DOI 10.18.276/978-83-8419-053-1-44

28th European Conference on Artificial Intelligence (ECAI 2025)

AUTONOMOUS VEHICLES AS A TOOL FOR IMPROVING ROAD SAFETY

Tomasz Kwarciński[a]

[a] *University of Szczecin, Institute of Management, Szczecin, Poland*

ABSTRACT

Purpose: *This article aims to evaluate autonomous vehicles based on artificial intelligence as a tool to influence road safety*

Need for the study: *The large number of road accidents and their consequences make it necessary to look for new solutions to improve road safety. Autonomous vehicles using artificial intelligence in road traffic can be a valuable solution supporting road traffic management.*

Methodology: *The article presents the benefits and risks associated with the implementation of autonomous vehicles as a road safety management tool. In the empirical layer, the resources of institutions and operators related to autonomous vehicles were used. The indicators of road incidents and disabled autonomous driving systems were presented in relation to the distance traveled (per 1 million km).*

Findings: *Autonomous vehicles have not brought a breakthrough in the number of road incidents in the areas where they are tested, in relation to the distance traveled. Although there is an improvement, the indicator remains higher than the indicator of road incidents involving motor vehicles. It should be remembered, however, that autonomous vehicles in most cases do not generate collisions or accidents. The results for the second analyzed indicator – system deactivation – are ambiguous.*

Practical Implications: *Road accidents rarely occur due to the fault of autonomous vehicles. However, the results concern a relatively small number of vehicles and the area of operation. Hence, it is worth conducting further research involving autonomous vehicles in the context of their safety. In addition, a reduction in passenger injuries in autonomous vehicles can be observed.*

Keywords: Autonomous Vehicles, Road Safety, Road Traffic Collision Rate Autonomous Vehicle Shutdown Rate, Traffic Management, Artificial Intelligence

Jel codes: O320, O180

1. INTRODUCTION

In 2021, approximately 1.2 million people were killed and 50 million were injured on roads worldwide. This represents an approximate 5% decrease in road casualties (1.25 million) compared to 2010. It should be noted that the decline in fatalities between 2010 and 2021 worldwide was associated with the rapid growth in the number of motor vehicles and the increase in population (from 6.8 billion to 7.9 billion).

Road accidents remain the 12th cause of death globally, but it is worth noting that as of 2019, they have become the primary cause of death for children and young people. In addition, road accidents generate high economic costs. The costs associated with them are estimated to be around USD 1 trillion, which, according to the WHO, is worth around 3 % of the world's gross domestic product (Global status, 2023).

Notably (Table 1), an above-average number of accidents and victims occur in low- and middle-income countries. High-income countries are home to about 16% of the population, which has 28% of the world's vehicles, 88% of non-urban paved roads, and where about 8% of all traffic accident victims die. By comparison, low-income countries have about 9% of the population with less than 1% of the world's vehicles and paved roads, with about 13% of the total road accident victims killed.

Table 1. Road accidents in countries with different income levels

State income level	Population (%)	Estimated road fatalities (%)	Powered vehicles (%)	Paved roads (%)
High-income	16	8	28	88
Upper middle-income	32	35	38	2
Lower middle-income	43	44	34	10
Low-income	9	13	1	1

Source: Global status report on road safety 2023, *WHO, p. 7.*

Worldwide statistics on road safety allow the following conclusions (Global status, 2023).

1. The most dangerous, from the point of view of the number of road accidents in the world, is Southeast Asia. This area accounts for about 30% of road fatalities

2. The most significant decrease in the number of fatalities between 2010 and 2021 was recorded in Europe. This area reduced fatalities by about 40% during the above period.

3. Globally, there is variation in the distribution of fatalities considering the type of road use. In general, the largest share of road casualties is associated with passenger cars (about 30%), followed by two – and three-wheeled motor vehicles (21%), pedestrians (23%), and cyclists (6%). The share of others is 21% (including buses).

4. Road accidents are the leading cause of death for children and adolescents as of 2019. In addition, 66% of victims are people of working age (19-60 years).

The UN has recognised the problem of global traffic safety. This is alluded to in the UN program Decade of Action for Road Safety 2021-2030 (Global Plan, 2020). It identifies measures to improve Road Safety regarding infrastructure development, improving the safety of vulnerable road users (cyclists, pedestrians), and public transport. It assumes, like previous EU programs, a decrease, between 2021 and 2030, in the number of victims on the roads by 50%.

The impact of road traffic accidents varies and depends on each country's population wealth. They are greater in developing countries with low and middle national incomes. The risk of dying as a result of being involved in a road traffic accident in these countries is three times higher than in highly developed and, therefore, high-income countries. This may be due to the lower road safety standards and poor infrastructure quality in low-income countries.

From the point of view of traffic participants involved in road accidents, passengers and drivers of passenger cars account for the largest share of victims in the EU, at about 45%. The share of pedestrians is about 18%, motorcyclists and their passengers 16%, cyclists about 10% and others 10%. Taking into account another parameter, the place of the accident, by far the most significant number took place on rural roads (52%); while 38% of accidents took place on urban roads. Only about 9% of accidents took place on highways.

Transport policy also influences road safety. A valuable example is the European Union's (EU) transport policy, which includes road safety as one of its pillars. The policy emphasises the need to reduce the number of accidents and the negative consequences associated with them, particularly fatalities and injuries.

Measures taken to reduce the risk of loss of life and injury in road traffic (legislative changes, good practices) have not led to significant improvements in road safety worldwide. It is therefore necessary to look for new and innovative solutions to improve road safety. Autonomous vehicles, as a tool related to traffic management, offer such opportunities. The artificial intelligence-based technology used in them, using algorithms and machine learning, increases the possibility of improving safety in transport. It is assumed that traffic management based on autonomous vehicles can be safer than by current passenger cars, especially those that are not equipped with any driver assistance devices. The intelligent system used in autonomous vehicles does not get tired or distracted like the average passenger car driver.

