Vida and Török
European Transport Research Review (2023) 15:17
https://doi.org/10.1186/s12544-023-00591-4

European Transport Research Review

ORIGINAL PAPER

Open Access

Expected effects of accident data recording technology evolution on the identification of accident causes and liability

Gábor Vida[1*] and Árpád Török[1]

Abstract

Background The classic accident reconstruction process is based on information recorded manually at the scene and gathered from witness statements. Liability cannot always be determined if no objective data are available, especially for accidents at traffic lights. Even Event Data Recorder (EDR) data (speed, braking, gas/brake pedal operation, etc.) will not improve the assessment of such a liability situation significantly, since vehicle movements cannot be synchronized in time with the phase plan of the intersection control. This problem could be solved if globally synchronized time data (Global Navigation Satellite Systems) were available, or a camera recorded the signal of the given traffic lights. In our study, the technology that goes beyond EDR data was defined as EDR+ data recording technology.

Aim The aim of this article is to rank the assessability of different types of accidents through the statistical analysis of a publicly available database, taking into account the different data recording technologies.

Methods An in-dept statistical analysis of 124 accidents and the corresponding liability investigations is provided. Also, analysis is carried out on estimated levels of assessability if modern data recording technologies had been applied for the same accident set.

Results This study reveals the impact of the introduction, spread and wide application of the examined types of data recording technology on assessability. It is also explored what kind of data recording technology would be necessary to ensure the level of assessability required to establish liability for accidents.

Conclusion The flexible framework presented here is suitable for comparing the assessability of road accidents according to accident type and data recording technology.

Keywords Event Data Recorder (EDR), Accident data, Road accident assessability, Statistical analysis, Non-parametric tests

1 Introduction

The continuous enhancement of road safety is considered as one of the primary goals of both the World Health Organization (WHO) and the European Union (EU) [7, 24]. Consequently, it is also a priority for Hungary to increase the level of traffic safety [10].

Moreover, advanced driver assistance systems and automated vehicle modules have excellent safety enhancing potentials, in line with international development goals [5]. Solely by allocating more resources to safety in the development process of modern vehicle and traffic

*Correspondence:
Gábor Vida
vida.gabor@kjk.bme.hu
[1] Department of Automotive Technologies, Faculty of Transportation Engineering and Vehicle Engineering (KJK), Budapest University of Technology and Economics (BME), Műegyetem rkp. 3, Budapest 1111, Hungary

systems, accident risk is continuously decreasing [1, 9, 15].

Despite diminishing accident risks, the deep analysis of occurring accidents will still remain of utmost importance, so that their exact causes could be revealed, and thus the necessary interventions and development directions could be determined. Furthermore, a detailed analysis of accident causes is also indispensable for answering the questions of liability in traffic accidents [6]. As a consequence, the collection of data on the causes of road collisions and their thorough analysis aiming to draw conclusions and to determine appropriate measures are also listed as important goals in the Valletta Declaration on Road Safety [5]: Points 3, 8 g).

The degree to which the causal relations of accidents and consequently, the liability of parties can be assessed differs for various accident types [12, 22]. The complexity of the causal chain increases as the automation level of vehicles is enhanced. Consequently, the role of the human factor in the driving process is to diminish, while the role of other factors is expected to increase. This may lead to a regrouping of liability relations (e.g. liability of the manufacturer, the supplier) [18].

The problem of liability is closely connected to accident reconstruction: based on well-established accident reconstruction calculations, liability can be determined with high certainty. The higher the quantity and quality of basic accident data are, the more assessable accident processes will be [4].

The present study explores the effects of basic data available for calculations and of data recording technologies on the accident reconstruction process, and thus on the possibility of determining liability. It is examined how assessability is expected to improve due to the introduction, spread, and wide application of certain data recording technologies. The types of data recording technologies required to ensure the expected level of assessability are also determined.

After reviewing the relevant literature, the methods followed in this study are described, and the accident database [21] is introduced. The accident types are illustrated by example accidents. Then the influence of data recording technologies on the assessability of accidents in our database is analyzed.

We have developed a methodological framework to evaluate the effects of future changes in accident forms and data recording technologies on accident assessability. Accordingly, the new method makes it possible to investigate, e.g., new forms of accidents arising with the appearance of autonomous vehicles and the effects of new data recording technologies on accident assessability [17].

