from the driving process, one hopes to eliminate driving errors (known as the main cause of accidents), to reduce traffic congestion by reducing the number of cars and to increase productivity of passengers for either business or pleasure. Among applications already envisioned for autonomous vehicles, we have [15]:

Valet assist: drop and take back vehicles from a distant parking lot;

Platooning: automated vehicles are attached to platoon and follow a lead vehicle, which may have a driver;

Shuttles: driverless vehicles on confined itineraries, urban cabs on open/closed circuits;

Automated traffic at intersections: Vehicles are remotely oriented at intersections. Lights are replaced by space-time lot allocations for each automated vehicle;

Automated vehicle delivery: AVs can remotely be delivered automatically to a given location;

Automated delivery: Automated delivery of merchandise or passengers from one location to another.

Further details on benefits of AVs and current trends in their development can be found in [16], [17], [18] and [19]. All these facts show that autonomous vehicles are indeed slowly but surely coming on our road. They will disrupt mobility patterns and lead to other major changes (work, housing, entertainment…). There is a difference, however, between prototyping and running a few autonomous cars and their large-scale deployment for everyone daily life transportation. The following sections discuss the (long) journey we still have ahead of us before such a deployment happens. In section II, we will first open the discussion by recalling some definitions that are important to better understanding what we are talking about and the deep relationship between many aspects (intelligence, autonomy, connectivity, robustness, reliability, complexity etc.) of the subject. We will also consider the core challenge of removing human intelligence in the driving process. In section III, we will discuss the vastness and openness of the world in which the vehicles must operate and its impact on system robustness. In section IV, we consider the nightmare of growing complexity in embedded systems and its impact on reliability, safety, risk assessment and the level of trust we should have in autonomous vehicles. In section V, we look at the various challenges brought by human-machine interactions. Cost issues are dealt with in section VI and new opportunities brought by autonomous vehicles to solve mobility and road transportation problems and its impact on urbanism and business models used by the automotive industry are investigated in section VII. The highly multidisciplinary nature of the future automotive sector and its impact on vehicle manufacturability, vehicle maintenance and future skilled workers education requirements to face the challenges in deploying autonomous vehicles are then discussed in section VIII. We will then conclude this survey paper with some remaining issues that would need to be addressed and future recommendations.

II. DEFINING THE SYSTEM

The increase volume of literature and patents published on the subject in recent years is a good metric to indicate the growing popularity of intelligent vehicles [20]. Intelligent vehicles are an integral part of what is known as Intelligent Transportation Systems (ITS). ITSs are defined as transportation systems that use computers, controls, communications, and various information technologies in order to enhance road safety and traffic efficiency. Although the scope of ITS is multimodal, road transportation is a dominant part of it.

In this context, the term ‘‘*intelligent*’’ is loosely defined and refers to incorporating a certain level of machine intelligence in the operation of a vehicle either to emulate some driving functions or to enhance some vehicle behavioral capabilities. A very good introduction on the subject can be found in [21]. Intelligence in road transportation systems can be embedded in different ways, as shown in figure 1.

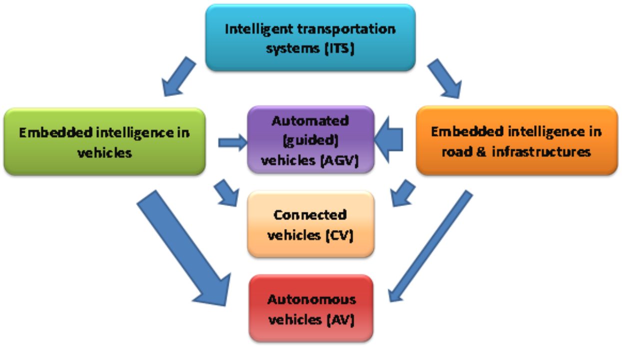


Figure 1: Trade-offs between intelligence embedded in vehicles versus intelligence embedded in road infrastructure. Guided automated vehicles rely more heavily on instrumented road infrastructure than autonomous vehicles. Connected vehicles imply distributed/shared intelligence from both sides for V2V and V2I scenarios. Autonomous vehicles imply that most embedded intelligence lies in the vehicle.

Nowadays, the usual anthropocentric view of intelligence may soon be exceeded in some ways by artificial systems, such as in sensing, communicating and computing capabilities. Advantages such as computing speed, low cost large memory capacity, communications range and sensors wavelength diversity can help to get beyond usual human driving performance and improve safety significantly. The hard part, however, is to replace the human brain at which it is strongest, that is to perform in real-time complex cognitive tasks and reasoning with uncertain knowledge. Although miniaturization and major progress in sensing and hardware/software embedded information processing systems have enabled a significant level of automatic and autonomous functions in modern vehicles, the artificial intelligence functions corresponding to the high level cognitive and reasoning capabilities of the human brain are still in their relative infancy and remain an active field of research.

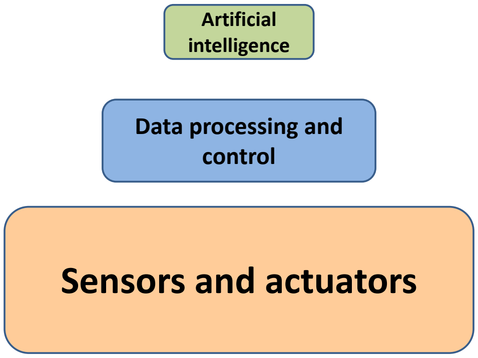


Figure 3: Current relative development and maturity of key components in autonomous vehicles. The AI part, which deals with reasoning, learning and interpretation, is still at a fairly primitive stage compared to solutions found at the sensors and data processing levels. So far, most of the progress in intelligent vehicles is due to advances in low cost miniaturized sensors and actuators.

The problem of replacing the human being by an artificial driver implies that the embedded systems must be able to reason, to learn, to recognize and to interpret efficiently and reliably highly complex and dynamic situations. We are not there yet. For one thing, the evidences provided from the sensors, which are describing a given object, may vary greatly, even if the sensors are operating perfectly. Take for example a pedestrian; its description may vary in an infinite ways according to several parameters such as pose, attitude, size, shape, color, movement, position, partial occlusions, lighting conditions, etc. With this kind of "imperfect" perceived objects, classical logic and deductive reasoning commonly found in extensional AI systems, such as rule-based expert systems are impractical and unreliable. There are simply too many "exceptions", leading to incoherent semantic and misled conclusions. These exceptions also lead to bidirectional inference and nonlocal dependencies, which are not handled properly by extensional systems. The nature of the problem thus precludes the benefits of locality and modularity, hence ease of computation and implementation, qualities usually encountered in those extensional systems. The alternative is to use intensional reasoning systems, such as Bayesian probabilistic engines and belief networks, which can handle bilateral inference, causality and avoid semantic incoherence. However, they are much more difficult to use as they do not exhibit the locality and modularity features of extensional systems allowing fast computations and easy implementation, unless we deal with the trivial case of having only independent evidences [22]. To circumvent this problem, some sort of local dependencies are used to simplify the reasoning system, for example, by using the Markovian property in decision-making processes. This leads to decision trees, which assume only local dependencies. Artificial neural networks constitute another AI approach to grasp human reasoning and cognitive capabilities. However, the inner mechanisms of artificial neural networks are still unclear for most non-trivial cases hence predicting their outcomes is still a challenge.