Research into levels of vehicle autonomy has been developed over many years. Commonly analysed and used in the literature is the Society of Automotive Engineers (SAE) classification, which distinguishes 6 levels of vehicle autonomisation, where 0 means no autonomisation at all in the driving process, 1 equipping vehicles with driver assistance systems, 2 limited autonomisation in the driving process, 3 conditioned autonomisation, 4 high autonomisation and 5 full driving autonomisation. Currently, the highest level of autonomous driving allowed is level 3. This means that the vehicle can drive autonomously under certain conditions, although it can also hand over control e.g. in adverse weather conditions to the driver (SAE, 2021)..

Their software is the basis for a properly functioning system based on autonomous vehicles. At successive levels, it must be increasingly reliable. Its role is to process large amounts of data based on which optimal decisions are made. Their operation is influenced by the following components, which are responsible for perception, prediction, planning and control (B. Paden et al 2016, p. 33-55, Takacs et al 2018, p. 106-112, C. Badue et al 2021, A. Yoganandhan et al, 2020, no 33, p. 3303-3310).

1. Perception module, which collects and processes sensor data, e.g. detects objects, maps the environment.

2. Prediction module, which predicts the behaviour of other traffic participants.

3. A planning module that determines the vehicle's navigation route using the perception and prediction module.

4. The control module, which controls the vehicle using the planning modules.

The autonomous system's basis is control and operation in various conditions. Lidar elements are essential to launch the autonomous system, which maps the vehicle's launch using laser pulses, cameras, and radar.

A well-developed infrastructure is required to properly implement and operate autonomous vehicles. It is formed by the following components: physical infrastructure: roads, vertical and horizontal markings, parking spaces, communication networks (4.5G), digital infrastructure sensors, transmitters, smart signals, high-resolution maps, etc. (Duvall T. et. al. 2019).

The artificial intelligence used allows navigation and real-time optimal decisions to be made independently of humans. This is all thanks to advanced technology and computing systems. The collaboration of these elements allows the autonomous vehicle to select optimal decisions.

When analysing autonomous vehicles, it is essential to keep in mind the risks associated with them. For example, they may be legal and relate to liability for accidents. Another problem seems more serious and is related to risks of an IT nature. It concerns the possible interference with the software of autonomous vehicles or the transport system (the issue of cybersecurity of autonomous vehicles).

Despite these reservations, autonomous vehicles can be a valuable solution for improving road safety. This can be facilitated by several constantly developing technical and technological solutions that support the driver or allow the information system to take full control of the vehicle. Autonomous vehicles, transport infrastructure adapted to their service, and mapped terrain facilitating vehicle movement support intelligent traffic management. Their emergence represents an important moment in the development of intelligent transport systems and, simultaneously, the new challenges involved.

2. LITERATURE REVIEW

Research on autonomous vehicles has been ongoing for many years and in various contexts. One of them concerns the possibility of improving road safety through autonomous vehicles.

In research related to autonomous vehicles, analyses are conducted in the context of their advantages and disadvantages. The literature points to safety as an advantage and the primary reason for developing autonomous vehicles. In this context, research focuses on analysing the impact of autonomous vehicles on preventing traffic accidents and, in particular, their negative effects, i.e., minimising fatalities and injuries (M. Abdel-Aty, S . Ding, 2024).

The assessment related to autonomous vehicles can be presented in the context of benefits and threats related to road traffic management. As a benefit, safety is indicated in the literature as the primary reason for implementing autonomous vehicles. In this context, the analyses focus on assessing the impact of autonomous vehicles on preventing road accidents and in particular, their negative effects, minimising casualties and injuries. (Abdel-Aty, S . Ding, 2024)

The operating system in autonomous vehicles allows for more precise vehicle control, relative to the driver's capabilities. This is facilitated by the artificial intelligence that controls the vehicle based on algorithms and cameras, radar and lidar. In addition, the autonomous system supported by the mapped terrain accurately detects threats and can respond to threats faster than humans. Importantly, the possibilities of reducing road accidents thanks to artificial intelligence are related to excluding drunk people from driving motor vehicles, distracting drivers by using mobile phones while driving, not exceeding speed limits, and better control of the environment (360 degrees) in which vehicles move. Undoubtedly, the arguments presented above indicate that autonomous vehicles can positively impact improving road safety. An AI-based accident avoidance feature used by an autonomous vehicle can reduce the number of road accidents and fatalities caused by distracted driving or human error in controlling the vehicle, and warn drivers of hazards (C.D. Harper et al., 2016, p. 1-9).

Taking control of an autonomous vehicle by artificial intelligence allows the driver to control work and entertainment while driving (V. Nagy, B. Horváth, 2020, 235-240). There may be a risk of shortening travel time to the destination or additional support when parking vehicles. (L.-J. Tian, at al, 2019, 258-278).

In the literature, it is also possible to see views highlighting the risks associated with developing autonomous vehicles. The main ones are related to the IT sphere of autonomous vehicles. They concern the failure of sensors, software, interference in the transmission of information between the vehicle and the infrastructure- V2I (D. González, 2016, pp. 1135-1145) the taking of wrong decisions by autonomous vehicles and the necessary reaction of the driver in such a case (A. Eriksson, N. A. Stanton, 2017, pp. 1233-1248, A. Calvi, at al., 2020. pp. 58-67) difficult for autonomous vehicles to assess the behaviour of other road users i.e. vehicle drivers, pedestrians, cyclists (J. Wang at al, 2020 p. 13).

