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Traffic Accidents with Autonomous Vehicles: Type of Collisions, Manoeuvres and Errors of Conventional Vehicles' Drivers

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Abstract

Autonomous vehicles have the potential to dramatically reduce traffic accidents. This assumption is based on the fact that autonomous vehicles eliminate the impact of a human factor on the occurrence of a traffic accident. Autonomous vehicle' testing in real traffic conditions is carried out worldwide. In this paper, we analyzed traffic accidents with autonomous vehicles that occurred in the US state of California in the period from 2015 to 2017. In order to better recognize the characteristics of traffic accidents with autonomous vehicles, we were carried out a comparative analysis of traffic accidents with only conventional vehicles at locations where occurred traffic accidents with autonomous vehicles. During the analysis of traffic accidents, we have put emphasis on the type of collision, manoeuvres and errors of the drivers of conventional vehicles that led to the traffic accident. Applying statistical analysis, we were found that the type of collision "rear-end" more often in traffic accidents with autonomous vehicles. Types of collisions "pedestrian" and "broadside" were less in traffic accidents with autonomous vehicles. Drivers' manoeuvres of conventional vehicles do not differ depending on whether an autonomous vehicle is involved in the traffic accident. Drivers' errors of conventional vehicles that are more often in accidents with autonomous vehicles are "unsafe speed" and "following too closely". The obtained results were used to propose measures that will improve communication between autonomous vehicles and drivers' conventional vehicle.

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1. Introduction

Autonomous vehicles (AV) are expected to have a significant impact on traffic in the future. Predictions show that AVs will start to commercially produce by 2020s (Lavasani et al., 2016; Litman, 2018). Lavasani et al. (2016) predicted that if AVs became available in 2025, the market might reach about 8 million in 10 years in the United States of America. It is expected that the massive use of AVs will result by reducing crashes, ease congestion, improve fuel economy, reduce parking needs, bring mobility to those unable to drive (Fagnant and Kockelman, 2015). In addition to the traffic benefits, also expect significant economic benefits. With only 10% market penetration expected that autonomous vehicles will bring economic benefits that could be in the range of $27 billion in the United States of America (Lavasani et al., 2016).

Although AVs are in the testing phase and traffic accident sample is limited, some authors have already examined traffic accidents with AVs (Dixit et al., 2016; Favarò et al., 2018, 2017). The first paper that examined this topic (Dixit et al., 2016) included data on testing AVs in the period from September 2014 to November 2015 in the territory of the state of California. The authors of this paper analyzed 12 traffic accidents. In later papers, authors also analyzed traffic accident with AVs in the state of California, but only in different time ranges until March 2017 – 26 traffic accidents (Favarò et al., 2017) and until July 2017 – 30 traffic accidents (Favarò et al., 2018). According to the Californian Department of Motor Vehicles (CA DMV, 2018a) there were 129 traffic accidents with AVs until December 2018. Despite the great expectations regarding the positive effects of AVs on road safety, all papers have found that traffic accidents with an AV occur more often than accidents with a conventional vehicle (CV).

Considering a small sample of traffic accidents with AVs in the conducted analyzes did not put special emphasis on the type of collisions, manoeuvers and errors for the occurrence of accidents. Favarò et al. (2017) found that the most frequent type of collision is rear-end – front bumper of CV and rear bumper of AV. Also, it was found that in the most cases the vehicle speed was less than 10 mph. Applying advanced software packages, some authors analyzed the impact of the introduction of AV in everyday traffic on the number and types of collisions (Tibljaš et al., 2018). Simulating introduction of AVs (10% - 50% in traffic flow) on 4 roundabouts in Croatia recorded an increase of rear-end type crashes (Tibljaš et al., 2018). Similar findings determined by Papadoulis et al. (2019). Authors found that with the increase in the share of connected AVs in traffic flow noted decreasing in the number of conflicts, but the share of rear-end conflict increase. Hence, we can notice that AVs prone involvement in rear-end traffic accidents both in reality and simulation packages. However, AVs will have more significant effects on road safety when increase their participation in traffic. Rahman et al. (2019) analyzed the effects of the introduction connected vehicles lower level automation on road safety in terms of time exposed time-to-collision, time-integrated time-to-collision, time exposed rear-end crash risk index, lane changing conflicts, and the number of critical jerks. Authors have found that positive effects on road safety in arterial segments can be expected with a share of more than 30% of this type of vehicle. Similarly, positive effects on road safety in intersections can be expected with a share of more than 40%. Morando et al. (2018) analyzed the impact of autonomous vehicles on the number of conflicts at the signalized intersections and roundabouts. In this paper, it is found that a share of 50% of autonomous vehicles in traffic can reduce the number of conflicts at signalized intersections by 20% and roundabouts by 29%. By contrast, manoeuvers and errors for the occurrence of accidents with AVs still have not been the subject of research.

