HORIZONTAL ROAD MARKINGS AND AUTONOMOUS DRIVING – BACK FROM THE FUTURE

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ABSTRACT

As the future of transportation, one can envisage fully Autonomous Vehicles (AV), on-demand moving people from place to place, guided by infallible technology imperceptible to the society. From a purely technical standpoint, the AV concept is a reality; all required technologies are available and the major deficiencies of Machine Vision (MV) are expected to be removed within the next few years. Nevertheless, the best current technology provides approximately 99.99% correctness, while for fully autonomously-driving cars demanded is a reliability exceeding 99.99999%, which is proven by the few accidents involving AV. In addition, with introduction of the first experimental AV, a plethora of ethical issues surfaced, which must be resolved before their really broad introduction. Policy change must be implemented, not only to permit driverless vehicles on the road, but also to regulate their presence amongst regular cars and the use of infrastructure. However, until vehicles based on fully AV technology become standard, human drivers would always have to be involved, which necessitates the presence of infrastructure readable by both humans and machines. Horizontal road markings belong to such critical road components, which at present cannot be replaced by any other means. While the current modern vehicles are equipped with assistance systems that can support the drivers in keeping them in the travel path, human vision and decisions remain critical, particularly in places where the machines may fail due to insufficient data. In the foreseeable future, the driver shall have to sit behind the wheel and occasionally take the vehicle steering in own hands. Hence, maintaining high quality of the existing infrastructure, including horizontal road markings is and shall remain of utmost importance.

1. INTRODUCTION

Transport is a key human activity, necessary not only for development, but also to maintain high quality of life. Whether it is a path in the wilderness or a modern multi-lane motorway, it serves the same purpose: moving of people and goods between places. The mode of surface transport has progressed from own feet, through horseback and horse-pulled carriages, to modern trains, lorries, coaches, and cars. Currently, there is a technological, society, and political push to take the driving activity from humans to computers. Progress in this field is enormous and appears to be accelerating exponentially. Indeed, just 125 years after Bertha Benz drove *Benz Patentmotorwagen Number 3* from Mannheim to Pforzheim, Germany, in the first overland motor vehicle trip, the same path was followed by *Mercedes Benz S-Class S 500 INTELLIGENT DRIVE* in a fully-autonomous way, as was reported by Ziegler and co-workers (2014). The key to the success was not the technology of the vehicle, but ***correct reading and assignment of horizontal road markings by machine vision (MV) sensors***, which were impeccably programmed and able to analyse all of the inputs.

Five levels of driving automaticity with various ethical, social, and policy issues that are associated with the completely driverless technology are briefly addressed. Since AV depend on MV technology, difficulties encountered in correct recognition of road markings are described. It is predicted that since the progress to fully autonomous cars would not occur immediately, maintenance of the existing road infrastructure at high quality would be necessary to permit its reading by both human eyes and by MV.

1.1. Horizontal Road Marking

Horizontal road markings are essential road safety features that cannot at present be replaced by any alternative technology. The markings' main role is keeping the drivers in the centre of the delineated travel path, which was established by Steyvers and de Waard (2000). Visible delineation is of critical importance particularly at night, because of scarcity of other visual cues, and that is when retroreflectivity (R_L) of road markings is perceived by drivers (Zwahlen and Schnell, 1999). Improved guidance at night is necessary, because in darkness the number and severity of vehicular accidents is disproportionally higher than during daytime (Plainis, Murray, and Pallikaris, 2005). A complicated statistical analysis of night time single-vehicle accidents that had occurred between intersections, done by Carlson and co-workers (2013), correlated a decrease in crashes by up to 23% with a 100 mcd/m²/lx increase in R_L.

The strictest current norms in Europe demand R_L of only 300 mcd/m²/lx (in dry conditions) and in most of the cases a drop to only 100 mcd/m²/lx is permitted, but the present ***advanced technology for glass beads permits for obtaining R_L exceeding 1,000 mcd/m²/lx.*** Such high R_L translates into improved durability of the entire road marking system, which is highly advantageous from the point of view of finances and society (Burghardt et al., 2018) and is environmentally friendly (Burghardt et al., 2016). Moreover, drivers do notice very high R_L and appreciate it, particularly during driving in poor weather conditions (Pashkevich and colleagues, 2017). It was reported by Davies (2017) that markings with high R_L are easier to read by MV, too.