In the technical-technological context, significant risks resulting in autonomous vehicle accidents can be software errors and traffic-related circumstances. It is important to emphasise that the system continuously analyses the traffic situation and selects optimal decisions through the algorithm. It is impossible to exclude a situation on the road that will not be included in the algorithm. Then, external assistance will be required, most likely from the human driver of the autonomous vehicles. The problem of the autonomous vehicle remains the system's failure to plan for all possible situations that may arise in traffic (M. L Cummings, 2021). The system may misjudge the traffic situation, which can lead to dangerous traffic situations, including accidents. Another risk associated with autonomous vehicles is that the autonomous vehicle system confuses traffic signs,

A significant challenge related to the development and deployment of autonomous vehicles remains the legal system that will ensure that society is adequately addressed in terms of liability for possible traffic incidents. Artificial intelligence applied to autonomous vehicles can reduce the number of traffic incidents, but they cannot be 100% excluded. Hence, it is also necessary to manage this issue by introducing appropriate regulations to assign liability for traffic incidents involving autonomous vehicles (Association for Computing Machinery). It is possible to identify several potential actors who could take responsibility for possible traffic incidents involving autonomous vehicles, i.e. the driver (tester), the vehicle owner, the system operator, the vehicle manufacturer and the software manufacturer. Perhaps, following the example of drivers, a separate fund should be set up to collect funds related to autonomous vehicles, dedicated to the consequences of accidents. Furthermore, the literature emphasises that artificial intelligence systems can make mistakes that humans do not make (M. Wansley, 2024) and, in addition, autonomous vehicles can make their own mistakes - coding errors (M. L Cummings, 2021 pp. 6-15).

Currently, there are no uniform regulations on the liability for accidents involving autonomous vehicles worldwide. There are also no such solutions at the European level. Appropriate regulations are only being created at the national level, but with numerous restrictions. For example, in Germany, it is possible to use level 3 autonomous vehicles but with a limited speed (up to 60 km per hour) on mapped sections. This allows for autonomous driving in Germany on approximately 13,000 km of motorways (Bundesamt für Güterverkehr). Regulations are also being introduced in the USA, but only at the federal level (R. Beidgelall, 2024). Legal regulations do not keep up with technological changes in autonomous transport. Some legal provisions block the possibility of testing autonomous vehicles. The basic challenge is related to liability for possible road accidents. The occurrence of such events cannot be ruled out. In the case of autonomous vehicles, it is necessary to determine the liability of the driver (vehicle owner) and the manufacturer. In this respect, regulations are needed at the national and European levels. At the moment, the Vienna Convention is the applicable legal act. Without legal changes, testing of autonomous vehicles is severely limited. On the other hand, without testing autonomous vehicles, it will not be possible to develop autonomous technologies, which is necessary for their mass implementation. Testing is an important process in preparing for the implementation of vehicles, because without gaining the trust of potential passengers, it will not be possible to gain trust in autonomous vehicles and, consequently, the process of their commercialization will be very difficult. Another threat remains cybersecurity. Criminals can exploit the imperfections of the IT system of autonomous vehicles to take control of them, e.g. over the steering system, braking, thus endangering other road users and passengers of the autonomous vehicle. The threat of cybersecurity increases with the development of software in autonomous vehicles and related network systems. (G. Bathla, 2022, pp. 1-36). The consequences of taking control of the vehicle can be tragic. They can lead to improper driver reactions, accidents and even death. This is related to the manipulation of the autonomous vehicle's operating system. The main threats related to the cybersecurity of autonomous vehicles are related to (S.F. Meyer, 2021 pp. 227-247, O. Sharma, 2021): disruptions in the operation of autonomous systems. Criminals hacking into the software of an autonomous vehicle can gain control over individual elements of the operating system, causing disruptions in its operation and thus exposing passengers and other road users (pedestrians, cyclists) to various dangers - data theft, data may be related to passengers but also to the autonomous vehicle, - disruptions in communication. Disruptions may concern data transfer between vehicles (V2V) and between vehicles and infrastructure (V2I). - threat of software destruction. Threats may be related to immobilization and a ransom demand for restoring the proper functioning of the autonomous vehicle. Reducing cybersecurity threats requires preparing appropriate security measures in the software. Cyberattacks are possible thanks to the constant connection of the vehicle to the network. This is necessary for the vehicle to communicate properly with its surroundings, including infrastructure. To some extent, protection against cyberattacks can be achieved by limiting access to external information transfer and downloading/transmitting information from specific locations.

Despite the continuous improvement of autonomous vehicles, there are concerns about their safety, and diverse views on this subject can be observed. Young, well-educated people and men are positively disposed towards autonomous vehicles (L. M. Hulse, at al,.2018, p. 1-13). From a different perspective, territorially, a difference in the perception of autonomous vehicles can be seen. In Europe, there is more pessimism, whereas in Asian countries, the population is more optimistic about autonomous vehicles in terms of their safety. Hence, it can be thought that in Asian countries, autonomous vehicles may, on a larger scale, emerge more quickly.

Despite the continuous improvement of autonomous vehicles, there are concerns about their safety while travelling, although diverse views on this subject can be seen. Young, well-educated people and men have a positive attitude towards autonomous vehicles. There is also a visible difference in the perception of autonomous vehicles in territorial terms. In Europe, there is greater pessimism, while in Asian countries, residents are more optimistic about autonomous vehicles in the context of their safety. Hence, it can be assumed that autonomous vehicles may appear on a larger scale and faster in Asian countries (J. Moody et al., 2020, pp. 634-650). Moreover, taking into account the accident rate that occurs in the global system (Table 1), greater acceptance of motor vehicles in Asian countries may bring more positive effects in terms of improving road safety than in European countries.

From the point of view of the article, it is essential to analyse the impact of autonomous vehicles on the level of road safety. Human error is estimated to influence more than 94% of road accidents (Critical Reasons..., 2015). This group includes road accidents caused by speeding, alcohol, non-compliance with traffic regulations and other causes. In this context, autonomous vehicles have the potential to reduce the number and consequences of road accidents fundamentally. This is alluded to in research by the Insurance Institute for Highway Safety (J. M. Anderson at al., 2016). Already, basic vehicle features such as frontal collision warning, lane assist and adaptive headlights can reduce the risk of an accident by 33%.

