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An attempt to evaluate the influence of automated vehicles on traffic flow and design of road infrastructure

Abstract: The article evaluates the impact of autonomous vehicles on road infrastructure design, road traffic conditions and safety based on a review of existing literature. Levels of driving automation and equipment of self-driving vehicles were presented. Attention was drawn to the benefits of developing communication systems between vehicle and the environment. The possible negative impact of autonomous vehicles on mixed traffic capacity was noted. The potential needs to adapt the road infrastructure to the traffic flow of automated vehicles were also presented. Separation of the lane, dedicated to self-driving vehicles, with a high share of these vehicles was presented as an element that improves the flow of traffic and safety.

Keywords: Autonomous vehicles; Road infrastructure; Self-driving cars

Introduction

Nowadays, more and more new vehicles are equipped with systems enabling partial automation of the driving process. Automotive manufacturers are aiming to build fully autonomous vehicles that will be able to make all decisions without the participation of the driver. While the perspective of cars of such vehicles, which are commonly found on roads, still seems quite distant, it should be noted that vehicles with a lower degree of automation are already involved in traffic and their number is increasing. Steering assistance systems, such as e.g. active cruise control, lane assistant, parking assistant, are amenities that are beginning to be standard on new vehicles. The increasing degree of car automation is aimed at improving safety, increasing traffic flow and making better use of road capacity. It is also important to increase the comfort of traveling, by relieving the driver of following the traffic situation and making decisions, including choosing optimal routes. Autonomous vehicles make it easier for people with reduced mobility to move around.

In connection with the development of technology in the field of vehicle automation, the following questions arise regarding the occurrence of self-driving vehicles in road traffic:

- whether the existing road infrastructure is well prepared for the movement of partly and fully autonomous vehicles?

- how automated vehicles can affect traffic safety and efficiency?
- whether the current road design rules should be changed in response to the growing share of vehicles with varying degrees of automation?

Searching for answers to these questions is extremely important in the aspect of the planned changes in technical and construction regulations in road engineering and has become the main inspiration of this article. To better familiarize the problems of automated vehicle traffic, the technical characteristics of these vehicles, their current participation in traffic and development perspectives were presented. Then, the issues of vehicle communication with the environment (V2V, V2I systems) and their possible impact on road traffic and road infrastructure design are discussed.

Characteristics of automated vehicles

The term "autonomous vehicle" suggests the independence of the vehicle control system, which allows driving without the driver being involved. However, there are 5 levels of automation that have been specified by SAE International [17]. Vehicles with automation level 0 do not have any driver assistance systems, while level 5 includes vehicles that do not require the presence of a driver and are not equipped with traditional controls. In the case of level 1, we can only talk about the presence of driver support elements in the vehicle, i.e. an emergency braking system, maintaining a distance from the vehicle in front, etc. Levels 2 and 3 define partially automated vehicles with more advanced systems that process several tasks simultaneously. The main difference between them is the degree of involvement of the driver. In the case of a lower level, the driver must constantly monitor driving, while a vehicle with a level 3 automation may require human intervention, assuming a delay of several seconds needed to analyze the situation and the driver's response. Full automation applies to level 4 - the vehicle travels the route by itself, but it is still equipped with the steering system and may require the driver to take control in exceptional situations [2],[12],[19].

Currently, there are no level 4 and 5 automation cars available on the market, only prototypes of such vehicles exist. However, it should be noted that cars with a lower level of automation (levels 2 and 3) are already available for sale and it can be assumed that their increasing share will have a significant impact on road traffic.

Table **1** presents the classification of automation levels according to SAE [13], where:

- levels 0-2 mean a low level of automation - man monitors the road's space and surroundings,
- levels 3-5 mean a high degree of automation - sensors in the vehicle monitor the road space and its surroundings.