1.2. Autonomous Driving

One of the first serious ventures into the development of autonomous driving began in the late 1980s, with an attempt to develop a spatio-temporal approach to automatic visual guidance of vehicles. Dickmanns, Mysliwetz, and Christians (1990) reported on the successful employment of video analysis and demonstrated that in laboratory scale it could be successfully utilised for keeping a vehicle within a path delimited by horizontal road markings. While modern computers can analyse data and react faster than humans, they require appropriate input from the field – and this is the key limitation at present.

The vast majority of current developments are aimed at improving MV, as if it could be independent of the existing infrastructure. Numerous patents have been filed and awarded and considerable academic research is being done. Bengler and colleagues (2014) summarised the developments in Driver Assistance Systems, including the MV-based features, while Hillel and co-workers (2014) and later Zhu et al. (2017) reviewed road and line detection by MV. However, there seems to be a lack of common ground and co-operation between engineers responsible for the newly developed MV algorithms and the engineers responsible for maintaining infrastructure. Indeed, a scientific literature search for ‘road marking’ and ‘machine vision’ produces thousands of results related to ‘machine vision of road marking’ and no results related to ***‘road marking modification to improve their vision by machine’***. This appears to be a serious lapse in the current developments.

2. AUTONOMOUS DRIVING LEVELS

The technological progress for fully autonomous driving cannot be an immediate process, because of the obvious issues associated with the infrastructure and driving equipment. The last major overnight change in driving regulations was done on 3rd September 1967 in Sweden, when the right-hand drive was changed to left-hand drive to match the rest of continental Europe (Wikipedia, 2018). At that time, there were only approximately 1.5 million vehicles in Sweden. The change was estimated to have cost about $6.0 \cdot 10^8$ SEK ($\pm 1.2 \cdot 10^8$ USD; an equivalent to $\pm\ 6.3 \cdot 10^9$ SEK or $\pm 9.3 \cdot 10^8$ USD inflation-adjusted to 2017 level). Cost of such immediate modification of the existing infrastructure worldwide to match fully-automated vehicles would be astronomical. Therefore, even the economics dictate slowness of the change, despite a field research based on observation of drivers’ behaviour that might suggest otherwise (Banks et al., 2018).

Five stages of progress in automaticity of driving are briefly described below, based on a definition given by SAE Standard J3016, followed by a discussion about the complications that are being encountered at Level 5.

2.1. Level 0 (no driving automation)

The starting level, when the human behind the wheel must make all of the decisions regarding driving. With progress in technology, the cognitive and physical work load decreased (drivers are no longer required to remember to control the choke, synchronise gears during their change; all of this is done automatically, while power steering and power brakes remove the need for physical strength). Simultaneously, due to increasing speeds, traffic load and various distractions (radio, mobile telephones, near-road advertising, etc.), drivers’ mental workload increased. Hence, there was a need to introduce Level 1 assistance.

2.2. Level 1 (driving assistance)

Level 1 Advanced Driver Assistance System (ADAS) include now-common amenities such as cruise-control allowing for unattended maintaining of driving speed, Anti-lock Braking Systems (ABS) permitting pulse-braking on slippery surfaces, traction control systems, and other. Those systems aid in driving and in keeping the vehicle on the set track, but simultaneously take some of the controls away from the driver.

2.3. Level 2 (partial driving automation)

At Level 2, more advanced ADAS were introduced. Current modern cars are equipped with features such as Lane Keeping Assistant System (LKAS) or Adaptive Cruise Control (ACC), in addition to parking assistant, sensors for reverse, or road signs recognition. Combination of LKAS and ACC can take over of vehicle control for short periods on well-marked roads and assures that the driver does not rear-end preceding vehicle.

This current technology is great and appears to be >99% reliable, but is still far from perfect and has numerous limitations in standard vehicles. The authors of this article are driving cars equipped with Level 2 of ADAS and notice the following frequent system errors:

- ACC works perfectly, but occasionally unnecessarily too early slows the vehicle while approaching someone ahead — to keep the distance, but that is a disruption of a smooth motorway drive and can also send inconsistent signals to other drivers.
- LKAS at times fails — without a warning — to recognise the travel path, particularly in poor weather, with low visibility or low contrast of markings, or in work zones.
- ACC and LKAS do not work at all during snow fall and display an error message.
- Parking assistant is unable to fit the car in a tight spot, where the driver can do it with two or three manoeuvres.
- Reverse sensors incorrectly detect an obstacle if the vehicle is being parked at an incline.
- Lane change and LKAS, giving a vibratory and ‘hard-steering’ warning if they sense the risk of getting in the path of other vehicle or lane change without a blinker, could be a safety hazard if a rapid manoeuvre would be necessary.
- Road sign recognition is not reliable in cases of parallel service roads, when limits apply only to certain weather conditions or times, and does not remember entering a reduced speed zone.