Ongoing tests of these vehicles can provide valuable opinions on the safety level of autonomous vehicles. This allows them to be developed effectively. Currently, most autonomous vehicle tests are conducted in the USA. This approach seems reasonable, as there is a lack of scientific and research work in the literature relating to road traffic incidents involving tested autonomous vehicles in the context of their safety (Wang J., 2020). For this reason, the research section of this article presents an analysis of road incidents related to autonomous vehicles based on data from the California Department of Motor Vehicles (USA), Waymo, the market leader in the number of kilometres travelled with autonomous vehicles, and the National Highway Traffic Safety Administration.

Statista, using databases from the US Department of Transportation and the California Highway Patrol, presented the collision rate for autonomous and traditional vehicles (www.statista.com). For 1 million miles travelled, the rate for autonomous vehicles in California is 26.3, for traditional vehicles it is about 0.7, and for the US, it is about 1.9. Other values are presented in the National Law Review studies, according to which 9 road accidents involving autonomous vehicles and 4 other vehicles per 1 million miles travelled (www.nstlaw.com). The above studies show that vehicles traditionally controlled by drivers cause fewer road accidents.

In addition to the assessment of autonomous vehicles taking into account the number of collisions and the distance travelled, the literature also examines autonomous vehicles in other cross-sections. The basic ones include:

- identification of challenges related to safety, including autonomous vehicle software, such as the need for reliable detection of errors in software, robust algorithms for decision-making (P. Penmetsa, 2021, pp. 485–492).

- Determination using statistical methods of the reliability of autonomous vehicles in the context of the distance they must travel to be competitive in terms of safety as vehicles controlled by drivers (N. Kalra, 2016, pp. 182–193).

- Analysis of the severity of accidents (S. Yan, 2023, pp. 1–28).

The tests of these vehicles can provide valuable opinions on the level of safety of autonomous vehicles. Thanks to them, they can be effectively developed while contributing to improving road traffic management. Currently, most autonomous vehicle tests are carried out in the USA. This approach seems valuable, because the literature lacks scientific and research works relating to road incidents related to tested autonomous vehicles in the context of their safety (J .Wang, 2020, pp. 1-13). For this reason, the research part of the article presents an analysis of road incidents related to autonomous vehicles based on the California Department of Motor Vehicles (USA) database. In the overall assessment, however, it should be noted that autonomous vehicles are used in a specific, limited area. Hence, the results in comparing autonomous vehicles and those driven by drivers should be cautiously approached. Importantly, the overall accident results of motor vehicles driven by drivers compared to autonomous vehicles are not worse. For example, in the USA in 2022, there will be 1 fatality per 100 million miles travelled, and excluding people under the influence of alcohol or drugs, there will be 1 fatality per 200 million miles travelled (Ph. Koopman, 2023).

There is no clear opinion in the literature on the level of safety of autonomous vehicles. (N. Norris, at al, 2023, pp. 251-260). .Generally, two different approaches can be distinguished (S. Ding, at al.).The first one indicates the advantage of autonomous vehicles over those controlled by drivers. This opinion was formulated based on research on autonomous vehicles and those driven by drivers in the context of fatalities. Analysis conducted on Google vehicles showed that there was no accident involving an autonomous vehicle in which a passenger died. In contrast, in vehicles controlled by drivers, 1 victim occurred every 108 million miles. The second approach questions the view that autonomous vehicles are safer than driver-driven ones. This is indicated by research considering the limited movement conditions of autonomous vehicles. It was also pointed out that autonomous vehicles often hit each other from behind, at a higher speed than conventional vehicles. This can be associated with the lower speeds that autonomous vehicles travel and with lower driver concentration (F.M. Favarò, et al, 2017).

Synthesising the opinions presented above on the possible impact of autonomous vehicles in the context of their safety, it can be seen that the advantages of autonomous vehicles are inspiring. However, it is premature to state that an autonomous vehicle is better than one driven by a human driver. Further multidisciplinary research is required in this area, considering autonomous vehicles, machine learning, software development and necessary changes in legal regulations (Ph. Koopmann, M. Wagner, 2017, pp. 90-99). It should also be noted that drivers of other vehicles cause the vast majority of accidents involving autonomous vehicles. Autonomous vehicles using artificial intelligence should be developed, although it is difficult to clearly determine when they will be safer than vehicles controlled by humans.

In general, it can be assumed that the effectiveness of the autonomous system will increase due to the development of its algorithms. Additionally, increasing the share of autonomous vehicles and extending the range of their functioning may contribute to safety.

The process of implementing autonomous vehicles will undoubtedly be long-term and will be evolutionary in nature. This will be partly due to technical and financial reasons. In addition to vehicles, the development of infrastructure (mapping, readers, etc.) will be necessary for the proper functioning of autonomous vehicles. Therefore, it is necessary to prepare for a situation where both types of vehicles (driver and autonomous) will operate on the same infrastructure for longer. In addition to changes in infrastructure, the challenge for the development of autonomous vehicles will be the necessary legal changes.

In summary, autonomous vehicles are a future solution for improving road safety. Higher levels of autonomy of means of transport reduce the role of humans in the movement process, which in some cases may reduce the risk of an accident and its consequences. In some cases, artificial intelligence may detect a threat faster than humans and more effectively prevent an accident, or reduce its negative consequences.

3. METHODOLOGY

The research methodology adopted for the purpose of the article included collecting data on autonomous vehicles, analysing them in the next stage, and proposing indicators reflecting the safety level of autonomous vehicles. Subsequently, the indicators of traffic incidents and disengagement of an autonomous vehicle controlled using artificial intelligence were calculated. Data for the empirical part came from three sources:

1. The National Highway Traffic Safety Administration.
2. Department of Motor Vehicles (DMV).
3. Entities developing software for autonomous vehicles with a focus on Waymo, the leader in autonomous transportation.

The National Highway Traffic Safety Administration is a government agency that publishes safety data in the USA. This institution presents general data on road safety in the USA, including the number of fatalities and injuries. Data for this article was obtained in this area.