Tab. 1. Levels of automation according to the SAE classification [17]

SAE level	Name	Steering, accelerating, braking	Monitoring of the surroundings	Activity in emergency situations	System capabilities (driving modes)
0	The lack of automation	👤	👤	👤	n/a
1	Driver support	👤 🚗	👤	👤	some driving modes
2	Partial automation	🚗	👤	👤	some driving modes
3	Conditional Automation	🚗	🚗	👤	some driving modes
4	High automation	🚗	🚗	🚗	some driving modes
5	Complete automation	🚗	🚗	🚗	some driving modes

Autonomous vehicle equipment

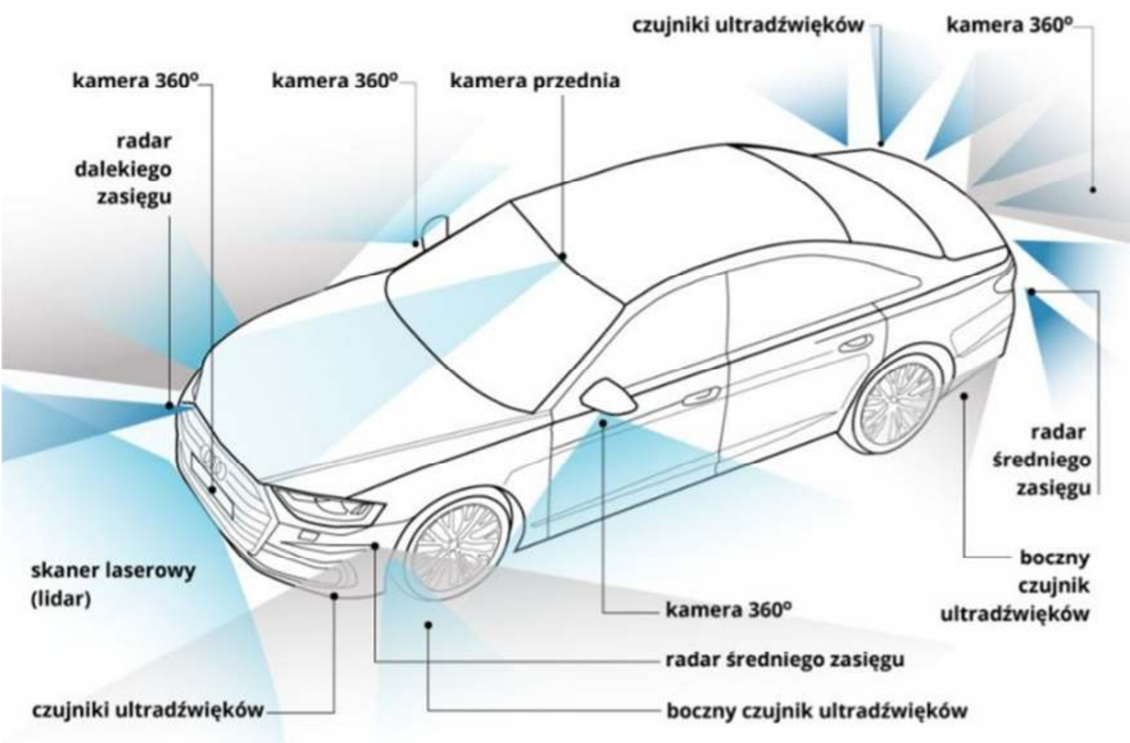
An important element of vehicles characterized by a certain degree of automation are sensors and lasers that enable both independent driving and are also intended to eliminate human errors in the process of driving such a vehicle. One of the systems used in self-driving vehicles is a satellite navigation system that receives and processes the signal from GPS, GLONASS, Galileo, and Beidou satellites, enabling the exact location to be determined.

In addition, these are used [11],[9]:

- LiDAR lasers - scanning the vehicle environment and creating a three-dimensional image of this environment,
- radars - determining the distance from other vehicles and the speed at which they move,
- cameras - detecting and interpreting, among others horizontal and vertical road marking,
- ultrasonic sensors - recognizing components located a short distance from the vehicle.