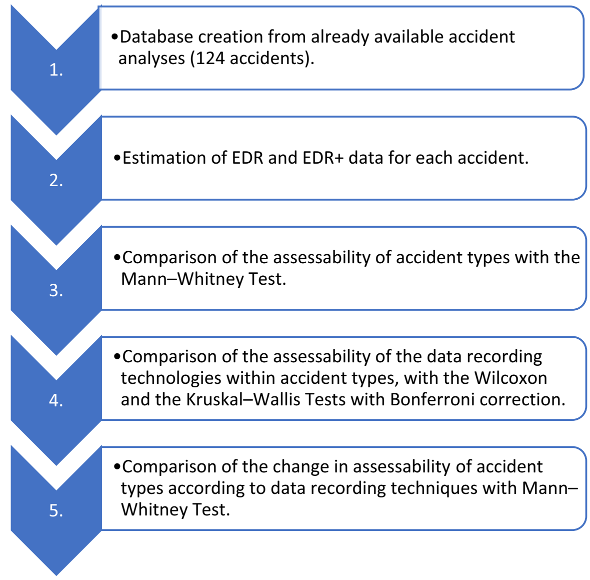

Fig. 1 Steps of the methodology presented here

2 Data and methods

This section describes the structure of the database used for our analysis and the accident types. The statistical methods used are introduced. The aim of the analysis is to reveal how various data recording technologies might influence the assessability of road accident causes and processes. The following flowchart depicts the methodological steps of the present research (Fig. 1).

2.1 Accident database

The databased used here was compiled from the data of 124 accidents which we had examined earlier as forensic experts [21]. The data in the database resulted from an in-depth analysis of the given accidents (full accident reconstruction, expert evaluation, simulation calculations, etc.), which in this form can be considered unique in this research field. Of course, more data would lead to a more accurate conclusion. At the same time, the applied statistical tests can also be used to comparisons of small sample sizes, so the conclusions drawn can be considered reliable.

2.1.1 Accident assessability

Collisions were grouped according to how much the accident process can be reconstructed and how well the cause of the accident and the liability for it can be determined.

An accident process can either be

- fully assessable (can be reconstructed to the required degree);

- or not or just partially assessable (cannot be reconstructed to the required degree).

The cause of the accident and liability could be

- determined;
- or not determined.

It must be highlighted that it is not the competence of the technical forensic expert to determine liability. From a technical point of view, liability is assessable if the cause of the accident can be determined, and a mistake in driving technique of the parties could be identified as a cause. Based on the above two parameters, accidents were put into one of the following four categories (Table 1).

- The assessability of a given accident is **Level 1**, if the accident process could not be reconstructed, or could be reconstructed only partially, and the cause of the accident or liability could not be determined.
- The assessability of a given accident is **Level 2**, if the accident process could be reconstructed to the required degree, but the cause of the accident or liability could not be determined.
- The assessability of a given accident is **Level 3**, if the accident process could not be reconstructed, or could be reconstructed only partially, but the cause of the accident or liability could be determined.
- The assessability of a given accident is **Level 4**, if the accident process could be reconstructed, and also the cause of the accident or liability could be determined.

2.1.2 Analyzed accident data recording technologies

This research investigates the assessability of accidents not only by looking at data collected in the traditional ways, but also by testing how the assessability level would change if data collected by EDR technology were available. The availability of data recorded by highly advanced data recording technologies applied in highly automated vehicles was also tested. In addition to data types of the DSSAD (Data Storage System for Automated Driving—video recordings, location, speed, and/or surroundings of a vehicle; [8, 20], further data types were considered which are required for controlling highly automated vehicles, e.g. the data flow between the electronic control units (ECUs) have also been considered. This third data category, which is related to automatic vehicles (AVs), is labelled EDR+ in this article. The three categories are discussed in detail below. Additionally, we also checked what kind of data exceeding the EDR+ category would have been required to reach Level 4 assessability for the given accident.

In sum, the data available for the accidents analyzed were recorded using the traditional data recording technologies. After analyzing the assessability of each accident, it was determined how assessability values would change if more advance data recording technologies (EDR, EDR+, respectively) had been used. Concerning the **traditional** (data recording technologies) category, in addition to data recorded at the accident scene by the police, data obtained later in the police investigation process (e.g. witness testimonies) were also considered.