The Department of Motor Vehicles (DMV) has, since 2014, introduced an autonomous testing program to test autonomous vehicles with a driver and, since 2018, without a driver. It should be noted that testing an autonomous vehicle without a driver is subject to much stricter rules than testing an autonomous vehicle with a driver (tester). The obtained license for testing an autonomous vehicle precisely defines the location (street names), weather conditions, time of day, and maximum speed for testing autonomous vehicles. failure by the company to submit an annual report will result in automatic revocation of the license.

The DMV administers the vehicle testing program and collects information about road incidents and autonomous mode deactivations. The results are published on the website. The report cannot be made later than 10 days after the collision. By April 2025, over 800 reports on road incidents had been published on the DMV website. In the article, those concerning 2019-2024 were used for statistical analysis.

There are currently 37 autonomous vehicle test operators active in California. However, in terms of annual mileage travelled, Waymo has become the leader in this market.

Based on information from the DMV, two indicators relating to the safety of autonomous vehicles, i.e., road incidents and outages, were calculated. The road incident indicator was calculated as a quotient, considering the number of road incidents and the total mileage of these vehicles. On the other hand, the takeover indicator shows the average distance travelled by the autonomous vehicle until the tester (driver) takes control of the vehicle, which was previously signalled by the vehicle.

The analysis was limited to California and DMV data because it is the only jurisdiction worldwide that publishes publicly available and reliable data on autonomous vehicle testing.

4. RESULTS

As of July 2024, about 4,000 traffic incidents related to autonomous vehicles have been recorded in the US, with about 12% of them in 2024. The data includes vehicles with ADAS, which supports the driver while driving (level 1-2 autonomization) and ADS, with limited or no driver support per vehicle (level 3-5 autonomization). To date, the highest number of traffic incidents recorded in 2022 was about 1,450. Among vehicles with ADAS, the highest number of road incidents was associated with TESLA (about 54%) and among vehicles with ADS, with Waymo (about 10%). This would imply that vehicles with higher levels of autonomization account for a smaller share of traffic incidents (nhtsa.gov)./. About half of the traffic incidents involving autonomous vehicles were reported in California. From the point of view of the autonomization of means of transportation, this is an important place on the world map, where the most autonomous vehicles are being tested. The number of autonomous vehicles tested in 2024 autonomous vehicles was about 2,800 (dmv.ca.gov). In previous years, it was respectively about 1.6 thousand (2023), about 1.5 thousand (2022), and about 1.1 thousand (2021).

The share of total kilometres driven, in 2021-2024, by Waymo autonomous vehicles in the state of California was: 58% (2021); 50% (2022), 68% (2023), and 62 % (2024). By comparison, during the same period, the shares of major competitors, in terms of miles travelled, were as follows:

- Cruse - 20% (2021), 30% (2022), 10% (2023), as of October 2023, due to an accident, the company suspended its services with autonomous vehicles

-Zoox 3% (2021), 9% (2022), 13% (2023),25% (2024).

The number of kilometres driven by driverless autonomous vehicles is also worth noting. In total, all companies licensed for such transportation drove about 900 thousand km (about 14.5%) in 2024, about 5.2 million km (about 56%) in 2023, about 990 thousand km (about 10%) in 2022, and 49 thousand km (about 0.6%) in 2021.

Autonomous cars with Waymo software (named after a new way forward in mobility) have driven a total of about 52 million km (about 33 million miles) since licensing, including about 2 million km (more than 1 million miles) without a driver. The autonomous transportation service is available in San Francisco, Los Angeles, Phoenix, and Austin (along with Uber). It covers an area of about 500 square miles, i.e. about half the area of the cities served. Approximately 100,000 customers use Waymo's services per week. In 2025, the company plans to expand its service to two more cities, Atlanta and Miami (waymo.com).

Commercial passenger transportation with Waymo's autonomous vehicles (with tester) began in 2021. However, since March 2022, autonomous vehicles have been controlled solely by artificial intelligence (driverless travel). After two years of driverless autonomous vehicles, surveys were conducted among passengers according to which (waymo.com):

-Only 37% of travellers said that the ride in an autonomous vehicle was comfortable, a decrease of 5pp. This may be due to the longer ride time. Compared to a driver-driven vehicle, it is longer by more than half

- There is a problem with space to get in and out of the vehicle, and the waiting time for an autonomous vehicle increases. According to passengers, the problem is the limited area served by autonomous vehicles.

- Advantages include a quiet ride, greater freedom of conversation (no tester), and more rigorous compliance by the autonomous vehicle system.

The higher cost of the trip relative to cabs (about $10 on average for the same distance) persists due to the fact that the technology used in autonomous vehicles is still expensive. However, it is anticipated that the development of autonomous vehicle technology and accompanying infrastructure should, in the future, contribute to lowering the cost of operating an autonomous vehicle system.

Since the introduction of autonomous vehicles with Waymo software, 3 accidents have been reported. According to Waymo's calculations, the risk of an autonomous vehicle accident ranges from 0.4-0.5 versus 1.2-3.9 for passenger cars driven by a driver over 1 million miles. This means that autonomous cars are between 3 and 6 times safer than human drivers. Considering the unit cost of traffic incidents, these are about 55% lower for autonomous vehicles. This may be due to the overriding principle associated with the speed limits of autonomous vehicles, which essentially leads to property damage while reducing the risk of injury to passengers (K. D. Kusano, 2024, p. 66).

It is also worth noting that other data shows safety improvements, using Waymo as an example. In doing so, it should be noted that the data presented considers the same distance and place on which autonomous vehicles and those driven by a human driver travel. Taking these assumptions into account, Waymo's autonomous vehicles had fewer airbag deployments (by 81%), injuries (by 78%) and fewer collision reports to the police (by 62%). It is worth noting at this point that companies with autonomous vehicles are more stringent when it comes to reporting collisions of their effects to both the Department and the police (waymo.com).