The aim of this paper is to determine the specific types of collisions, manoeuvers and errors of the drivers CVs in traffic accidents with AVs. For that reason, we have carried out a comparative analysis of traffic accidents with AVs and traffic accidents with only CVs at locations where traffic accidents with AVs occurred. In this manner, we improve the understanding of the relationship between AVs and other road users (primarily CVs drivers) in terms of traffic accidents. So far, this is very unknown (Dixit et al., 2016; Kyriakidis et al., 2017; Morando et al., 2018). The obtained results were used to propose measures that will improve communication between AVs and CV drivers. As a result of the measures would be a decrease in the number of traffic accidents with AVs.

2. Methodology

2.1. Data

In this paper, we analyzed traffic accidents occurred in the US state of California (counties San Francisco, Santa Clara and Contra Costa). Data on traffic accidents with AVs are collected by the Californian Department of Motor Vehicles and these data are publicly available (CA DMV, 2018a). According to the regulations applicable in the state of California, the manufacturer of the AV involved in a traffic accident should submit a Report of Traffic Collision Involving an Autonomous Vehicle to the Californian Department of Motor Vehicles within 10 days after the accident (CA DMV, 2018b). In this paper, data on traffic accidents with CVs were used from the Transportation Injury Mapping System (TIMS) database (TIMS, 2019) due to the mapping of traffic accidents in the state of California. The TIMS database was developed with the cooperation of the University of California – Safe Transportation Research and Education Center and the Californian Office of Traffic Safety.

We analyzed traffic accidents from January 2015 to December 2017. During the observed three-year period occurred 53 traffic accidents with AVs. These traffic accidents happened at 46 locations. At same locations occurred 247 traffic accidents with only CVs.

Overall, AVs have a greater risk of involving in traffic accidents with casualties per vehicles kilometres travelled. Risk of a traffic accident with only CVs with causalities per 10^8 vehicles kilometres travelled in three observed counties is 35. (TIMS, 2019). Based on Reports of Traffic Collision Involving an Autonomous Vehicle risk of a traffic accident with AVs with causalities per 10^8 vehicles kilometres travelled is almost 8 times higher and is 266. However, traffic accident with fatality in that AV involved has not occurred. Also, a traffic accident with only two AVs has not occurred.

2.2. Database correction

A total of 8 categories types of collisions were considered: "head-on", "side swipe", "rear-end", "broadside", "hit object", "overturned", "pedestrian" and "other". However, within a sample of only 9 accidents are "head-on" (7) and "overturned" (2), so these categories are merged with category "other". Therefore, in the final analysis, we considered 6 types of collisions.

From a total of 12 different manoeuvers of the drivers CVs which led to the occurrence of a traffic accident in the final analysis considered 8 manoeuvers. The subject of the research was the following manoeuvers: "stopped/slowing", "proceeding straight", "making right turn", "making left turn", "passing other vehicle", "changing lanes", "entering traffic" and "other". The remaining 4 types of manoeuvers are merged with the category "other" due to low frequencies: "making U-turn" (2), "backing" (3), "crossing into opposite lane" (1) and "parking manoeuvers" (4).

Also, we considered 12 most frequent errors which led to the occurrence of traffic accidents made by drivers CVs. However, in the final analysis, we considered the 9 most frequent errors of CVs drivers: "driving under the influence alcohol/drug", "traffic signals and signs violation", "unsafe speed", "unsafe lane change", "right of way violation", "pedestrian violation", "following too closely", "improper turning" and "other/unknown". Also, we merged categories of errors "unsafe lane change" (12) and "improper passing" (15) due to the similarity of errors and low frequencies. Remaining errors "driving on wrong side of road" (5) and "unsafe starting or backing" (7) merged with the category "other" due to low frequencies.