Table 1 Accident assessability levels

Accident cause liability	Accident process	
	Not or partly determinable	Fully determinable
Not determinable	Level 1	Level 2
Determinable	Level 3	Level 4

2.1.3 Accident types

The 124 accidents analyzed here proved that the assessability of road collisions require categories that make it possible to separate factors that fundamentally influence assessability, such as: accident cause (e.g. roadway departure), location (e.g. crossroads with traffic lights) or the movement of the vehicle (turning or going straight). Thus the categories were established from the perspective of assessability. Naturally, not all theoretically possible accidents can be fit easily into this categorization, but the overwhelming majority of cases can be assigned to one of the following types [13, 19].

1. **Destabilization** or **roadway departure** of a vehicle causes the accident.
2. **A vehicle turning left** collides with a vehicle overtaking it.
3. **A turning vehicle** collides with another vehicle going straight.
4. **Head-on collision** occurs when a vehicle goes over to the lane serving the opposite direction.
5. At least one of the affected vehicles **changes the lane** immediately prior to the accident or during the accident process.
6. A **rear-end collision** occurs when a vehicle crashes into the one in front of it, or at least one of the vehicles is **backing**.
7. For collisions in crossings with **traffic lights**, the colour of the lights at the time of the accident must be determined.

The aim of the categorization was to determine the major contributory factors that influence the assessability of a given accident. Although generally a given accident could be assigned to more than one category, each collision was put into the most characteristic group. Thus disjoint sets were created, each accident was assigned to one single category.

Explanatory figures and descriptions of the investigated types of accidents can be found in "Appendix 1".

2.2 Methodology

The examined data recording technologies (traditional, EDR, EDR+) are denoted T_0, T_1, and T_2, respectively. As a starting point, all accidents in the database were assessed based on data recorded by traditional techniques (T_0). For the next steps, it was supposed that EDR (T_1) and also EDR+ (T_2) data were available. The accident process was determined again with the extended data sets, and the change in the level of assessability was determined.

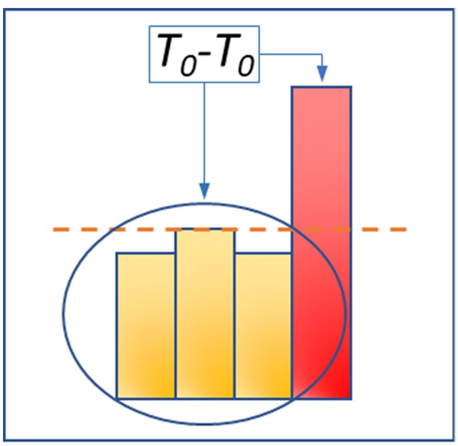

Fig. 2 Comparison of the assessability of one accident type to that of all the others, data are recorded traditionally. (Red—examined accident type, data recorded by T_0; yellow—all other accident types, data recorded by T_0.)

The assessability of accidents was compared in several ways. For the first three tests, a pairwise comparison of independent, non-normally distributed samples was carried out, by applying the Mann–Whitney Test [14, 16].

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 \quad (1)$$

$$U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_2 \quad (2)$$

$$Z = \frac{U - \frac{n_1 n_2}{2}}{\sqrt{\frac{n_1 n_2 (n_1+n_2+1)}{12}}} \quad (3)$$

where n_1, number of elements in Sample 1; n_2, number of elements in Sample 2; R_1, sum of the ranks in Sample 1; R_2, sum of the ranks in Sample 2; U_1, test function value for Sample 1; U_2, test function value for Sample 1; Z, value of function approaching the normal distribution.

In Figs. 2, 3, 4, 5, 6, 7, 8, 9 below illustrate what categories were compared in the tests. The tests make it possible to reveal how assessability changes for a given accident type compared to other categories if data recording technologies develop. In the figures, individual columns represent the assessability of a given accident category, the