Driverless autonomous vehicles with Waymo software have driven more than 1.5 million km by January 2023. During this time, 20 road incidents were recorded, most of which were road collisions related to reversing another vehicle (8 out of 20 cases). At this point, the autonomous vehicle was not moving. The second most common road incident was a rear-end collision with an autonomous vehicle (6 out of 20 cases). Another 5 cases were related to objects lying on the road. One side impact was also recorded. A garbage truck hit an autonomous vehicle. Most road incidents caused minor damage, and nine out of 20 events did not cause any damage. 55% of road incidents occurred with a stationary Waymo vehicle, and 40% were related to parking. (V. Safety, 2023).

Most road incidents were recorded during the day. This may be because between 8:00 a.m. and 4:00 p.m. 22:00 6:00, cyclists' traffic is lower by about 85%, motorcyclists' by 83% and pedestrians' by 63%. The share of road accidents at night was about 10%. It should also be emphasised that the demand for trips at these hours is lower. Only about 20% of trips were made at night. This result contrasts with general studies, because the risk of road accidents for vehicles that move at night and are driven by drivers is higher (Varghese & Shankar, 2007). This may be facilitated by alcohol abuse by drivers, excessive speed or driver fatigue.

It should be emphasised that among the 20 cases of road incidents, none were recorded as related to any passenger injuries. This results from the company's general strategy, indicating that the primary goal is to ensure safe, responsible and defensive driving. Hence, the algorithm developed by Waymo effectively eliminates the risk of serious accidents. Autonomous vehicle safety research may concern the frequency of road collisions and the driver (tester) taking control of the autonomous vehicle. They can be presented using the road incident indicator, the quotient of the number of road incidents and their total mileage (Tables 2 and 3) and the shutdown indicator, which reflects the average distance to the moment the driver takes control of the vehicle (Table 4). The analysis presented in the article includes data from the DMV database from 2019 to 2024. At the outset, it should be emphasised that the presented indicators should be approached with caution, which results from area restrictions, the speed of autonomous vehicles and, additionally, the underestimation of road incidents in the case of vehicles driven by drivers. It is estimated that about ¼ of accidents and 60% of collisions are not reported to the police (L., Blincoe, 2023).

Table 2. Road collision rate of autonomous vehicles in 2021-2024

Name	2019	2020	2021	2022	2023	2024
Number of road accidents	104	44	117	150	127	102
Mileage of autonomous vehicles (in million km)	4,48	3,12	6,48	9,54	9,2	6,26
Collision rate of autonomous vehicles	**23,21**	**14,10**	**18,05**	**15,72**	**13,68**	**16,29**

Source: own elaboration own elaboration based on 2019- 2024 Autonomous Vehicle Disengagement Reports 2019-2024 Autonomous Mileage Reports.

There has been a visible decline in autonomous vehicle-related collisions in California since 2019. However, the significant decline in autonomous vehicle miles travelled over the past year (by about 1/3) has caused the overall autonomous vehicle collision rate to increase. The number of collisions per 1 million kilometres travelled decreased from 23 to 16, or about 30%. This fact should be considered positive because it indicates the technological development of autonomous vehicles, including autonomous systems based on artificial intelligence. The low number of collisions and distances travelled by autonomous vehicles in 2020 may be due to the restrictions that occurred at that time and were related to the COVID-19 pandemic.

Table 3. Autonomous Vehicle Road Collision Rate for Leading Companies 2019-2024

Company name	2019	2020	2021	2022	2023	2024
Waymo	10,77	11.0	20,1	15,3	8,4	17,1
Zoox	70,0	65,0	33,3	33,0	13,2	15,1
Apple	83,3	-	300,0	35,0	12,5	8,333
Cruse	46,2	12,3	22,1	12,0	40,0	-

Source: based on 2019- 2024 Autonomous Vehicle Disengagement Reports 2019-2024 Autonomous Mileage Reports.

The road collision rate for individual companies varies. Only in the case of Apple can we see an annual decrease in the rate, which may indicate an improvement in the quality of the autonomous vehicle software of this entity. In the case of Waymo, apart from 2024, the collision rate also had a downward trend. For Cruse, 2022 was a relatively good year regarding the number of road collisions. In 2023, there was a tragic accident involving an autonomous vehicle with Cruise software. This situation caused the company to withdraw from testing autonomous vehicles.

Another measure reflecting the degree of reliability of autonomous vehicles is the disengagement rate. It determines the average distance vehicles can travel in autonomous mode, after which the driver (tester) intervenes. This is conditioned by the occurrence of a dangerous situation on the road or a suggestion from the system about the need for a human to take over such control. The tester's takeover of control is intended to prevent potential collisions/road accidents, or to find ways out of a difficult situation on the road in which the autonomous algorithm cannot be divided independently.

Table 4. Disengagement rate – 3 best results in the year under review (in thousands of km)

2019	2020	2021	2022	2023	2024
Baidu 28,8	Waymo 47,9	AutoX 80,1	Cruse 153,4	Zoox 44,7	Zoox 283,2
Waymo 20,8	Cruse 45,2	Cruise 66,7	AutoX 79,6	WeRide 30,0	WeRide 33,7
Cruse 19,2	AutoX 32,4	Argo.AI 58,7	Zoox 49,1	Pony AI 27,3	Waymo 27,6

Source: based on 2019- 2024 Autonomous Vehicle Disengagement Reports 2019-2024 Autonomous Mileage Reports.

In the analyzed years, the rate was very diverse. The best rate was obtained by Zoox (in 2023, the driver took control of the vehicle on disengagement average every 290,000 km). However, it must be borne in mind that it is the companies that decide what to include and report as the driver taking control of the vehicle and in which areas the autonomous system is tested. In the case of Waymo, autonomous vehicles move in city centers and in the case of other companies in the areas of smaller towns or rural areas. Hence, in order to obtain reliable data, it is required that the technologies are tested in the same conditions.

5. CONCLUSION AND DISCUSSION

Autonomous vehicles seem to be a promising solution for improving road safety. Equipping autonomous vehicles with technical and technological tools that support the driver or allow the driver to take full control of the vehicle will facilitate this.

The presented research results indicate a further need to improve autonomous driving systems. This is indicated by the still-high rates of road accidents and system disengagement, at which point the driver takes control of the vehicle.