It is important to highlight missing values within some traffic accidents with only CVs for some variables.

2.3. Analysis

Due to the specificity of the variables and the sample size, examination of statistically significant differences in the distribution of types of collisions, manoeuvers and errors of the drivers CVs is performed by Pearson χ^2 (chi-square) test of independence. After determining statistically significant differences in variables, we performed examinations of statistically significant differences for each category of variables. Examination of statistically significant differences for each category is performed comparing specific category with all other categories (coded

as one category). In these cases, Pearson χ^2 test of independence is corrected by Yates's Correction for Continuity that compensates the estimated value of the χ^2 test due to the small number of dimension table 2x2 (Yates, 1934). If the minimum frequency requirement for variables in table 2x2 cells was not fulfilled, we used Fisher's Exact Probability Test. The threshold of statistical significance was set at the level of 0.05.

If there are statistically significant differences, we will calculate the effect size. The effect size for table 2x2 is expressed by φ (phi) coefficient, in other cases used Cramer's V coefficient. Cohen (1992) suggested that 0.1 be considered a "small" effect size, 0.3 represents a "medium" effect size and 0.5 a "large" effect size.

3. Results

In the first step, we analyzed the differences in the distribution of types of collisions depending on whether examined traffic accidents with AVs or traffic accidents or with only CVs (Fig. 1). Applying χ^2 test of independence, it is concluded that the distribution of accidents by types of collisions is statistically significantly different (χ^2 (5, 293) = 33.098, p < 0.001, V = 0.336). Analyzing the differences for each type of collision, there are statistically significant differences in the types of collision "rear-end", "broadside" and "pedestrian". Namely, type of collision "rear-end" is statistically significant more frequent in traffic accidents with AVs (χ^2 (1, 293) = 22.989, p < 0.001, φ = 0.289). By contrast, types of collisions "broadside" (F (293), p < 0.001, φ = -0.187) and "pedestrian" (F (293), p < 0.001, φ = -0.184) is statistically significant more frequent in traffic accidents with only CVs. Analyzing types of collisions "side swipe" (p = 0.719), "hit object" (p = 1.000) and "other" (p = 0.861) did not observe statistically significant differences.
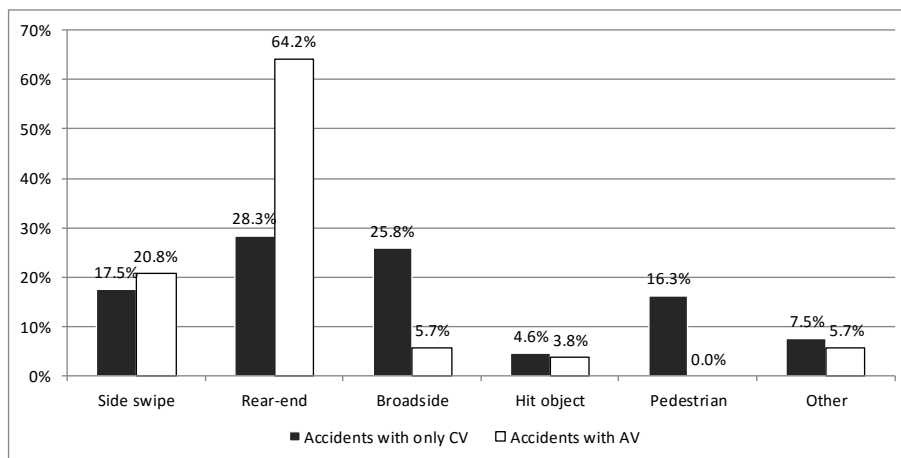

Fig. 1. Traffic accidents distribution by type of collision

Analyzing the manoeuvers of the drivers CVs, we found that the distribution of manoeuvers did not statistically significantly different, depending on whether examined traffic accidents with AVs or traffic accidents with only CVs (χ^2 (7, 279) = 13.718, p = 0.056). Also, there is no statistically significant difference for each particular manoeuvers of the drivers CVs (Fig. 2). Specifically, the statistical significance for each manoeuver is: "stopped/slowing" (p = 0.105), "proceeding straight" (p = 0.089), "making right turn" (p = 1.000), "making left turn" (p = 0.906), "passing other vehicle" (p = 0.108), "changing lanes" (p = 0.622), "entering traffic" (p = 0.897) and "other" (p = 0.120).