Currently, the leading car manufacturers have in their offer vehicles with automation levels 1 and 2, while in the case of level 3 only one model at the moment meets the adopted assumptions of this level. It allows semi-autonomous driving and does not require constant attention from the driver [5].

Figure **1** shows a diagram of the location of sensors and radars in an automated vehicle.



1. An example of the arrangement of sensors and detectors in an automated vehicle. Source: [14]

It can be expected that thanks to the use of many advanced systems in the vehicle, the probability of making a mistake by the driving system will be low. Statistics show, however, that the need for driver intervention during test drives is not uncommon. According to the DMV (The California Department of Motor Vehicles) report [18], covering the period from December 2017 to November 2018, when testing autonomous vehicles on public roads in California, the driver took control of the vehicle 143 720 times. The total length of road sections covered by 496 test vehicles of various manufacturers was 3 258 074 km. These results show that further research is needed to develop the control technologies used in vehicles. It can also be assumed that sensors and radars are not sufficient for vehicles to move in a completely safe and comfortable way. Systems that enable communication between vehicles - V2V (vehicle-to-vehicle), as well as between vehicles and the environment - V2I (vehicle-to-infrastructure) and I2V (infrastructure-to-vehicle) are an indispensable element increasing safety and improving traffic conditions. The V2V system allows the exchange of information between automated vehicles located close to each other. By notifying, e.g. about sudden braking of another vehicle, the driver can react early enough to an unusual traffic situation. The V2I and I2V systems are responsible for the intelligent cooperation of vehicles and infrastructure [10],[13].

Fully autonomous cars are currently not yet available for sale, but the proportion of partially automated vehicles is growing, which is already about 5%, and by 2030 partly and fully automated vehicles will constitute about 15-18% of the vehicle fleet [2]. Until only unmanned vehicles are on the road, mixed traffic will be present for many years, i.e. traditional and autonomous vehicles.

According to the vision of the European Union, by 2050 total fatalities on European roads are to be eliminated, and the implementation of this plan is based on automated mobility, integrated with the entire transport system. It is estimated that by 2020 some vehicles with a higher level of automation (3 and 4) should be available, e.g. with autopilot on the highway, or self-parking cars. In [7], attention was paid to the benefits of communication between vehicles, which will enable intelligent traffic control, ensuring safety and smooth traffic. For this reason, it is expected that by 2022 all new cars should have an internet connection.

Autonomous vehicle communication systems

Due to the low share of partially automated cars to date, investments in adapting the infrastructure to the needs of the functioning of communication systems between vehicles and the environment are limited. However, there are also places in Europe where the V2X (vehicle-to-everything) system is tested). This system is a combination of V2V, V2I and V2P systems, enabling, among others vehicle communication with traffic lights and road signs. Ultimately, it can be used to control traffic - instead of induction loops or cameras, reporting the demand for a given maneuver at the intersection can be done automatically by passing information from the vehicle. Having information about the route of each of the autonomous vehicles enables optimization of traffic control and more efficient use of infrastructure [11], [15].

In Vienna, Kapsch TrafficCom proposed a solution consisting of ensuring connectivity of vehicles and roadside elements with a central traffic management system that generates messages for drivers. For this purpose, a radio network with a frequency of 5.9 GHz is used, which, unlike GSM or GPS, is to guarantee no delays in transmitting information. The reliability of the networks used for data transmission is very important for traffic safety and efficiency. Notifications, e.g. about emergency braking or opening of airbags, are sent to a central traffic management system, are analyzed and can be sent to other traffic participants. Infrastructure communication with vehicles also makes it possible to inform about obstacles and accidents. The discussed solution is tested in Vienna and Prague, and ultimately it is to operate on all roads, the so-called "European Corridor" [16].