However, it is worth noting that road accidents decrease with increased vehicle autonomy. Although the rates of road collisions and shutdowns cannot be considered satisfactory, a year-on-year improvement in this area should be noted (especially until 2023). Methodological discrepancies should also be taken into account when determining them. Firstly, there is a general agreement that the number of road accidents involving drivers is underestimated. Secondly, road accidents are not caused mainly by autonomous vehicles. In most cases, cars driven by drivers hit autonomous vehicles. Various objects that appear on the road are also a problem. It is difficult for autonomous vehicle systems to predict driver behaviour, let alone prevent it. Therefore, it can be assumed that as the number of autonomous cars on the roads increases, the risk of road accidents will decrease, especially since autonomous vehicles will communicate with each other, thus preventing certain events resulting from a lack of concentration among drivers (rear-end collisions, front-end collisions of autonomous vehicles). In addition, the development of autonomous vehicle systems should consider learning the behaviour of drivers, pedestrians or cyclists, thus influencing the autonomous vehicle systems' learning (development) process.

Autonomous vehicles comply with road traffic regulations more than drivers (road signs, speed, and alcohol). Additionally, their operation is limited in speed, time of service or weather conditions. This means that even if a road collision occurs, the effects are relatively small compared to those of vehicles driven by drivers. This thesis is confirmed by data from insurance companies such as Swiss Re (one of the leading reinsurers in the world). The costs of road accidents generated by autonomous vehicles are lower than those caused by humans. The highest costs associated with road accidents concern people killed or seriously injured (service involvement, medical costs, etc.). And there are a few of these in the case of autonomous vehicles.

The decrease in the number of kilometres travelled by autonomous vehicles in 2024 may result from the loss of passenger confidence in this form of transport. This may have been influenced by October 2023, when one of the autonomous vehicles hit a pedestrian. This event resulted in the company's withdrawal, but it may also be affecting passenger confidence in autonomous vehicles.

A drawback of the autonomous vehicle system is the limited area of operation. This is due, among other things, to the necessary infrastructure that conditions the proper and safe operation of autonomous vehicles. Including motorways and expressways would be a desirable action conducive to more efficient use of autonomous vehicles. Drivers could spend long, monotonous routes in more comfortable conditions. Another concern is the possibility of uninterrupted use of services. The current system does not guarantee continuous operation, which is important in transport. Some companies restrict providing services at night during unfavourable weather (heavy rainfall, thick fog, etc.). The limited speed means that the service provided by autonomous vehicles is slower; the lack of convenient designated places for boarding and alighting compounds the problem.

The development of autonomous vehicles and their wider implementation are expected to reduce the number of road collisions and their severity in the long term. This will be correlated with the need for:

1. Increasing acceptance of autonomous vehicles. This will be related to the need to increase public awareness of road safety, including the indication that most often (over 90%) accidents are caused by improper human behaviour.

2. Further development of autonomous vehicles towards reducing road incidents involving them. In this respect, we can cite the example of air transport, where since the 1950s we have been observing a significant improvement in safety thanks to technological development Statistical Analysis)

3. Development of infrastructure, changes in legal regulations (the issue of changes in liability for road accidents) and social acceptance. The perception of autonomous vehicles could improve if autonomous solutions are cheaper than traditional driver-based solutions.

In summary, autonomous vehicle technology, although promising, requires continuous development, and its full use depends on the development of autonomous vehicle systems, infrastructure development and unification of regulations. The issue related to protection against cyberattacks of the autonomous vehicle system is crucial for the functioning of autonomous systems.

Funding: Co-financed by the Minister of Science under the "Regional Excellence Initiative".

Regionalna Inicjatywa Doskonałości
Ministry of Science and Higher Education Republic of Poland

REFERENCES

Abdel-Aty M., Ding S., (2024), A matched case-control analysis of autonomous vs human-driven vehicle accidents. *Nature Communications 15*.

Anderson J.M., Kalra N., (2016), Stanley K. D., Sorensen P., Samaras C, Oluwatola O.A., Autonomous Vehicle Technology: A Guide for Policymakers, *RAND Corporation*, Santa Monica, CA, USA.

Autonomous Mileage Reports 2019, 2020, 2021, 2022, 2023, 2024.

Autonomous Vehicle Disengagement Reports 2019, 20260, 2021, 2022, 2023, 2024.

Badue C., Guidolini R., Carneiro R. V, Azevedo P. Cardoso .V. B. Forechi A., Jesus L., Berriel R., Paixão T.M., Mutz F., Veronese L., Santos T. O., De Souza A. F., (2021), Self-Driving Cars: A Survey, *Expert Systems With Applications, vol. 165.*

Bathla, G., Bhadane, K.V., Singh, R.K.; Kumar, R., Aluvalu, R., Krishnamurthi R., Kumar, A.; Thakur, R.N., Basheer, S., (2022), Autonomous Vehicles and Intelligent Automation: Applications, Challenges, and Opportunities. *Mobile Information Systems*.

Bennett R., Vijaygopal R., Kottasz R., (2020), Willingness of people who are blind to accept autonomous vehicles: an empirical investigation, *Transportation Research Part F: Traffic Psychology and Behaviour, vol. 69.*

Blincoe L., Miller T., Wang J.-S., Swedler D., Coughlin T., Lawrence, B., Guo, F., Klauer S., Dingus T., (2023), The economic and societal impact of motor vehicle crashes, 2019, *National Highway Traffic Safety Administration.*

Bridgelall R.; Tolliver D., (2024), Deciphering autonomous vehicle regulations with machine learning. *Applied* Sciences, vol 14, issue 4.