Learning is another human quality, which is still a research challenge. So far, learning in autonomous vehicles is reduced to "map updating" where information gather from the sensors are being used to update and refine a "world map" of the local environment of the vehicle. Hence, memory in a vehicle is reduced to gather new evidences from sensors, which are fused to a current map of the vehicles surrounding or to the vehicle's states. However, current learning approaches do not necessarily exploit long term behaviors of the environment or the user (seasonal climate changes, mobility habits of users, traffic peak hours conditions etc.). Knowledge building involving complex memory structures, for example with short-term and long-term memories are not yet applied to vehicular applications.

In view of all this, AI has become a major field of research in today's automotive industry. Most traditional automakers are catching up and several of them recently announced very large investments in new research facilities dedicated to artificial intelligence applied to automated driving and autonomous vehicles [23], [24], [25]. Furthermore, a whole new generation of start-up companies is emerging to address these specific AI issues [25], [26]. However, the recent and tragic lethal accident that occurred involving a Tesla Motors car that crashed onto a trailer truck while using its "Autopilot" feature offers a strong call to remind us that we are still in uncharted territory and it demonstrates how far the AI technology has to go before fully autonomous vehicles can truly arrive [27]. In our opinion, it is not only a question of proper sensors' choice. Lack of reliable reasoning systems dealing efficiently with such exceptions is also part of the problem. It should also be noted that aggressive premature marketing strategies and misuse of terms such as "autopilot" may lead the customers to believe that their vehicles are able to do things beyond what is has been initially designed for.

For this reason alone, it is appropriate to discuss in more details the semantic of several terms commonly used in the literature. For example, the difference in meaning between *automated* functions and *autonomous* beings. In the current ITS literature, the words autonomous and automated are often used indistinguishably as if having the same meaning, which contribute to maintaining confusion on some important concepts and keeping overoptimistic prognostic on the short-term deployment of these vehicles.

Roughly speaking, the word "*automation*" refers to programming a machine to carry out repetitive tasks using a predefined course of actions in a given set of known operating conditions. Leonardo da Vinci was one of the first to invent a mechanical machine on three wheels able to ride a specific path automatically []. Automata became popular in France and Great Britain as far back as the 17th and 18th centuries. In 1738, the French inventor Vaucanson was famous in Lyon and Paris for his automata with a high level of behavioral realism [28]. Those were artificial animals, chess players, or dancers executing different figures or tasks. They were "programmed" with gears and other mechanical components in complex delicate mechanisms. Robotic manipulators in contemporary assembly plants correspond to a more recent example of automation. They are programmed to execute in a repetitive manner a given set of movements and manipulations confined in a known operating space. It involves the extensive use of markers and reference points into that space, where the robot used some set of sensors (usually based on laser or vision sensors) in order to perform the proper object tracking and its own trajectory controls required to execute the task at hand in a precise and synchronous manner. By heavily using these reference points and controlling the working space, one minimizes the uncertainty and variability of the operating conditions, thus reducing the number of exceptions and lowering the level of embedded "intelligence" required by the robotic arm. It usually corresponds namely to raw signal and image processing, supervised training for object detection, recognition and tracking, as well as actuators control. The "ideal" environment in which automata operate is thus usually well define, has small number of exceptions and is mainly deterministic in nature. Computationally fast extensional reasoning systems can then be designed and used for these applications. In transportation, a somewhat analogous vehicular example of automata corresponds to "guided vehicles", such as subway trains. Those are following fixed and predefined paths and their path are heavily constrained, using infrastructure equipment such as landmarks or even rails. The highway car platooning demonstration that was performed in San Diego (California) within the National Automated Highway Systems Consortium in the 80s and 90s using magnetic landmarks embedded in the highway pavement at regular distance is a good illustration of this kind of automation in road transportation [29]. Other examples of guided vehicles involve low-speed vehicles in airport, campus or urban zone applications [30].

Autonomous systems, on the other hand, refer to systems having a much higher level of intelligence, being able to adapt and operate correctly in an open and highly dynamic environment. Those systems usually have learning capabilities, thus gaining experience and making them more efficient over time. They are able to handle unlimited number of exceptions, solve complex cognitive tasks such as the interpretation of complex dynamic scenes, can process uncertain data and distill them into useful information and knowledge upon which they can perform reasoning and inference through analysis, synthesis and decision-making processes. Autonomous vehicles also require to position themselves and to build their own "map" of the real world surrounding them, such that they can navigate and "behave" correctly while executing their transportation tasks. Originating from the mobile robotic field in the 70s, Simultaneous Localization And Mapping (SLAM) [31] has been a popular approach to make vehicles autonomous, building real-time knowledge of the environment for the embedded decision making processes. It was adopted in most Darpa Challenges and the first generations of Google cars.

In short, autonomous vehicles involve the full automation of the driving process. Although autonomous vehicles are implicitly considered as "self-sufficient" in terms of embedded intelligence and sensing capabilities, they can also interact with the road infrastructure or with other vehicles in order to exchange relevant information, to cooperate or to collaborate, as salient beings such as humans do.

At first glance, this semantic discussion on these two terms – *automated* and *autonomous* – may seem unimportant, but the differences between the two concepts have a significant impact in terms of embedded technological maturity, reliability and complexity, as well as important non-technological (societal, legal and economical, even ethical) implications on the future development of autonomous vehicles and road transportation solutions. Clearly, trade-offs between automation and full autonomy have to be made, in this case, between the amount of intelligence embedded in vehicles versus the level of landmarks (guides) and instrumentation we embed in the road infrastructure. The more instrumented are the road infrastructures, the less stringent will be the system complexity and level of intelligence required into the vehicles to achieve a given level of safety (reliability and robustness). This trade-off alone will have a major impact on the pace at which driverless vehicles will be deployed on the roads. An example of this is the strategy adopted in Japan where highways segments are to be properly instrumented to facilitate driving automation in a short-term future [32].