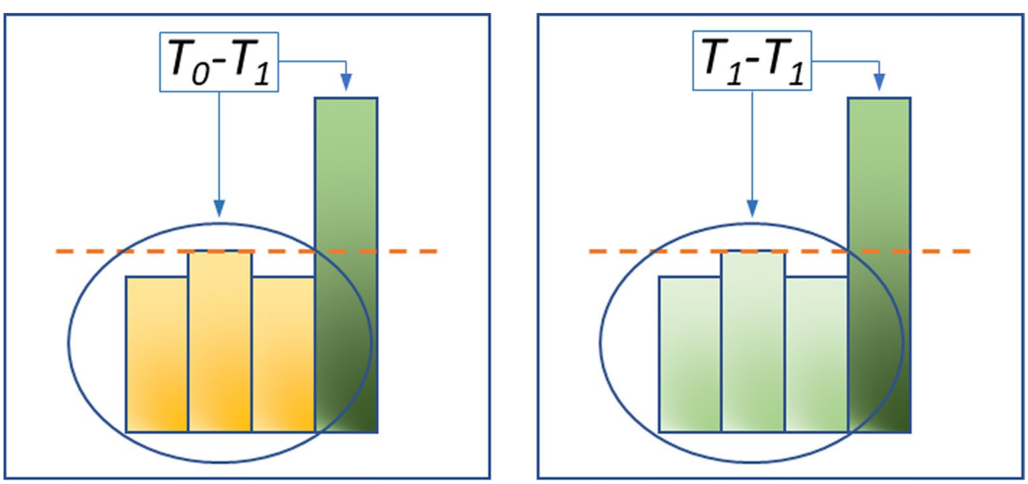

Fig. 3 Comparison of the assessability a given accident type, with EDR data recording and the average assessability of a type in the case of traditional versus EDR technologies. (Dark green—examined accident type, data recorded by T_1; yellow—other accident types, data recorded by T_0; light green—other types, data recorded by T_1.)

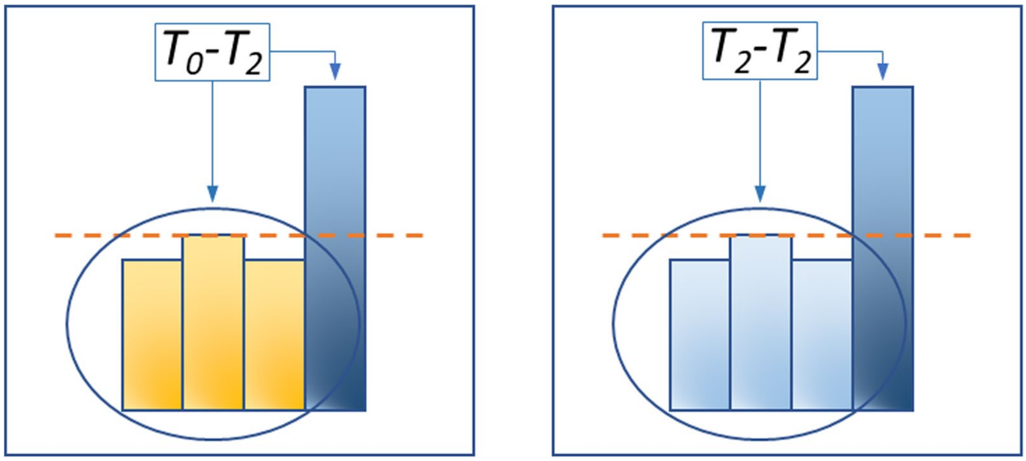

Fig. 4 Comparison of the assessability a given accident type, with EDR+ data recording and the average assessability of a type in the case of traditional versus EDR+ technologies. (Dark blue—examined accident type, data recorded by T_2; yellow—other types, data recorded by T_0; light blue—other types, data recorded by T_2.)

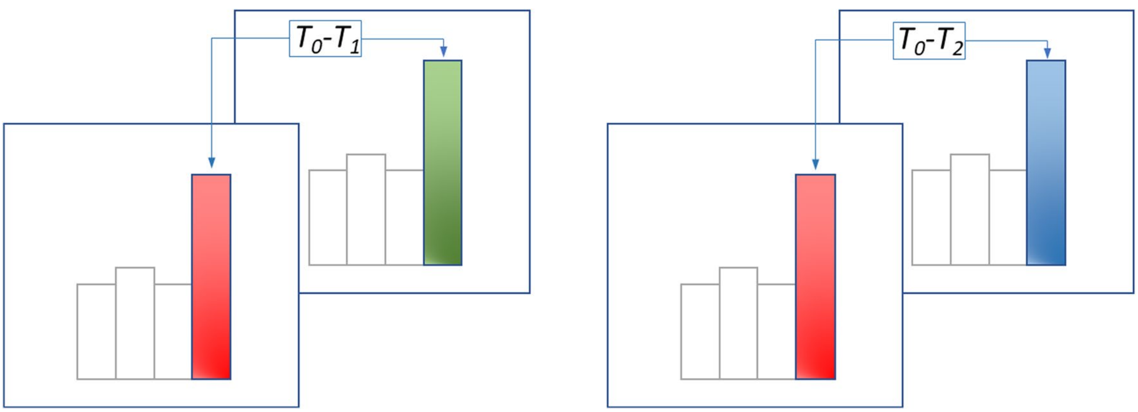

Fig. 5 Comparison of the assessability of data recording technologies for a given accident type. (Red—T_0; dark green—T_1; dark blue—T_2.)