Systems enabling communication between vehicles and infrastructure are necessary, from a safety point of view, to complement the sensors and radars in which vehicles are equipped. It should be noted that in case of adverse weather conditions, rainfall or improper maintenance of vertical and horizontal signs, there may be a problem with the identification of the marking by cameras placed in the vehicle. The record obtained thanks to them is processed into a series of still images. Then they undergo the edge detection process, which consists of identifying points at which the brightness of the image suddenly changes. Studies [12] were carried out, which show that the use of linear prediction, which predicts future signal values based on past and present values, allows the recognition of the STOP sign even in difficult weather conditions and with partial snowing of the sign. Work is still ongoing on an effective and reliable recognition system for other characters, e.g. speed limits.

Zones, potentially problematic for autonomous vehicles, may be intersections and roads on which traffic lanes are not marked with lines or marking is not properly maintained. For this reason, communication between vehicles and between vehicles and infrastructure is particularly important. Creating databases in which information on roads and their surroundings would be digitally recorded would allow for more effective vehicle control due to the smaller amount of data analyzed in real-time and elimination of the problem related to marking identification [6]. However, such a solution requires considerable financial outlays and it may take many years before it becomes common.

Autonomous vehicles vs. infrastructure design and its capacity

It is assumed that autonomous vehicles will ultimately increase road capacity and traffic flow and enable more economical road infrastructure design [1], [2], [11]. However, before the traffic will be dominated by self-steering vehicles, they will probably coexist with conventional vehicles for several dozen years. Therefore, questions arise as to how this situation will affect road capacity and how should the current road infrastructure be adapted to the transition period?

In [5] the potential impact of autonomous vehicles on capacity was analyzed depending on the share of these vehicles in traffic. It was assumed to reduce the time between fully autonomous vehicles to 0.5 s, with average intervals maintained by drivers of conventional vehicles equal to 1.15 s. In the case of "self-driving vehicle - conventional vehicle" the time interval between them would be 0.9 s because of the comfort of a conventional vehicle driver. The results of the analyzes, taking into account the above assumptions, indicate the possibility of a significant increase in capacity with the increasing share of autonomous vehicles (e.g. by about 40% with the share of autonomous vehicles in traffic equal to 70%). It should be noted, however, that with their share lower than 50% the capacity increases very slowly (with a 50% share there is an increase of about 20%), while above this value the increase is much faster and can reach 75% for fully autonomous traffic.

Given the possible increase in capacity with a high proportion of automated vehicles, segregation of self-driving and conventional vehicles by separating the lanes dedicated only to autonomous vehicles seems to be beneficial. Due to traffic uniformity, it is possible to increase traffic flow and improve safety by avoiding potentially collision or accident situations in mixed traffic. A lane dedicated to autonomous vehicles would allow driving at the same speed while maintaining a constant spacing between them.

Unlike self-driving vehicles, the speed at which conventional vehicles move, the intervals between them, as well as the way drivers drive are varied and largely result from the individual characteristics of the drivers. Thus, mixed traffic can cause problems with the appropriate response of autonomous vehicle control systems to unusual actions taken by drivers. On the other hand, drivers may negatively perceive the driving style of self-driving cars, which by adapting to speed limits can create columns that are difficult to overtake. The legal aspect is not without significance - it is necessary to create provisions regulating the principles of decision making by control systems that are associated with ethical dilemmas and indicating the entity responsible for any accidents [11]. Despite the clear benefits arising from the segregation of autonomous and traditional vehicles, it was pointed out in [2] that with a small share of the former, the separation of lanes intended only for autonomous traffic would be economically unjustified. In [3] an analysis was carried out, which shows that with the participation of autonomous vehicles less than 20%, the use of separate lanes is not recommended. On the other hand, the tests described in [20] indicate that it is beneficial to separate the lane in the case of 40% share of autonomous vehicles in traffic or 30%, assuming higher speed limits in a separate lane, concerning the speed limit for traditional vehicles.