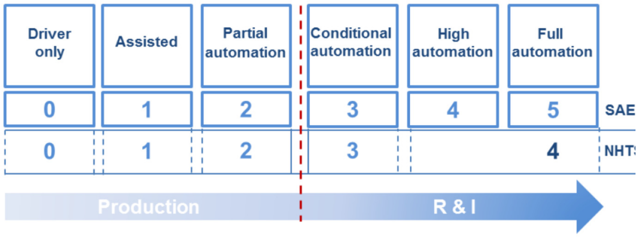


Figure 2: Current level of driving automation achieved in commercial vehicles (red line) according to SAE and NHTSA scales (Source: European Roadmap Smart Systems for Automated Driving, VDI/VDE-IT) Berlin, April 1, 2015)

As we still debate upon and wonder about the essence of human or “natural” intelligence, there is still no definite conclusion on what an “intelligent vehicle” should be or what functions are essential to make a vehicle really intelligent and autonomous, despite the current enthusiasm among automakers, researchers and government agencies. Even today, researchers still argue about what kinds of vehicles can be called intelligent ones, connected ones or autonomous ones. Definitions on levels of automation have been provided by the SAE (standard SAE-J3016) or NHTSA (see discussion in [33]). They are mainly based on the relative human dependency, human intervention and human interaction while carrying out the various driving tasks. The two ends of the scale being the fully manual driving mode (full human control) and the fully automated driving mode (no human intervention) in order to complete an entire trip from origin to destinations while avoiding obstacles and obeying traffic laws respectively.

Most expert agree that, although nowadays commercialized vehicles have reached SAE level 2 (partial automation), level 3 (conditional automation) might not be achievable due to the difficult control transition from human to the system and vice-versa, whereas level 4 (high automation) might be tough to reach in a commercial product. The recent tragic accident in Florida with the Tesla vehicle, while in the “auto-pilot mode”, illustrates how difficult it is for human to maintain a proper level of attention and regain control of the vehicle on time in case of emergency. Some experts even predict there will be a jump to level 4 and 5 (full driving automation, what we would refer here to autonomous vehicles) directly from level 2 precisely for that reason. Giving the control back from the computer to humans needs a kind of “restart”: the vehicle must safely stop, as we would do to change human drivers []. So we see that the relationship between humans and intelligent vehicles really depend on what is considered.

Using human capabilities as a reference template to compare the intelligence embedded in cars may be a good starting point. However, one should remember that, to bring a human being to full autonomy as an adult, parents must usually easily invest over twenty years of time and efforts into the growing child (those who have kids will understand clearly what we mean here). A case in point is that usually, driver licenses are not delivered to children below age 16 (or 18) for obvious safety reasons. Therefore, to make a vehicle autonomous in an open and general environment is not trivial and shortcuts need to be taken to get there in a practical time frame. Driver models, world models and vehicle dynamic models are being developed and improved steadily, such that the driving tasks performed by the car itself are becoming smoother and more “natural”. This leads to the question of complexity – complexity of the surrounding world and complexity of the systems – as we will discuss further in section IV.

In many publications and public organizations, particularly in North America, the term “*connected vehicles*” is also often misleadingly used to refer to the field of intelligent vehicles as a whole, sometimes including driving automation as well. This is unfortunate as it contributes further to the confusion among the general public and non-technical experts. The terms “*connected*” and “*connectivity*” should be used strictly in reference to embedded communication systems and information sharing capabilities in ITS applications, such as in VANETS, V2X or some other form of communicating links between vehicles and/or road infrastructure. Connectivity is closely related to two other terms often confused in the literature: “*cooperation*” and *collaboration*”. Indeed, cooperative and collaborative ITS applications always require some form of information-sharing mechanisms or connectivity. Roughly speaking, “*cooperation*” can be defined as vehicles working together to accomplish “*shared”* goals. Therefore, cooperation is more focused on working together to fulfill the end goal of each vehicle. For example, a cluster of vehicles may share information in order to improve their own individual localization or perception processes [34]. Cooperation is thus achieved when all vehicles do their assigned parts separately and share their information to improve their own jobs. Each vehicle remains responsible to reach its own goal. Cooperation can be seen as a protocol that allows you not to get in “each other’s way” as you work and therefore, reflects a more “*decentralized*” architecture. Cooperation does not imply a well define cluster and membership. For example, the goal achieved by one vehicle will not necessarily benefit to others.

In contrast, “*collaboration*” is a method where a cluster of vehicles work together to achieve a “common” goal, while respecting each individual vehicle’s contribution to the whole. For example, a cluster of vehicles will work together to optimize traffic flow, say at an intersection or on a highway (platooning). Therefore, collaboration requires the vehicles to share information in the process of realizing a common goal. A single vehicle cannot achieve by itself the common goal in a collaborative architecture. Collaboration can be seen as a protocol that requires the participation of all vehicles to realize a common goal and correspond closer to a “*centralized*” architecture. Collaboration does imply a well-defined membership and the achieved goal will necessarily benefit to all participant vehicles.

Those concepts being clarified let us now consider a bit more the vehicle itself. While the automotive industry has followed a path of steady but slow technological evolution over the last 100 years, dramatic changes have been happening during the last few years that lead to major impacts, not only technological, but also economic, environmental, and social as well. As mentioned a while ago by [35], "in the wake of the computer and information revolutions, motor vehicles are undergoing the most dramatic changes in their capabilities and how they interact with drivers since the early years of the century." Indeed, the automotive industry experiences two major transitions since the end of the 20th century: powertrain electrification and driving automation. Undoubtedly, future vehicles will one way or another implies both changes. They are in fact coupled, as optimization of energy consumption (for example by increased knowledge of the itinerary or through optimized trip planning using the on-board navigation system), residual distance estimation (considering the current on-board residual energy, vehicle weight and path topology) and recharging space and time scheduling (vehicle position relative to smart grid currently available charging stations locations) are just but a few examples of subtasks that need to be performed by intelligent electrical vehicles.

Intelligent embedded systems, which are able to control the vehicle dynamic in certain specific emergency scenarios, have already started to appear in commercial vehicles. These systems, however, still require the drivers to keep their eyes on the road and their hands on the steering wheel. Since the last 3 years, most OEMs have been exhibiting their new “autonomous” vehicle prototypes in trade shows. Most of them declare that commercialization of autonomous vehicles will be feasible within the next five to ten years or so.