The limitations and errors listed above may be just mildly annoying, but in case of higher levels must be eliminated altogether.

2.4. Level 3 (conditional driving automation)

Autonomous Driving System (ADS) would be taking over all aspects of driving, including navigation, passing, and lane changes. This technology is currently available at an experimental level but is already available to customers in several high-end vehicle models. Whereas Level 3 vehicle should be able to respond to the majority of road situations, human driver intervention is necessary to overcome special situations and during driving on roadways without improvement.

2.5. Level 4 (high driving automation)

Level 4 vehicles must be equipped with a steering wheel, but are driving autonomously, based on the person’s input of the destination. Such an AV should be responsible not only for the task of driving under various conditions, on all types of roads (including dirt roads, and likely also tracks accessible only for four-wheel-drive high-clearance vehicles), but also for monitoring of the surroundings. Communication between vehicles and vehicle-infrastructure information exchange, which are presently already available, would have to become standard for improved quality of travel. Prediction of the behaviour of pedestrians, two-wheel vehicles, or other drivers needs to be done reliably. In case of emergency or lack of roadway data, the human should be able to take over driving to bring the vehicle to a safe stop, drive to an improved terrain, or to a repair facility.

2.6. Level 5 (full driving automation)

The ultimate self-driving vehicle is envisaged as devoid of the steering wheel and with all of the processes of driving taken over by the machine. For this level, there would be the necessity of not only correct assessment of the surroundings and proper reaction by the steering computer, but also constant communication with other vehicles and the infrastructure. It is at present not known what infrastructural elements would be necessary to assure safety and reliability under all circumstances. It is possible that the vehicles would need horizontal road markings as guiding paths, but also it is possible that they would be receiving location signals from vertical markers or through other positioning system(s). Futurists predict how the world with fully autonomous vehicles would look, but their prediction tend to be mostly incorrect. Major issues with such vehicles, based on technological, social, ethical perplexity, and policy considerations are briefly addressed below.

2.6.1. Level 5 self-driving cars and technology

The current MV and computing technology is able to reach Level 5 of AV under most conditions. However, difficulties and untrustworthiness occur when the environmental situations become unfavourable. Correct and fully reliable MV is necessary, because of the infrastructural limitations and lack of alternative common modes of AV-infrastructure and AV-AV communication.

It is generally accepted that since 90% of accidents are attributed to human error, reduction in crashes by 90% should be expected with AV. An interesting perspective on this topic was given by Noy, Shinar, and Horrey (2018), who recognised that frequently an error is attributed to a person whereas it could be attributed to inappropriate infrastructure. They justly raised the problem of ***ironies of automation***, which currently works best at simple tasks that are similarly well handled by humans, but fails under critical situation. Overconfidence in infallibility of the technology could cause accidents and their type may be different than usually caused by human errors. As an example, given was the doomed Air France 447 plane crash, where the autopilot failed imperceptibly, and then the human pilots were not able to recover control because of ***lack of understanding of the nature of the failure*** (Salmon et al., 2016).

An interesting technology failure case is the accident caused by a Google self-driving vehicle, in which the computer assumed during merging that a human-driven vehicle would permit it to merge, but in reality the human had the right of way and did not yield (Ziegler, 2016). It is not known and cannot be known if a human driver in place of the automaton would try to merge in identical situation, if a human driver would use the full vehicle accelerating power and drive dangerously close to the preceding vehicle to merge, or if a human driver would behave in a completely different manner. Similar issues apply to the recent accident, where an AV killed a pedestrian (Bradshaw, 2018). While, based on the brief press report and a released video footage (YouTube, 2018), the pedestrian was guilty because of entering from a median into the path of the vehicle, a question remains whether a human driver who would see someone ahead in the median would not change lanes to keep away from a person obviously violating a traffic law. While some might argue that the machine can see only as much as a human driver and in this case the person was not visible, it is absolutely incorrect: ***a machine can and should see much more than a human***, because it has access to a significantly broader electromagnetic spectrum than human eye. Radar, lidar, infrared, laser, and echolocation are quite common technologies that enhance MV beyond human ability. In the case of said accident, an infrared sensor should clearly identify a person wearing black during night time and react appropriately. What machine cannot do is to assess the type of pedestrian based on the person's appearance, which is natural only for humans. Therefore, the predicted 90% reduction in accidents should be discounted as inappropriately low.