Distribution of errors of the drivers CVs is shown as 9 most frequent errors that led to the traffic accident (Fig. 3). Applying χ^2 test of independence, it is concluded that the distribution of accidents by errors of the drivers CVs is statistically significantly different depending on whether the accident occurred with AV (χ^2 (8, 284) = 50.128, p < 0.001, V = 0.420). Errors of the drivers CVs that often led to traffic accidents with AV are "unsafe speed" (χ^2 (1, 284) = 6.843, p < 0.01, φ = 0.166) and "following too closely" (χ^2 (1, 284) = 24.846, p < 0.001, φ = 0.314). By contrast, errors of the drivers CVs that rarely led to traffic accidents with AV are "right of way violation" (F (284), p

< 0.05, φ = -0.165) and "other/unknown" (F (284), p < 0.01, φ = -0.173). Analyzing other errors of the drivers CVs did not observe statistically significant differences: "driving under the influence alcohol/drug" (p = 1.000), "traffic signals and signs violation" (p = 0.808), "unsafe lane change" (p = 0.823) and "improper turning" (p = 0.524).
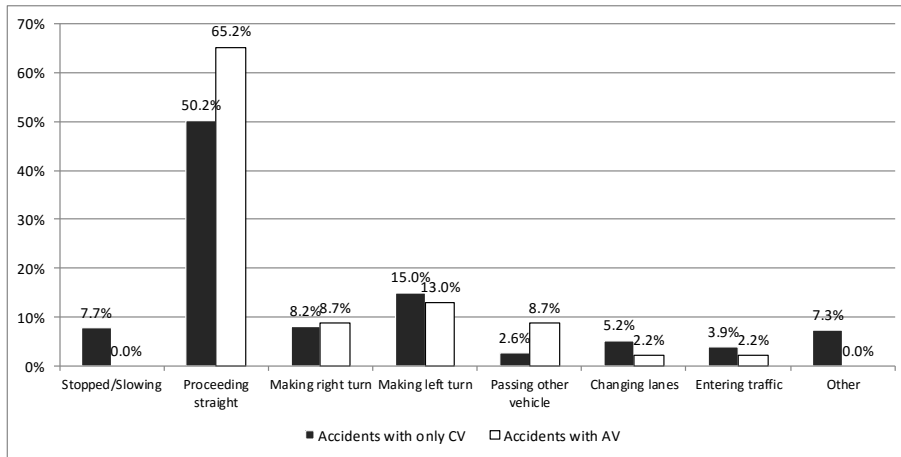

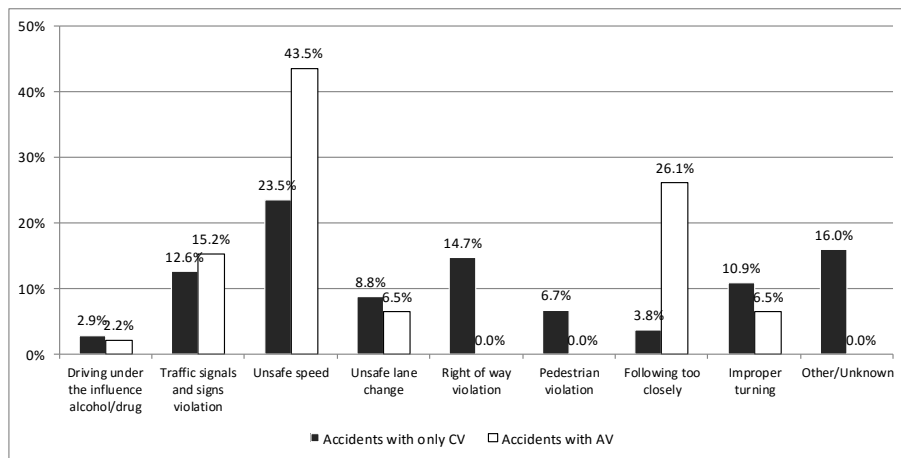Fig. 2. Traffic accidents distribution by manoeuvers of the drivers CVs