In order to profit from the “golden rush” occurring from the technological advances that appeared during the last two decades, car makers are increasingly featuring new “intelligent” functionalities in their new car models, thus making their vehicles with an ever-increasing ability to drive themselves in various specific situations (ex. parallel parking assist) with the potential to increase safety and reduce traffic congestion. Obviously, the pace at which the OEMs are introducing their various functions automating driving maneuvers is impressive but it emphasizes the intelligence problem, even if system complexity does not seem to be an obstacle to business so far. Currently, most stakeholders believe that autonomous vehicles are feasible and that they are expected to be of benefits. The automotive market is a highly competitive one, to say the least, in which the manufacturers of high-end vehicles are racing to seduce potential customers with the latest technologies available. This leads naturally to the question of the economic analysis of autonomous vehicles, which will be further discussed in sections VI and VII.

Safety is also in the balance. Data collected from U.S. auto insurers show that cars with forward collision warning systems, which either warn the driver about an impending crash or apply the brakes automatically, are involved in far fewer crashes than cars without them [36]. This is only one aspect of the whole picture but in the automotive sector, where every penny counts, one cannot avoid the question.

All these appealing applications and foreseen advantages have made such that the growing interest toward autonomous vehicles has translated today into a major public hype and an unbounded optimism that need to be somewhat rationalized in order for the various stakeholders to take proper long-term decisions and ensure a viable deployment of those vehicles, which hopefully, will help to improve human mobility and make future road transportation systems wiser and more efficient.

III. THE VASTNESS AND OPENNESS OF A CHANGING WORLD

Apart from the human driver behavior in current vehicles, safety is basically related to two important properties of embedded systems in cars: *robustness* and *reliability*. Those two parameters directly affect the level of safety the general public might be willing to accept, when it comes to using driverless cars. *Robustness* is known as the faculty to adapt and operate properly under a large diversity of operating conditions (ex. weather, lightning, traffic conditions etc.), whereas *reliability* relates to the shortest time for a given system to fail and probability of malfunction at a given time given a level of system complexity. It should be noted that a system error such as a misjudgment in a decision-making process (ex. false alarm or a miss in object detection) or signal degradation at the input of a sensor, such as a GPS signal loss in a urban canyon, should not be considered strictly speaking as signs of system unreliability. The former is due to the limitations of a given system specifications in nominal operating conditions, whereas the latter is due to variability in operating conditions themselves. In automotive applications, high level of robustness is difficult to achieve for mainly two reasons: 1) outdoor conditions variability and 2) inherent mobility of the vehicle.

Examples of harsh variations of operating conditions are illustrated in Figure 3. So far, most of the prototypes of autonomous have been operated in ideal “Californian” weather conditions and at daylight. Vision based systems, for example, to detect painted lane on the road operate relatively well under these nice conditions, provided the painted lanes also are of good quality. However, torn and dusty road infrastructure, poor weather or difficult lighting conditions, to name a few, may rapidly and significantly degrade sensors performance in particular and overall system performance as a whole. Unfortunately, it may not always be feasible to rely heavily on Geographic Information Systems (GIS) or high resolution digital maps, as many current prototype systems do. If the autonomous vehicles rely on very accurate maps, then their embedded systems have to be robust enough to the situation where those maps may be wrong. Furthermore, keeping those detailed accurate maps up to date is hard work, as it requires regular data exchange between the vehicles and some central database.

Figure 3. Above: Glowing from the sun and high dynamic range of illumination; Below: Typical snow storms in northern countries.

Highly dynamic variations, due to the inherent mobility of vehicles also constitute a main reason for seeking system robustness. At 100 km/h, the surroundings of a typical vehicle changes completely every 2 to 3 seconds. Therefore we foresee automated driving to be deployed at first limited to relatively simple situations, mainly automated highway driving and low speed urban guided vehicles, because the technology still can’t respond properly to numerous uncertainties posed by complex urban traffic scenes involving densely packed mobile and fixed objects. Properly interpreting a scene, representing the world and being able to predict what might happen every 20 ms in this highly dynamic and hardly predictive environment is still a huge challenge, where our current technologies may be decades behind human cognitive and reasoning capabilities. Hence, the automotive community has to be careful not to overhype how well it works.

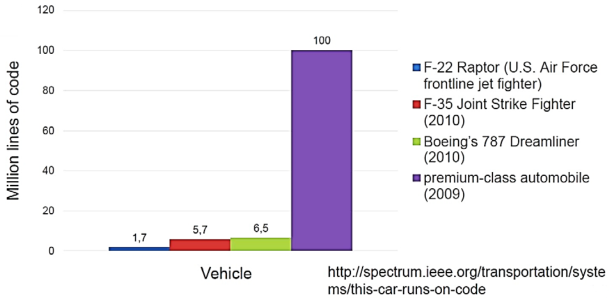
Interpreting a situation becomes exponentially more difficult as the road becomes more complex. Once you leave the highway and once you go onto the average urban road, environment perception and interpretation of traffic situations (because there can be an infinite number of them) need to get much better. Common driving scenarios such as those encountered at traffic light intersections, 4-stop intersections and roundabouts are in fact very tricky for an autonomous vehicle as it must determine when it is time to wait and when it is time to go and thus avoiding what is known as the “deadlock” problem, where several autonomous vehicles are stalled, waiting endlessly for each other until one of them finally makes the first move. Similarly to traffic lights that nowadays coordinate traffic flows, solutions need to be developed to maintain traffic coherence, for example, using the infrastructure to coordinate autonomous vehicles, with a high level of reliable connectivity between vehicles (V2V) and connectivity between vehicles and infrastructure (V2I).

In order to achieve a higher robustness against wide variability of operating conditions, current autonomous vehicle prototypes are using a wide variety of sensors operating at different wavelengths and having different strengths and weaknesses. This diversity in embedded sensors allows increasing the sensory capability of the vehicles. In addition, the information collected from all these sensors are synchronized and registered in a common reference frame in order to “fuse” the data using some sort data fusion filters [37]. This typical approach helps in improving the overall robustness and reliability of the decision-making processes by exploiting redundant and complementary pieces of information, but the added cost is still prohibitive for commercialization and mass production.

Now, as things in life are not so simple, it is not rare to find ourselves in driving situations where both poor weather and complex traffic environment are occurring at the same time. We may envision a sort of automatic shutdown of the autonomous vehicle when the driving conditions are not good enough, however, how to define the level at which “not good enough” corresponds is still unclear and a big technological challenge.