A statistical research done by Teoh and Kidd (2017) has shown that Google self-driving cars were involved in fewer accidents than human-driven vehicles. The most common type of collision was rear-ending of the machine-driven vehicle by a human-driven one, which might be an indication that computer reaction times were too quick, but a different, ***unhuman and thus unnatural reaction kind of AV*** should not be excluded. Indeed, the analysis has shown that the rate of rear-end collisions of human-driven vehicles was much lower than for the computer-driven ones. Even though rather low number of data points for AV could be a source of bias, such results suggest that additional research is required.

A vital and unsolved technological issue is security of AV programming. Modern computer software requires constant updates and with every update a new issue surfaces, which has to be solved by yet another update. Major computer software companies consistently fail to address known software errors and inefficiencies, instead concentrating on purely visual modifications and removing controls from the users ('we, corporations, know better what the user wants') – the same situation can be expected with AV as their market penetration increases. Additionally, AV could be hacked, the same way as computers are hacked, and re-programmed to 'misbehave'.

2.6.2. Level 5 self-driving cars and society

An important issue is social reception of the change. Judging by the acceptance of computers (with their constant software failures, break-downs, limitations, security breaches, and necessity of updates), no real opposition to an introduction of fully autonomous vehicles can be anticipated, particularly amongst younger people. Persons interested in this topic can consult a recent review by Becker and Axhausen (2017).

As an interesting side note, one should mention that the switch to left-hand driving in Sweden in the 1960s was opposed, in a referendum, by 82.6% of voters! Yet, the government decided to proceed. Could such a situation occur with AV in the contemporary society?

2.6.3. Level 5 self-driving cars and ethical perplexity

Technological advance and social acceptance may be easier to resolve than ethical issues. It is not only the question of responsibility for eventual accidents – in a world of only self-driving vehicles it could happen only because of a mechanical failure of the vehicle or the infrastructure (who is responsible in that case – the manufacturer, the owner, the maintenance professional, the designer, the computer programmer?) or a sabotage (but in that case, should those who designed the corrupted item not be responsible?). Ethical issues like the traditional socio-psychological runaway trolley problem in the myriad of its varieties cannot be programmed into computer (Thomson, 1976). Bonnefon, Shariff, and Rahwan (2016) approached people with the dilemma and concluded their research acknowledging a natural fact: people generally opt for 'lesser evil', but passengers of an autonomously-driven vehicle would opt to be saved, even at a cost of other lives being lost. However, such utilitarian programming of AV to protect their occupants at cost of other, less protected road users, is not a correct solution to the posed ethical problem, because of various other considerations, which were thoroughly discussed by JafariNaimi (2017). Approach to this issue from the point of view of criminal law was pondered upon by Coca-Vila (2018). This ***ethical conundrum remains unsolved***.

2.6.4. Level 5 self-driving cars and policy

Policymakers can and should slowly prepare the ground for autonomously driving vehicles. The first steps are already being done. Recently, California legislature (California Code of Regulations, Title 13, Division 1, Chapter 1, §227.38) permitted for testing of AV without a driver to take over steering in emergency situation. It is not known if AV should be strictly regulated or their manufacturers should be able to experiment and find the best solutions. Noy, Shinar, and Horrey (2018) proposed as the most reasonable path for development of AV not regulating development or the final product, but full transparency and due diligence of the research and development process. Amongst current unanswered questions remain identification of standard and permitted ranges of AV (i.e. roads where they would not be restricted and roadways, which they may enter under certain circumstances), their interaction with traditional vehicles, the financial and ethical liability, etc. With the present knowledge, road infrastructure for AV must be maintained at a high level, but nobody really knows what level is really required.

3. HORIZONTAL ROAD MARKING FOR MACHINE VISION

The current research on MV of road markings is concentrating on solving the ***issues of visibility***. There are following major obstacles:

- Absence of marking.
- Obstruction of marking.
- Lack of standardization.
- Visibility in inclement weather.
- Visibility in excellent weather.
- Handling of roadway in poor condition.
- Phantom marking.
- Handling of temporary markings.