Fig. 3. Traffic accidents distribution by errors of the drivers CVs

4. Discussion

4.1. Type of collision

Analyzing the effect size, we noted the most significant difference in the type of collision "rear-end". Namely, the share of traffic accidents of this type of collision is higher in accidents with AVs (64.2%) as opposed to accidents with only CVs (28.3%). The assumption for this difference is that drivers of the CVs are not accustomed to the driving style of AVs in the convoy. AVs absolutely comply with traffic regulations and do not: speeding, aggressive driving, over-compensation, inexperience, slow reaction times, inattention and various other CV drivers' shortcomings (Fagnant and Kockelman, 2015). On the other hand, the self-reported percentage of speeding of the CV drivers in the settlement in 38 countries of the world is 61% (Meesmann et al., 2018). In reality, this percentage is higher. It is assumed that the initial introduction of AVs contributes to reducing the traffic flow and occurrence of congestion (Martínez-Díaz and Soriguera, 2018; Ntousakis et al., 2015; UK Department of Transport, 2016).

Consequently, the errors of the CV drivers due to aggressive driving in the convoy lead to the occurrence of traffic accidents "rear-end" type. This finding is consistent with Favarò et al. (2017). The increase in the share "rear-end" type of collision with the introduction of AV note Tibljaš et al. (2018) and Papadoulis et al. (2019) applying traffic simulation software packages.

The smaller effect size is observed within types of collision "broadside" and "pedestrian". These two types of traffic accident represent a total of 5.7% of accidents with AVs versus 42.1% of accidents with only CVs. The main reason for these results is the assumption that AV is more carefully approaching the intersections (Smith, 2012), in these locations "broadside" collisions most frequently occurred. Also, AVs are prone to frequent stops to let pedestrian right of way (Smith, 2012). Using complex systems for perceiving the environment (LiDAR - Light Detection and Ranging System, sensors, cameras), AV is able to locate and track stationary and moving objects in a very large area (Waymo, 2018). Combs et al. (2019) estimated that the use of these systems can reduce the number of traffic accidents with pedestrians up to 90%. Also, we can assume that these systems can provide very good sight distance at intersections for AVs. Although some authors have concerns about the impact of AV on the vulnerable road users safety (Brar and Caulfield, 2017; Sandt and Owens, 2017), we assume that the introduction of AVs will have a positive impact on their safety.

In other types of collision, we did not find statistically significant differences between traffic accidents with AV and accidents with only CVs. However, it should be noted that some types of accidents were merged into the category "others" and their differences could not be examined. In general, it can be noticed that the introduction of AVs has a positive impact on the distribution of types of collision, because the share of accidents that often have severe consequences ("broadside" and "pedestrian") decreases, while the share of accidents that usually have only damage consequences ("rear-end") increases.

4.2. Manoeuvers of the drivers CVs

Within so far conducted researches, manoeuvers of the drivers CVs were not in the focus of the authors. Based on analysis of the manoeuvers of the drivers CVs, we noticed that there is no significant difference in the manoeuvers depending on whether drivers of CVs involved in the accident with AV. This finding was expected, considering the small number of AVs on the roads and lack of adjustment driving task of CVs drivers for AVs movement. Also, this fact can be enjoyed by companies that testing AVs, because it shows that drivers of CV did not take more specific manoeuvers when they involved in accidents with AV.

4.3. Errors of the drivers CVs

Generally, there are significant differences in errors of the drivers CVs depending on whether they are involved in accidents with AV. The biggest effect size was observed within the error of the drivers CVs "following too closely". Namely, this error of the drivers CVs is significantly more frequent in accidents with AV. Similar results it is noted for the error of the drivers CVs "unsafe speed" with smaller effect size. The reason for these results is that drivers are not sufficiently accustomed to moving AV in the convoy, and consequence of these results is a higher rate of accidents "rear-end" type with AV. Namely, AVs gently accelerate and decelerate in order to provide greater comfort to their passengers (Le Vine et al., 2015; Ntousakis et al., 2015), while drivers of the CVs have a more aggressive driving style (Fagnant and Kockelman, 2015; Martínez-Díaz and Soriguera, 2018). In terms of traffic accident occurrence, the critical activity of AV is acceleration that is lower in comparison with the acceleration of CV. During the movement in a convoy, AV slowly starts the movement so drivers of CV are at risk of causing a "rear-end" traffic accident due to a more aggressive start of the movement.