IV. THE NIGHTMARE OF COMPLEXITY

To adapt vehicles to the conditions described in the previous section, car makers have put many (sub-) systems to help humans while driving. Current cars are the most complex man-made objects with over 50,000 parts, 100 ECUs and the astonishing number of over 100 million lines of code [37] (also see Figure 4). In order to profit from the optimism generated from the recent technological advances that appeared during the last two decades, car makers are increasingly featuring new “intelligent” functionalities in their new car models, thus making their vehicles with an ever-increasing ability to drive themselves in various specific situations (ex. parallel parking assist) with the potential to increase safety and reduce traffic congestion. Many prognostics currently circulating in the media are forecasting commercialization of autonomous vehicles within the next 5 to 10 years.



http://spectrum.ieee.org/transportation/systems/this-car-runs-on-code

Figure 4. Number of lines of code in embedded software for typical jet fighters and commercial airliner vs current high-end commercial cars.

But such projections tend to overlook just how challenging it will be to make a driverless car due to complexity. If autonomous driving is to change transportation dramatically, it needs to be both widespread and flawless. Turning such a complex technology into a commercial product is far from being simple. It could take decades for the technologies to come down in cost, size and volume, and it might take even longer for it to work safely enough that we trust fully autonomous vehicles to drive us around. The war against system complexity appears in many fronts, some of the most important ones being:

1) Vehicle design, integration and manufacturability, 2) Systems reliability evaluation and risk assessment and 3) Testing, validation and homologation of autonomous vehicles.

Much of the hype about autonomous driving has, unsurprisingly, focused on Google’s self-driving project. The cars are impressive, and the company has no doubt insinuated the possibility of driverless vehicles into the imaginations of many. Nowadays, most OEMs are all busy trying to change autonomous driving from a research effort into a viable option on their newest models. Both IT and automotive sectors have not been used to such systems complexity in the design and manufacturing before. But for all its expertise in developing search technology and software systems, Google and more recently Apple have relatively little experience in building cars. On the other end, most OEMs had until recently marginal in-house expertise in information technologies, complex information systems, robotics and artificial intelligence to name a few. This lack of experience building these new robots on wheels will likely reduce the speed at which low cost autonomous vehicles will be deployed in a large scale and as a consumer product. The recent agreement between Google and Ford is a case in point to face this dilemma in producing autonomous vehicles [39]. Integration of technologies to make a coherent system is also a challenge, considering that most engineering teams in OEMs and tiers companies have been used to work in a modular subsystem approach. The increasing intelligence and sophistication of driver advisory, car control and passenger infotainment systems in current vehicles is providing major integration challenges for the industry across the supply chain. A new automotive safety standard, ISO 26262, demands that OEMs and the supply chain view and demonstrate the safety of complex systems in ways very different than previously.

In order to ensure social acceptance of autonomous vehicles, any issues that concern data security and liability of produced systems and solutions, must be solved. Not only the embedded systems themselves, but also the security of data has to be ensured on a multitude of levels. In a recent, but limited survey [40], about 500 people driving a car regularly in 3 different western countries were asked about the level of automation they would like to have for their vehicle. The results are somewhat amazing and also annoying for the OEMs and for those who expects the AVs to be on the road anytime soon: 44% do not want it at all; 40.5% prefer ADAS or some form of driving assistance. Finally, only 15.5% await eagerly the advent of autonomous cars. For the 60 years and older, 50% of them do not want assistance and only 11% want full autonomy. This reaction is particularly annoying considering that this age group would probably be the one to gain most from the use of driving automation, thus improving their mobility.

Processing of large amount of data followed by their storage and accessibility in real-time is usually essential for proper on-board decision-making processes and steady communication between a car and its environment (other vehicles, road infrastructure, services and platforms). Questions that concern data ownership, data evaluation and interpretation, or data misuse may also slow down the fast deployment of autonomous vehicles significantly, if not solved properly in parallel to technology development. The “Preliminary Statement of Policy Concerning Automated Vehicles” which was published by NHTSA in the U.S. in 2013 [41], states that regulations need to be made to avoid issues of who can handle the data which were recorded by the vehicle’s own monitoring systems. This implies that a number of abuse cases have to be analyzed before creating regulations for the use of traffic data in a fair and ethical manner.

A defining characteristic of new intelligent vehicles is that they are no longer self-contained; they observe and interact with their surroundings. A second defining characteristic is that the control of the vehicle is no longer fully assumed by the driver, if at all. On-board decision-making processes are complex and based on multiple heterogeneous parameters as well as internal and external sources of information leading to highly dimensional data spaces. Sparsity of data in those spaces leads to unreliable statistics, making the rigorous evaluation of those systems even more difficult. Testing scenario parameters, measurement noise, process noise, non-modelled dynamics and various types of faults construct an n-dimensional “perturbation” space for a given vehicular system or ADAS under test. Physical testing on test tracks generates only very sparse data in this highly dimensional space and are very expensive to make. Test drives carried out on normal roads using fleet of prototypes is becoming a popular alternative because it allows to run and record on-board systems tests during several thousands of hours in normal operating (driving) conditions. The amount of data generated from those tests, however, is at best gigantic, typically in the order of several petabytes for vison-based ADAS. This bring huge burden during off-line post-processing and analysis of those data, which need to be performed in a reasonable time frame and requiring sometimes post-processing much faster than real-time.

Mathematical modelling and “virtual” prototyping through simulation also play an increasingly key role in the system design, commissioning and testing. Automotive manufacturers will increase the use of simulations to reduce time-to-market and R&D cost, to increase end-user functionality and quality, to increase safety by optimizing robustness and reliability and to comply with commissioning and vehicle homologation. Connection to real subsystems and modules through X-in-the-Loop (HIL) has become a standard critical testing strategy. Validation of sensors/ processors/ controllers before integrating into the prototype vehicle reduces errors and costs. Validation of model against the real thing improves the whole process, dramatically reducing development cycles and time-to-market.

Sparsity leads to approximate solution using randomized algorithms (RA) such as Monte Carlo, Las Vegas, sequential and other probabilistic algorithms. The use of an RA can turn an intractable problem into a tractable one. The price to pay is a probability that the RA fails to be arbitrarily close to, but nevertheless, larger than zero. This probability depends on the sample complexity, i.e. the number of simulations performed and other simulation design parameters. An important issue is therefore the necessary sample complexity that guarantees a certain level of confidence for the simulation outcome. It can be shown that this sample complexity is bounded, depending on the desired level of accuracy and reliability [42].

These bounds are rather conservative, however. There is therefore a need for randomized algorithms (RA), kernel methods and bootstrapping techniques to generate data test points in the perturbation space. The quality outcome of the simulation approach also greatly depends on the modelling effort. The empirical mean does not say anything about the minimum or maximum level of performance that can be expected. It may well be that a control system has a good average performance, but also a poor worst-case performance. Worst-case analysis is often used, however, it leads to conservative processing/control system design, which limits the functional performance of the system under investigation.