One example of a study on the impact of partially automated vehicles on road traffic is the study described in [2]. As part of this research, a simulation model of a 3-lane motorway section was built, on which mixed traffic was assumed, with different participation of vehicles with a low level of automation. It was noted that in the case of mixed traffic, partially automated vehicles, with their share less than about 80%, may have a slightly negative effect on capacity (a decrease in capacity by 1-7% depending on the assumed time intervals between vehicles). The main reason for the deterioration of traffic conditions is for partially automated vehicles to maintain larger gaps between the predecessor if the driver must take over control.

The research described above raises the question of whether considering the transition period with the coexistence of conventional and automated vehicles, should the infrastructure be changed to better adapt it to the specifics of "mixed" traffic? As previously noted, lane separation only for self-steering vehicles can only be cost-effective if they become more common. Even though the transitional period will continue for many years, it does not seem necessary to expand the infrastructure dedicated to automated vehicles. The possible decrease in road capacity in the presence of 'mixed' traffic is estimated in many studies as insignificant. It should be noted, however, that such estimates are based on many assumptions and simplifications that are difficult to verify by performing empirical studies (low share of these vehicles in motion).

Ultimately, autonomous vehicles are to enable more economical lane design, which may be narrower than for conventional vehicles. In connection with the above, it may be necessary to undergo verification of the design method of the road pavement structure. Self-driving vehicles will move on a strictly designated driving path, constantly loading the structure on the same track. It is different in the case of conventional vehicles, for which it is necessary to design wider lanes, but the loads are distributed more unevenly, due to the different driving patterns of drivers. With the increasing share of autonomous vehicles in traffic, they can harm the fatigue life of the pavement.

The condition of the road surface is an important factor affecting driving comfort and safety. An autonomous vehicle should be able to identify any damage and adjust its speed depending on the conditions. Tire concepts with fiber optic sensors are already emerging to monitor road conditions and combine the data received with information from V2V and V2I communications [15]. Such a system makes it possible to adjust the speed, depending on weather conditions, which have a significant impact on the braking distance.

An important aspect that should be considered in the context of adapting the infrastructure to autonomous vehicle traffic is pedestrian safety. The vehicle can identify these road users using two methods. The first is detection using sensors and lasers mounted in the vehicle. An important limitation of such detection is the need for good visibility, otherwise, there is no certainty that the sensor system will work correctly. Therefore, pedestrians coming out from behind the visibility limiting element (e.g. passing between parked vehicles) may not be successfully identified. The second method is based on wireless communication between the vehicle and the pedestrian and assumes the use of WiFi network extension (IEEE 802.11p) or cellular networks (3G, LTE). In [1], it was noted that the use of current communication technologies to develop V2P (vehicle-to-pedestrian) communication does not require infrastructure investment. A smartphone belonging to a pedestrian would automatically send information about its current position and speed of movement, as well as additional data such as route history or maximum pedestrian speed. The use of advanced filtering, using data obtained from pedestrians and vehicles, would allow collision risk assessment. If it turned out to be high, threat information would be sent to both the vehicle and the pedestrian's smartphone. Restrictions on this method apply to the pedestrian's need to have a smartphone and battery life [4]. The combination of both methods increases pedestrian safety and does not require additional infrastructure investments.

Another important aspect related to the interaction between pedestrians and autonomous vehicles is the definition of the driving nature of self-driving vehicles. Assuming a more aggressive driving style (smaller spacing between vehicles, giving way to pedestrians only if necessary), they can cause a decrease in safety, while for a more conservative driving style (greater spacing between vehicles, giving way to pedestrians in any case) can traffic conditions deteriorate. Therefore, research is needed to determine the optimal control parameters from the point of view of safety and traffic conditions.

The growing share of level 3 and 4 automated vehicles may affect the applicable rules for road infrastructure design. Table **2** presents design problems and the potential impact of the growing share of automated vehicles on design. This statement shows that the scope of changes in the rules of road infrastructure design will be determined by the pace of vehicle fleet change and the development of assistance systems in vehicles. Due to the large share of international transit traffic, it will also be very important to harmonize certain design requirements resulting from the automation of vehicles on a European scale.