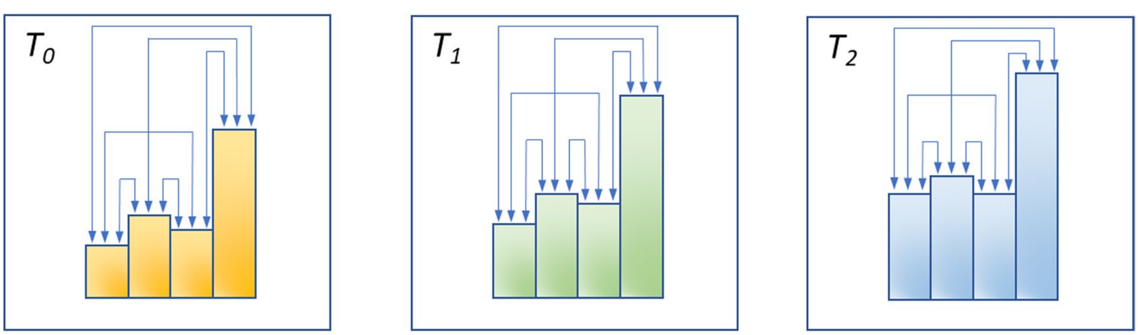

Fig. 6 The assessability of accident types according to data recording technology with Kruskal–Wallis Test. (Yellow—T_0, green—T_1, blue—T_2)

colours encode the data recording technology, which is also marked by labels T_0, T_1 and T_2 (denoting traditional, EDR and EDR+ technologies, respectively).

For the comparisons, a given subset is chosen from the databased (e.g. Accident Type 1, T_0 data recording technology), and assessability is compared to the relevant total set (e.g. all accident types, T_0 data recording

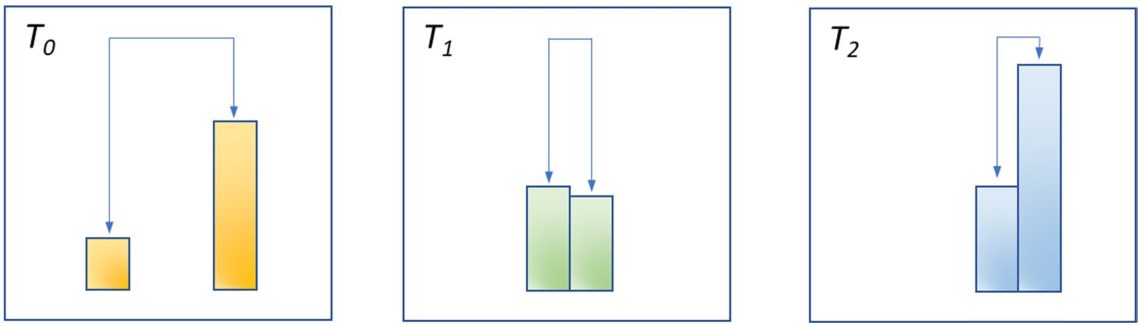

Fig. 7 Comparison of pairs with a significant difference with Mann–Whitney Test. (Yellow—T_0, green—T_1, blue—T_2)

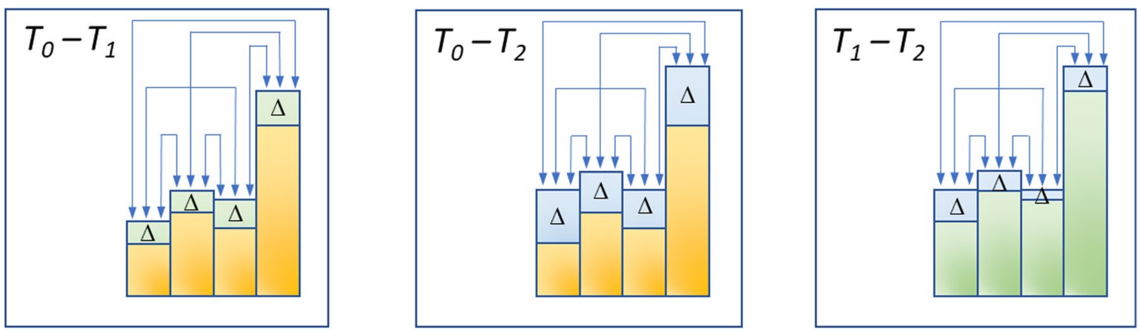

Fig. 8 The assessability change (Δ) of accident types according to the development in data recording technology with Kruskal–Wallis Test. (Yellow—T_0, green—T_1, blue—T_2)