To design efficient test programs to cover the entire set of operating conditions (efficiency here is defined in terms of a minimum number of experiments to be performed, in order to reduce the costs for validation) is in itself a daunting task and is still a subject of research. Figure 5 illustrates our proposed architecture where physical test scenarios are combined and enhanced with simulation tools in order to cope with the above complexity problems.

Another approach considered by the automakers to handle the reliability issue is on-board prognostic. Prognostic concern the real-time prediction of the remaining service life of components or systems that is how much longer will an embedded component or system last? Although actual implemented prognostic systems are fine for deciding when to replace tires, brakes, oil or batteries, they are currently far from adequate to handle complex processing and reasoning systems embedded in autonomous systems. Will the on-board intelligent systems operate properly next time I will use the vehicle? Clearly prognostic is becoming a technical research area of increasing importance. Many automakers think that the desired prognostic approach shall be designed to be a customer centric, because, in terms of product acceptance, it is not really quality that is perceived by the customer, but reliability. If the predictive nature of the prognostic software can become at least 90% accurate in determining when a component (or system) fails or falls out of specification, that would greatly enhance the car's owner impression of reliability [43].

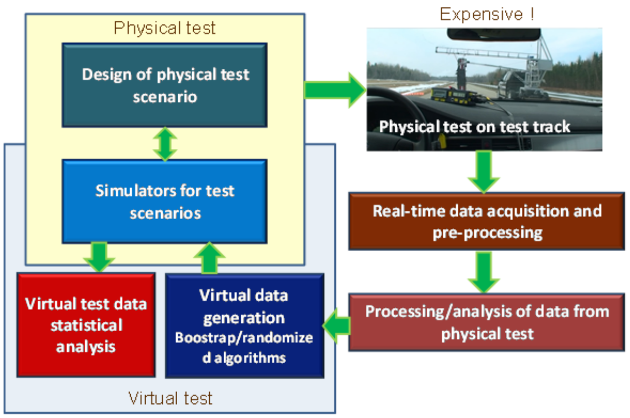


Figure 5. Possible extended testing scenarios for ADAS and intelligent vehicles.

To handle the increasing probability of system failure at a given time, due to the exploding number of parts, components and processes required in autonomous vehicles, redundancy and fault-tolerance measures are often considered to increase reliability at the expense of additional costs and complexity! At the end, more complexity is brought to solve the problems induced by complexity; a nightmare.

Most challenging, however, are the remaining computer science and artificial-intelligence aspects of the problem. Implemented algorithms must be extremely reliable, while keeping the computing resources at a reasonable cost and computation time at a reasonable level. After over 40 years of our modern computing era, software engineering still relies mainly on deterministic and primitive programming where the slightest programming error may lead to a total system failure. The devil lies in the details as we say. New machine learning approaches such as the so-called "deep learning" neural-network based architectures may help resolving some of these issues. Thoroughly testing software systems involving over 100 million lines of codes is a daunting task, if not practically impossible. Other testing tools, such as those based on statistical sampling and Monte Carlo techniques may help, but the outcome will be a probabilistic go/no-go at best.

Finally, we see that the vastness and dynamics of the real world induce a complexity in vehicular systems that will be difficult and challenging to manage. This problem has a clear bound: the risk we are ready to take by letting autonomous vehicles drive us on our roads. However, what is an acceptable risk is not only an engineering question (e.g. measured using safety criteria based on quantitative metrics), but also a social and economic question. Hence the next two sections deal with human issues and costs.

V. HUMAN – AUTONOMOUS VEHICLE INTERACTIONS

With current ADAS and automated commercialized functions, drivers are expected to assume a kind of supervisory role, requiring them to be ready to retake control as soon as the automated system gets outside its "comfort zone". That means that current version of intelligent vehicles requires keeping the actual human vehicle interface including the steering wheel as well as brake and acceleration pedals. In the case of near fully autonomous vehicles, should the human always be able to quickly regain control in case of emergency? Although this issue is still under debate, in emergency situations with fully autonomous vehicles, the answer is no.

Human can quickly get accustomed to automated driving and loose significantly their level of attention. Furthermore, human beings require several seconds if not minutes to quickly change the object of concentration and transfer a high level of attention from one activity to another. Reaction time of humans is simply too slow to allow safe passage of control from vehicles to humans in case of emergency, hence the difficulty to achieve level 3 of automation according to SAE and NHTSA definitions. Whenever all embedded backup systems fail in presence of passengers, what can we do? There could be a big red button in the car that produces emergency shutdown procedures. Would it be safer? Not sure, because some "failures" (meaning unsolvable problems) could be caused by an "impossible" situation (e.g. 120 km/h and a wall 10 m ahead). Ideally, one should have an emergency braking and collision mitigating systems on and reliable all the time, but this is unrealistic. So finally, the way the autonomous vehicle shuts down should be controlled by the vehicle itself, but this implies that the system perfectly knows when it needs to shut down. This kind of paradox leads some expert to believe autonomous vehicles should just jump to level 5 without incrementally going through levels 3 and 4. But this leads to other problems that need to be solved, such as mastering fully the design and fabrication of complex cognitive and reasoning systems as described in the previous section.

If the autonomous vehicle design allows for it, however, regaining control by humans in a non-emergency (non-safety critical) situation may be possible. Some OEMs'AV prototypes allow for a 20 to 30 seconds period for passing from autonomous to human control and vice-versa in normal non-critical situations [44]. However, the relationship between human and autonomous vehicle could be surprisingly fraught. It's all too easy to lose focus, and difficult to get it back. As suggested in [36], [45] factors related to the human experience (ex. intuition) might be the inhibiting ones in the development of driverless cars. In an effort to address this issue, carmakers have been thinking about ways to prevent drivers from becoming too distracted, and ways to bring them back to the driving task as smoothly as possible. This may mean monitoring drivers' attention and alerting them if they're becoming too disengaged, something likely to be annoying to drivers if too sensitive or improperly tuned.

Because of this inability of humans to get back fast enough to the driving process in an emergency, an important challenge with a system that drives all by itself, but only some of the time, is that it must be able to predict when it may be about to fail, to either give the driver enough time to take over or properly handle a safe termination of the driving process. This vehicle ability is limited by the range of a car's sensors and by the inherent difficulty of predicting the outcome of a complex situation. It may take as much as five, six, seven seconds to come back to the driving task, meaning the car has to know in advance when its limitation is reached. The challenge is very big, considering that at 100 km/h, the surrounding environment completely changes in a matter of a few seconds. Worse, on the long run, humans may gradually lose their driving skills due to lack of practice, thus making such transition even more dangerous.