Tab. 2, The potential impact of automated vehicles on road infrastructure design

DESIGN PROBLEM	POTENTIAL IMPACT ON DESIGN
Design and authoritative speed	Possibility to define a specific value of design speed for individual sections of a given road class, designing road elements adapted to this speed as the maximum
	Possibility of linking the design speed value with the optimal flow of the vehicle stream, i.e. maximizing the capacity (the effect of maintaining smaller distances by autonomous vehicles, greater uniformity of traffic)
	No need to define and determine the authoritative speed due to the known maximum speed at which autonomous vehicles will travel
Lane width	Reducing the width of lanes, especially at high speeds (taking into account the requirements arising from the dimensions of vehicles authorized for traffic on a given road)
Horizontal arc rays	The possibility of individual design with local conditions (automatic identification of geometrical parameters of the road with adjustment of speed to these parameters)
Maximum length of straight section	No need to specify the maximum length of the straight section (no threat of monotony of driving and the need for the driver to estimate the speed of vehicles moving from the opposite direction)
Intersections	Indirect impact through the ability to individually define the design speed within an intersection
Technical road equipment	The possibility of reducing the distance of side obstacles from the road edge
	No need to use barriers due to the minimization of the number of accidents (occurrence of potentially dangerous situations, only in the event of a failure of the control system), on the other hand, the lack of safety-related devices can be difficult to accept by people traveling in an autonomous vehicle (aspects of subjective risk assessment)
Road surface design	The need to maintain the surface in good condition, due to the inability of the driver to assess its condition and adapt the speed to the conditions or the use of sensors that by providing information, using communication systems (I2V), regarding the current condition of the surface, would allow individual speed adaptation and determination of the braking distances
	Repeatability of loads within narrow bands requires strengthening of a pavement structure
Visibility	Possibility of limiting the required visibility distance to stop by automatic identification of sections with speed limits caused by lack of visibility
	Adapting visibility requirements to detection capabilities by sensor and laser systems

Conclusions

Currently, autonomous vehicles with different levels of automation represent a small percentage of all road users, but an increase in their future participation seems inevitable. Such development is supported, among others by European Union policy [7]. Therefore, justified questions arise about the potential impact of these vehicles on traffic and the design and maintenance of road infrastructure.

Many studies indicate that basing the control system solely on signals from sensors and lasers placed in the vehicle may be insufficient for the safety and efficiency of movement. Attention is also drawn to possible difficulties in identifying signs resulting from inadequate road maintenance or difficult weather conditions. Therefore, investments are necessary for the development of a vehicle communication system with infrastructure that would allow a real-time exchange of information and access to a map database containing reliable data on the road and its surroundings.

A transition period during which mixed traffic of autonomous and conventional vehicles will occur is considered very difficult. The main problems of this coexistence concern road safety and capacity. Only with a high proportion of self-driving vehicles, an increase in the capacity of roads and intersections can be achieved, while in the case of a low proportion of partially automated vehicles, a small decrease in capacity may occur. For traffic safety, it is important to introduce legal regulations defining the entity responsible for decisions taken by autonomous vehicle control systems.

Ultimately, the expansion of autonomous vehicles is to enable more economical road infrastructure design. The occurrence of mixed traffic of autonomous and conventional vehicles does not require major changes in the existing methods of road infrastructure design, although deterioration of traffic conditions during the transition period with a predominant share of conventional vehicles can be expected. The solution to increasing safety and improving traffic flow in the mentioned period can be belts dedicated only to self-driving vehicles. However, their separation from existing road cross-sections, at the expense of reducing the number of lanes for conventional vehicles, is justified only in the case of a large proportion of autonomous vehicles in traffic exceeding 30-40%.

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