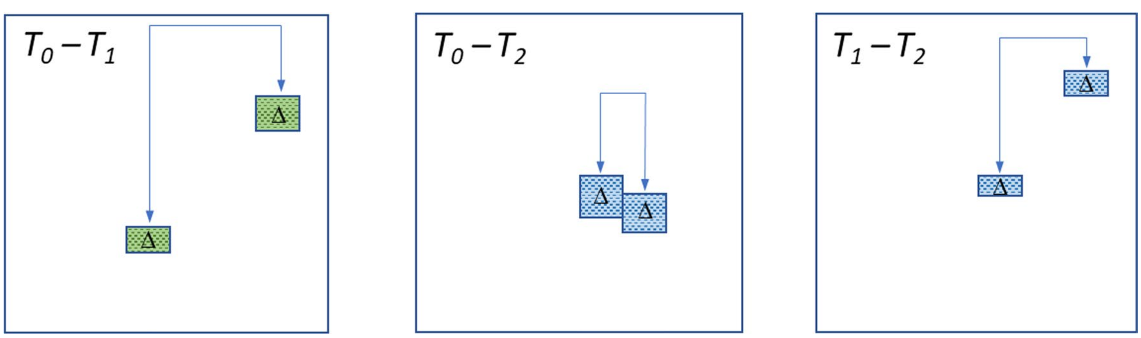

Fig. 9 The comparison of significantly different changes (Δ) with the Mann–Whitney Test. (Yellow—T_0, green—T_1, blue—T_2)

technology) and also to the relevant complementary set (e.g. Accident Types 2–7, T_0 data recording technology). In Figs. 2, 3, 4, 5, 6, 7, 8, 9, the dashed line represents comparison with the relevant total set, while the ellipsis illustrates comparison with the complementary set. In the course of our investigations, following the general methodology, we compared the investigated accident category with the group representing the population. During the comparison, the group representing the population may include all accident categories, including the investigated accident category (total set), or all accident categories without the investigated accident category (complementary set). To avoid drawing false conclusions, we performed both types of comparisons in our analyses.

At first, the assessability of the different accident types was compared to that of all the other accident types, given that data are recorded by T_0.

Then, we compared the assessability of the different accident types concerning the average assessability for T_0 and T_1 techniques, respectively.

In the next test, we compared the assessability of the different accident groups concerning the average assessability of T_0 and T_2 techniques, respectively.

In the next step, we analyzed the deviation between T_0 and T_1, T_2 data recording technologies by accident types.

The pairwise comparison of connected groups with non-normal distribution was carried out with the Wilcoxon Test [23]: value pairs of the samples are matched with the signs of the difference between the sample value pairs, and sample values are summed, distinguishing between negative and positive values (W^+, W^-).

$$W^+ = \sum_{Y_i - X_i > 0} R_i \tag{5}$$

$$W^- = \sum_{Y_i - X_i < 0} R_i \tag{6}$$

$$W = W^+ - W^- \tag{7}$$

In order to rank the assessability of accident types, a group comparison was carried out for the various data recording technologies (T_0, T_1, T_2). In order to diminish the probability of a Type I Error arising from the analysis of multiple hypothesis, the results of the following pairwise comparisons were statistically corrected.

Similarly to the previous methodological step, to rank the change (Δ in Figs. 8, 9) in the assessability of accident types, a group comparison was carried out for the various data recording technologies (T_0, T_1, T_2). In order to diminish the probability of a Type I Error arising from the analysis of multiple hypothesis, the results of the following pairwise comparisons were statistically corrected.