So far, we have only briefly analyzed the driver-vehicle interactions and we can see how complex they can be. But the problem is much worse, we can think of other types of interactions, such as autonomous and human-driven vehicles interactions in mixed traffic, or with pedestrians and other road users (not speaking of animals). There are similar questions of what a good interaction is and how to design the system to react properly. But all this leads to social and ethical issues: still a long road ahead!

VI. EVERY PENNY COUNTS

For one thing, many of the sensors and computers embedded in the actual autonomous vehicle prototypes are still too expensive to be deployed widely. And achieving an even more complete autonomy will probably mean using more advanced, more expensive sensors and computers. The rotating laser radar, or LIDAR, seen on the roof of Google's cars, for instance, provides a very good 3-D virtual map of the surrounding world, accurate down to two centimeters, but still sells currently for several tens of thousands of dollars, still orders of magnitude too expensive for usual retail price cars. Such instruments will also need to be miniaturized and redesigned to improve packaging size and weight, increasing costs further until large volume sales are reached. According to recent studies, the overall price of a typical autonomous vehicle prototypes ranges currently from a quarter to half a million dollars [46]. They suggest that much of the technology that has helped autonomous car prototypes to deal with complex urban environments in research projects, some of which has been used in Google's cars today, may never be cheap or compact enough to be employed in commercially available vehicles. This issue does not involve only the LIDAR but also other high-end components such as, for example, inertial navigation system, which provides precise positioning information by monitoring the vehicle's own dynamics and fusing the dead-reckoning data with differential GPS and a highly accurate digital map.

Clearly we are still far away from a consumer product price tag. Manufacturability, life-cycle, after sale maintenance, warranties and recycling of autonomous vehicles are still topics that have been barely touched upon, which may take years to develop sustainable solutions for these issues. Furthermore, validation and certification of AVs due to their inherent complexity will become a costly business, as we see for example in aeronautics, thus adding costs to the retail price. If we admit the first generations of autonomous vehicles will indeed be expensive yet useful, we need to study how to use this technology in a rentable way. This is the topic of the next section.

VII. IMPACT OF AVS ON TRANSPORTATION BUSINESS MODELS

So far, in our current direct sales business model, these intelligent technologies are used to enable manufacturers to differentiate their offerings and are adapted to the cost and time to market requirements of the automotive market. But as for any newly introduced technology, it can be used either wrongly, for example, based solely on short-term profit strategy or wisely for the long term benefit of society.

Apart from safety issues, congestion is known to be a major source of costs and inefficiencies in mobility and road transportation [47]. Continued growth in the vehicle density per km and the continuous rise of population concentration in major urban centers, all this combined with often outdated road infrastructure, which become more and more overcrowded well beyond their nominal capacity, make the problem even worse at the expense of public transportation solutions. The current road transportation systems in the largest metropolitan areas are downright excruciating. For these reasons, much hope is put on autonomous vehicles as a potential solution to traffic optimization and congestion reduction problems. Several researchers and companies believe that driving automation could allow significant savings on passengers' time, on fuel and also on increasing car density per highway segment, thus claiming to increase road infrastructure efficiency [48], [49]. However, increasing traffic densities on existing road infrastructure, which are already torn and exhausted, could turn out to be unwise in a long-term investment strategy. Furthermore, reducing spacing between vehicles on highways at high speed could simply offset the fast computing and reaction time safety benefits offered by the technology.

If we are looking for better efficiency in mobility solutions, one needs, in our opinion, to consider AVs in a service-based business model, particularly in dense urban areas. There's nothing more inefficient than the current direct-sell automotive business model used in today's mobility solutions. In our actual road transportation systems, the vehicles are parked and unused 95% of the time [50]. The payload (weight passenger versus vehicle weight) is in the order of 3% to 5%. The time lost in commuting through jammed traffic by a large portion of the working population is of the order of several hours per day. Only replacing current vehicles on our roads by electric “green” vehicles without radically changing the way we do business in road transportation, is like putting a bandage to cure a cancer.

Autonomous vehicles can help us improve the figures mentioned above and deploy efficient solutions in dense populated areas. We believe the right use of AVs is this case would be to opt for a taxi-robot-style solution, that is, to resolve the "last kilometer" problem (between the position of an individual and the nearest public transportation facility). Keeping a 'direct-sell' business model for the end-users of road transportation, will simply aggravate the situation as OEMs will keep selling us more and more vehicles. Selling transportation services instead, as found in business models currently used in telecommunications is a more sustainable approach. Telecom operators usually provides the hardware and customers pay according to the time-bandwidth used for various data/voice/video transfers on a monthly basis. Similarly, the use of AVs as taxi robots will allow customers to pay only for driving services performed, that is, to pay according to a given number of kilometers per month. As in telecommunications, a multitude of transportation service packages based on various km/month volume and features can be offered using various marketing strategies. This business model will help solving the current road transportation problem by drastically increase the time percentage use by those vehicles (since the robot taxis will be constantly used on demand and also shared) and by drastically reducing the number of vehicles needed in circulation, therefore reducing air pollution and allowing a greater preservation of our road infrastructure. Moving from direct ownership to service contract business models will also greatly simplify the life of the end-users and reduce their costs. Indeed, no more need to buy vehicles, no more need to get driver licences or pay for car insurances. Also, there will be no more need to build new parking lots, no more need to buy energy (gas or electric) or lose time for vehicle maintenance. Furthermore, a service business model would imply fleets of vehicles managed by a single entity, thus make it easier to develop collaborative architectures required in traffic optimization for instance.

For the current automotive industry, things may not be so bad either as it may look at first. Indeed, the actual life-cycle of a nowadays vehicle, which is around 12 years, will also be reduced significantly as the taxi-robots will be used in a much greater proportion of time, thus reducing their total life span, despite the fact that the number of AVs sold may be much less than the one in the direct-sell business model, which we are in. Also, the service providers, owner of AV fleets, may well be able to afford to pay more for their vehicles through higher vehicle usage. This could relax the cost constraints in producing, testing and maintaining those vehicles.

In our humble opinion, this is the wisest and most sustainable way to use AVs in metropolitan areas with highly dense population zones. But such scenario, many could label it as “utopia”, will face huge resistance from traditional OEMs and tier companies, at least in the short-term, considering the current profit driven economic system and the strong lobby of those companies. It may therefore take a very long time before AVs could be deployed as taxi-robots and before a service-based business model is largely adopted. Emerging companies in road transportation solutions, such as Uber, ZipCar, Google and Apple have all well understood this and may bring the required competition and innovation to break the actual road transportation deadlocks.