Calvi A., D'Amico F., Ferrante Ch., Ciampoli L. B., (2020), Driving simulator study to assess driver performance during a car-following manoeuvre after switching from automated control to manual control, *Transportation Research Part F: Traffic Psychology and Behaviour*, *vol. 70,*

Chen J.J., Shladover S.E., (2024). Initial Indications of Driverless Automated Driving Systems Safety. *arXiv.*

Kusano K.D., Scanlon J.M., Chen Y-H., McMurry T.L., Chen R., Gode T., Victor T., Comparison of Waymo Rider-only crash data to human benchmarks at 7.1 million miles *(*2024*), Traffic Injury Prevention vol. 25, issue 1.*

Cummings M.L. Bauchwitz B., (2022), Safety Implications of Variability in Autonomous Driving Assist Alerting, *IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 8*.

Cummings M.L., (*2021), Rethinking the Maturity of Artificial Intelligence in Safety-Critical Settings. *AI Magazine, vol. 42, no 1.*

Di Lillo L., Gode T., Zhou X., Atzei M., Chen[e,] R., Victor T., (2024), Comparative safety performance of autonomous and human drivers: A real-world case study of the Waymo Driver. *Heliyon, vol. 10, issue 14.*

Ding S., Abdel-Aty, M. Wang D. Wang Z Zheng O., Barbour N., Yua R., (2023), Exploratory Analysis of the Crash Severity between Vehicular Automation (SAE L 2-5) with Multi-Source Data. *arXiv.*

dmv.ca.gov

Duvall T., Hannon E., Katseff J., Safran, B., Wallace, T.A. *(*2019), *New Look at Autonomous-vehicle Infrastructure, McKinsey & Company.*

ec.europa.eu/eurostat

Eriksson A., Stanton N. A., (2017), Driving Performance after self-regulated control transitions in highly automated vehicles*, Human Factors, vol. 59.*

Favarò F. M., Nader N., Eurich S. O., Tripp M. Varadaraju N.,. (2017), Examining accident reports involving autonomous vehicles in California*, PLoS One 12.*

Global Plan. Decade of Action for Road Safety 2021-2030, 2020), *WHO.*

Global status report on road safety 2023, (2023), *WHO.*

Global status report on road safety, (2023), *WHO.*

González D., A review of motion planning techniques for automated vehicles (2016), *IEEE Transactions on Intelligent Transportation Systems, vol. 17, no. 4.*

Harper C.D., Hendrickson C.T., Mangones S., Samaras C, (2016),. Estimating Potential Increases in Travel with Autonomous Vehicles for the Non-Driving, Elderly and People with Travel-Restrictive Medical Conditions. *Transportation Research Part C: Emerging Technologies, 72.*

https://www.nstlaw.com/guides/self-driving-car-statistics/

Hulse L.M., Xie H., Galea E.R., (2018), Perceptions of autonomous vehicles: relationships with road users, risk, gender and age, *Safety Science, vol. 102.*

Kalra N., Paddock S.M., (2016), Driving to safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability? *Transp. Res. Part A, vol. 94.*

Koopman Ph., (2023), Autonomous Ground Vehicle Safety: lessons to learn.

Koopman Ph., Wagner M., (2017), Autonomous Vehicle Safety: An Interdisciplinary Challenge, IEEE Intelligent Transportation Systems Magazine, vol. 9, issue 1.

Kusano K.D., Scanlon J.M., Chen Y-H, McMurry T.L., Chen R., Gode T., Victor T., Meyer S.F.; Elvik R., Johnsson E., (2021), Risk Analysis for Forecasting Cyberattacks against Connected and Autonomous Vehicles. *Journal of Transportation Security, vol. 14.*

Moody J., Bailey N., Zhao J., (2020), Public perceptions of autonomous vehicle safety: an international comparison, *Safety Science, vol. 121.*

Nagy V., Horváth B., (2020), The effects of autonomous buses to vehicle scheduling system, *Procedia Computer Science, vol. 170.*

nhtsa.gov/

Norris N., Emmanuel K., Boniphace K., Angela, E. K. (2023),, A comparative study of collision types between automated and conventional vehicles using Bayesian probabilistic inferences. *Journal of Safety Research, no. 84.*

Paden B., Čáp M., Yong S. Z., Yershov D., Frazzoli E., (2016), A Survey Of Motion Planning And Control Techniques For Self-Driving Urban Vehicles, *IEEE Transactions On Intelligent Vehicle, vol. 1.*

Penmetsa P., Sheinidashtegol P., Musaev A., Adanu E. K., Hudnall M., (2021), Effects of the autonomous vehicle crashes on public perception of the technology. *IATSS Research. vol. 45, issue. 4.*

SAE, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, (2021), *Society of Automotive Engineers (SAE), J3016.*

Safety V., (2023), Performance of the Waymo Rider-Only Automated Driving System at One Million Miles Trent Victor Waymo, LLC.

Sharma O., Sahoo N.C., Puhan N.B., (2021), Recent Advances in Motion and Behavior Planning Techniques for Software Architecture of Autonomous Vehicles: A State-of-the-Art Survey. Engineering Applications of Artificial Intelligence, vol. 101,

Singh S., (2015), Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey, NHTSA, Washington, DC.

Takacs A., Rudas I. J., Bösl D., Haidegge T., (2018), Highly Automated Vehicles And Self-Driving Cars [Industry Tutorial, IEEE Robotics & Automation Magazine 25, no. 4.

Tian L.-J., Sheu J.-B., Huang H.-J. (2019), The morning commute problem with endogenous shared autonomous vehicle penetration and parking space constraint, Transportation Research Part B: Methodological, vol. 123.

Wang J., Zhang L., Huang Y., Zhao J., (2020), Safety of Autonomous Vehicles, Journal of Advanced Transportation.

Wansley M.T., (2024), Regulating Driving Automation Safety. Emory Law Journal, vol. 73, issue 3.

waymo.com

Yan S., Huang C., He D., (2023), A comparison of patterns and contributing factors of ADAS and ADS involved crashes. Journal of Transportation Safety and Security. vol. 16, issue 9.

Yoganandhan A., Subhash S.D., Hebinson Jothi J., Mohanavel V., (2020), Fundamentals And Development Of Self-Driving Cars, Materials Today: Proceedings no 33, part 7.