A smaller effect size is observed in error of the drivers CVs "right of way violation". This error of the drivers CVs is significantly lower in accidents with AV. This finding shows that AVs with their defensive driving style (Waymo, 2018) are able to compensate error of the driver CVs "right of way violation". Although a sample of traffic accidents with AV small, this finding is very encouraging.

Also, significant differences are noted on the error of the driver CVs "other/unknown". This is a consequence of incomplete and inaccurate database of traffic accidents with only CVs. Namely, for some traffic accidents with only CVs were not found an error of the driver CVs that led to the accident. The reason for this is the existence of traffic

accidents that one of the participants left the scene of a traffic accident or the official person did not want to define an error. By contrast, based on the Reports of Traffic Collision Involving an Autonomous Vehicle, if there were an error of the driver CV, we always determined it.

Within the other errors of the driver CVs, we did not find statistically significant differences between traffic accidents with AV and accidents with only CVs. However, it should be noted that no traffic accidents with AV were caused due to the specific error "pedestrian violation". This finding shows that AVs satisfactory compensates both errors of the driver CVs and errors of pedestrians. On the other hand, it is noticed more often error of the driver CVs "traffic signals and signs violation" in a traffic accident with AV. This finding suggests that the AVs worse compensate risk for the other road users if at the same time is a defined traffic signalization.

5. Conclusion

The aim of this paper is to determine the specific features of traffic accidents with AVs. It is important to note that this paper did not analyze the frequency of traffic accidents with AV, but their distribution of types of collisions, manoeuvers and errors of the drivers CVs. In total, we analyzed 300 traffic accidents with AV and only CVs on a total of 46 locations in the state of California. It is important to highlight that AVs is still in the testing phase, therefore the traffic accident sample is limited and also the technology could further improve.

The three main conclusions of the research reported in this paper can be summarized as follows:

- Introduction of AVs reduce the share of types of collision "broadside" and "pedestrian".
- AVs are able to compensate error of the driver CVs "right of way violation".
- Introduction of AV increase the share of "rear-end" traffic accident due to errors of the driver CVs "following too closely" and "unsafe speed". The reason for this conclusion is that drivers are not sufficiently accustomed to dynamic characteristics of AV (acceleration and deceleration) in the convoy.

Reducing the negative consequences of the introduction of AV can be done by applying different measures. First, the definition of unique marks for AV has the potential to reduce their involvement in the "rear-end" type of traffic accidents. For example, we suggest the sign on the rear of the vehicle that marks AV and warns CV drivers to be more careful. Also, it is important to educate the population about the characteristics of AV in traffic flow. This would raise the population's awareness of the differences in dynamic characteristics that have AV. In addition, it is necessary to reconsider the dynamic characteristics of AV and the ability to adapt to different traffic conditions. Furthermore, Morando et al. (2018) suggest shorter headways and more aggressive acceleration. These measures have the potential to improve communication between AV and CV drivers and reduce the number of traffic accidents with AVs.

It is important to highlight the limitations of this study. Because AV is still in the testing phase, the number of traffic accidents with AVs is small. Also, Reports of Traffic Collision Involving an Autonomous Vehicle is filled by the staff of testing company opposite to data of traffic accident with only CVs that is gathered by the police. In addition, AVs are not recognized as a category of vehicles that have involved in traffic accidents in many states.

Increase the sample of traffic accidents with AV creates a lot of opportunities for carrying out future research. A larger sample will enable a more comprehensive analysis of types of collisions, manoeuvers and errors of the drivers CVs. In future papers, special emphasis should be put on the mode of movement of autonomous vehicles. Also, it is important to examine how road (road type, number of traffic lanes, traffic signalization etc.) and environmental factors (weather, temperature, visibility etc.) effect on traffic accidents with AVs.

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