In long distance inter-urban areas, it can also be envisioned that platooning of AVs (including autonomous buses and trucks) on highways may be an early scenario favoured over costly traditional high-speed train or short haul airborne solutions.

Clearly, for sustainable and long-term transportation solutions, one needs to think outside the box and consider totally new paradigms in vehicle deployment and usage as well as new economic business models for the automotive industrial sector and road transportation. For example, considering a direct sales model, when people can do other things in their cars instead of driving, the value of their time that is freed up could be immense for the economy. Research is needed to explore ways that employers in particular could make better use of this time and possibly include this time within contracted work hours, thus freeing up employees to enjoy more personal time not lost in commuting. AVs will bring disrupted and impacted business models, newly created business models, assets changing value such as land, properties, stocks, investments by pension funds, etc.

However, there will be downsides as well, including direct employment displacement, such as in driving-related industries: transport truck and courier service drivers; taxi drivers/chauffeurs; bus drivers; auto-body repair; auto insurance; traffic police; tow-truck drivers; driving instructors/trainers; parking lot/parking garage operators, etc. Deployment of AVs may also shift major portion of traditional automotive workers from material, mechanical, manufacturing and car dealers sectors to computers, software, information technologies and servicing sectors.

There will also be significant but indirect socio-economic ripple effects resulting in employment displacement in many other aspects of daily life. For example, a significant reduction in car crashes will affect staff required for hospital emergency rooms, critical care, rehabilitation in the community etc., and may well also significantly impact organ and tissue donation. In short, numerous business models will evolve or will be created by AVs that will spawn many new industries.

VIII. THE NEED FOR MULTIDISCIPLNARY QUALIFIED PEOPLE

The previous sections try to sketch a balanced vision: trading off between pros and cons. Autonomous vehicles are going to deeply change our world but maybe not in the next five or ten years. We need time to prepare the transformation. And one key aspect is the need for skilled people mastering these systems. Intelligent vehicles cover a large and diverse range of technologies that span from dynamics of vehicles to information, communications, electronics, automation, human factors, etc. As such, research, development, and design of intelligent vehicles require expertise and knowledge of various disciplines. However, the science behind most of the industrial development has been proprietary (protected by patents) or remains unpublished. Government efforts have focused on exploratory analyses, identification of requirements, development of standards, and laboratory and field operational tests and evaluations. Currently, there are resources available within different scientific journals, conferences, and engineering professional societies that cover various aspects of intelligent vehicles, but they are very much field focused. For example, some journals cover control systems or vehicular dynamics. Other journals focus on communications or human factors, etc. Among engineering societies, IEEE (Institute for Electrical and Electronics Engineers) and SAE (Society of Automotive Engineers) have specific divisions, conferences, and transactions that cover intelligent transportation systems and intelligent vehicles. There are also a few other journals dedicated to this topic. The technical methods and engineering of intelligent vehicles have been disseminated through a number of scientific and engineering journals and conferences such as those sponsored by IEEE ITS Society, ITS America, ERTICO/ITS Europe, SAE, and others. However, the scientific articles are typically focused on very specific problems and do not necessarily provide a broader picture or comprehensive coverage of large topics such as ‘‘intelligent vehicles’’ in a pedagogical sense. Similar comments may be said about books. So far very few textbooks covering the whole picture are available.

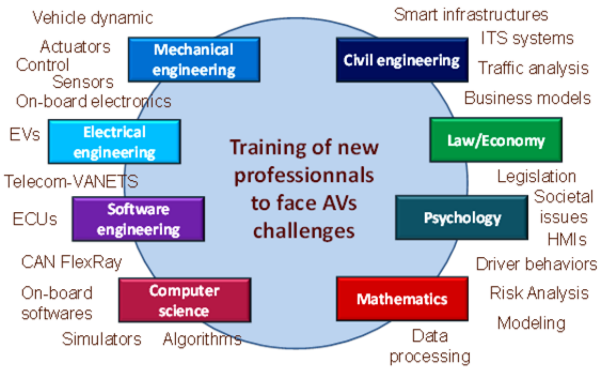


Figure 6. Development and proper deployment of AVs will require a wide range of disciplines and know-hows.

Despite the fact that the progress and technological development have been rapid, the maturity of knowledge on intelligent vehicles remains very young and fragmented. No readily available engineering textbooks cover the entire intelligent vehicle topic, thus making it difficult to build a course in the field for undergraduates. Indeed, very little pedagogical sources exist to culminate technological developments and new emerging systems in a comprehensive format for students. Considering the scope of knowledge involved in the design, development, manufacturing, testing and deployment of AVs, our engineering curricula also need to be adapted and we may well envision the need for complete undergraduate engineering as well as technician programs dedicated specifically to ITS and intelligent vehicles. The field still being largely at the research and prototyping levels, the construction of such curricula in our education systems may also take several years before being implemented in our schools.

As consumer products, intelligent vehicles, whether at their present state or at a future more autonomous state, affect our mobility and touch our everyday lives. Thus it is imperative that the scientific community working in the field provides the knowledge base and resources necessary for further developments of pedagogical tools and resources in order to train a new generation of engineers capable of facing the challenges in the field.

IX. CONCLUSION & PERSPECTIVES

Fully autonomous vehicles as they are being developed today might be seen in the long term future as a key technological revolution that paved the way to the existence of salient intelligent artificial beings. In the mean time, other factors will also come into play to slow down a large-scale deployment of autonomous vehicles. Legal issues and standard legislation are some of them [50], [51]. While several U.S. states (ex. California, Nevada) have passed laws permitting autonomous cars to be tested on their roads, the National Highway Traffic Safety Administration has yet to devise regulations for testing and certifying the safety and reliability of autonomous features. Two major international treaties, the Vienna Convention on Road Traffic and the Geneva Convention on Road Traffic, may need to be changed for the cars to be used in Europe and the United States, as both documents state that a driver must be in full control of a vehicle at all times.

This paper aimed at shedding some light onto some of the challenges that should restrain the current enthusiasm for the commercial trajectory that autonomous driving has taken since the last few years. It is by no means exhaustive neither aiming at discouraging progress. However, it is hoped that some of the fundamental questions addressed in this paper will sparkle some thoughts within our community and rise concerns about an accelerated and premature deployment of complex automated driving maneuvers that could only harm the inexorable, but so attractive, deployment of intelligence into our vehicles.

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