Amongst the paucity of published research, one must note two reports that address the issue of R_L. Davies (2017) has performed a static test by placing 2.4 m long panels of white and yellow pavement markings, either 10 or 15 cm wide, in front of a stationary vehicle equipped with a MV. Acceptable detection of yellow marking occurred only at distances shorter than 15 m, whereas white was detected at approximately 18 m. Higher R_L lead to improved detection, but there was an indication that there might be an R_L ceiling for recognition improvements. Colour played a role, with yellow being more difficult to detect. Consistently, lines 15 cm wide were detected better than 10 cm wide, even if they had lower R_L. Conditions of wetness caused a drop in detection quality, even with markings of high R_L (unfortunately, retroreflection values under wet conditions were not provided). Importance of R_L could also be concluded from analysis done by Matowicki and co-workers (2016) who found that poor quality road marking, with R_L mostly below 50 mcd/m²/lx, could not be recognised and classified. Poor markings recognition at longer distances and under the conditions of wetness is quite disturbing, because for a successful Level 5 AV, the detection must suffice for adequate steering and emergency braking at any speed under any conditions.

Much broader work done in the field by Carlson and Poorsartep (2017) demonstrated the fallibilities of the current road marking systems used in North America for MV. The main issues identified were lack of line detection in case of poor contrast and incorrect line assignment in case of poorly maintained roads and in strong sunshine providing excessive contrast. In spite of ongoing developments, current MV technology has real difficulties in handling road surface irregularities like potholes, cracks, repair marks, or wheel ruts. Marking features that are partially missing cannot be detected, either, even if they are obvious to human eyes. These include phantom markings and temporary markings in various level of disrepair. In addition, MV may be inefficient in case of inclement weather and marking obstruction by snow, ice, rain, mist, black ice, and other natural weather phenomena. Issues with correct interpretation of various markings were addressed by Mathibela and co-workers (2015).

4. DISCUSSION AND CONCLUSIONS

It is quite likely that future Level 5 AV would need horizontal road marking for their guidance, but perhaps the new lane markings will look differently than nowadays. Plausibly, Level 5 AV shall be designed to follow a continuous lane marked in the middle of the travel lane. Simultaneously, one must acknowledge that a strict adherence to a travel path would mean excessive wear on the road surface, which would in that case require re-designing.

Amongst issues related to AV that rely on MV, completely unassessed appears the issue of recognising signs given by human traffic regulators (police or fire departments, road maintenance crews, military, or casual citizens responding to an emergency) and in case of official vehicles convoys. Can AV respond to an approaching emergency vehicle by violating the traffic law and thus permitting the vehicle to pass or shall it only pull over and stop (as too many human drivers do), without considering that this way the emergency vehicle may be delayed? Can AV correctly interpret signalling by an untrained and unaided human?

Amongst other unanswered considerations, one must mention the issue of AV carrying Very Important Persons (VIP): would they be given a priority in protecting the VIP over the utilitarian approach of minimising the human casualties? Would police and official AV be programmed differently and to what extend the programming might differ? Who would supervise programming and who would guarantee that there would be no security breaches and no overcontrol by various possibly-malicious agencies?

Before transportation can be taken completely from human hands, one must return from the far future to present day reality. Roads must be maintained for ***both human perception and for MV*** in the oncoming several decades, until all of the vehicles would be autonomous and they would start relying on features imperceptible to humans. High R_L of road markings is important for MV, but primarily it must be maintained for the benefits of people. Analyses have demonstrated that an increase in R_L is correlated with a decrease in accidents (Carlson and co-workers, 2013) and that it is needed for elderly drivers (Underwood et al., 2005). The modern advanced technology allows for obtaining R_L beyond the normative requirements; thus, modification of norms appears to be in order as a way to match the current developments. It should not happen that road administrators cannot demand very high R_L just because there is no such normative regulation. Road safety, social benefits, and durability of the road marking systems should be primary considerations, particularly if the high-end solutions can bring financial benefits in the overall life cycle analysis (Burghardt et al., 2018). An ageing population in Europe requires a higher level of road maintenance and Diamandouros and Gatscha (2016) demonstrated that ***high R_L of road markings increases driver comfort*** and makes driving easier particularly for elderly population.

In this brief overview, selected current issues associated with driverless cars were summarised and some unanswered questions related to AV were posed. High quality of horizontal road markings is absolutely critical for human drivers, but it is equally important for MV guiding the future driverless vehicle. Therefore, the ultimate goal is an increase in road safety, regardless whether the driver is human or machine, and the increase in retroreflectivity of horizontal road markings is one of the methods to accomplish it.

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