The Kruskal–Wallis Test was applied in order to compare independent groups with a non-normal distribution [11].

$$H = (N-1)\frac{\sum_{i=1}^{g} n_i(\overline{r}_{i.} - \overline{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i}(r_{ij} - \overline{r})^2} \tag{7}$$

where n_i, is the number of elements in the ith sample; r_{ij}, is the rank (among all elements) of the jth element in the ith sample; N, is the number of elements across all groups; $\overline{r}_{i.}$, is the average rank of the ith sample; $\overline{r}$, is the average rank of all the r_{ij} in the unified sample; g, is the number of samples.

In order to minimize the Type I Error, the Bonferroni Correction was used. The aim of the Bonferroni correction is the correct the unfavourable effect of the Type I error, which increases when comparing groups [2]. When multiple hypothesis tests are applied simultaneously, the probability of dropping the null hypothesis erroneously. In order to avoid this, the significance level *(α)* is lowered proportionally to the number of hypothesis tests (m). Consequently, the null hypothesis is dropped if for the value p_i of the ith hypothesis test ($p_i < \frac{\alpha}{m}$) proves to be true.

The applicability of the Bonferroni correction is supported by the following inequity [3], where m_0 marks the number of true null hypotheses.

$$EF = P\left\{\bigcup_{i=1}^{m_0}\left(p_i \leq \frac{\alpha}{m}\right)\right\} \leq \sum_{i=1}^{m_0}\left\{P\left(p_i \leq \frac{\alpha}{m}\right)\right\} = m_0\frac{\alpha}{m} \leq \alpha \tag{8}$$

3 Results and discussion

3.1 Evaluation of the current situation—traditional data recording

The following analysis compared the assessability of each accident type to that of the complementary set and the unified, total set. The rank averages of the examined sets were analyzed using the Mann–Whitney Test, as two independent groups were compared with non-normal distributions.

If the p value of the applied statistical test is lower than $\alpha = 0.05$ (i.e. $p < 0.05$), the H_1 hypothesis is accepted.

In the present case, Sample 1 is the set of the examined accident type, while Sample 2 is the complementary set, and the whole set of the accidents. The results of the statistical tests are given in Table 2.

The values in Table 2 prove that the assessability of categories 5 and 7 is significantly lower than that of other accident types and also than that of the whole set of accidents for the T_0 technique. Accidents occurring while lane changing or at crossings with traffic lights are considerably less assessable than other accident types.

Table 2 The assessability of accident types—T_0—*p* values of the Mann–Whitney Test

Accident type	1. Complementary set *p* values	2. Total set *p* values
1	0.9291	0.9209
2	0.2273	0.2584
3	0.9993	0.9915
4	0.2339	0.2584
5	0.007413*	0.02168*
6	0.5258	0.5222
7	0.03809*	0.05073*

Values below the significance level are indicated with an asterisk (*)

The reason for this is that the data recorded after the collision involving lane change are usually insufficient for determining the route of the given vehicle prior to the crash. At the same time, for determining the liability for the collision, it is crucial to decide which driver started the given maneuver earlier in a way that the other driver could sense it.

As for accidents in crossings with traffic lights, responsibility crucially depends on the fact which driver entered the crossing when the traffic lights were green. However, the data recorded at the accident site are generally not sufficient for determining this.

3.2 Forecast—EDR technology

The aim of this step of the analysis was to estimate how much accident assessability would increase if EDR data were available. For this, the assessability of a given accident type using T_0 and T_1 data was compared to the assessability of the complementary set without T_1 data, and the total set without T_1 data, respectively.

Furthermore, it is also estimated how assessability will increase when T_1 technology is spread. For this, the above comparisons are carried out, but the availability of T_1 data is supposed for all sets (i.e. the given type, the complementary set, the total set of accidents).

In Table 3, Columns 1 and 3 show the *p* value for the comparison of the assessability of the given accident type set with T_1 data and that of the complementary set (without and with T_1 data, respectively). Columns 2 and 4 show the *p* value for the comparison of the assessability of the given accident type set with T_1 data and that of the total set (without and with T_1 data, respectively).

For Type 5 accidents, the inclusion of T_1 data would improve assessability (cf. Columns 1 and 2 in Table 2). This result is in line with expectations. EDR data make it possible to reconstruct the route of vehicles prior to the collision. Consequently, the accident is more assessable.

However, as for Type 7 accidents, even data provided by the T_1 technology prove insufficient to determine which vehicle entered the crossing while the traffic lights were green or red. Consequently, the assessability of such accidents is not enhanced.

Moreover, due to the general improvement in assessability owing to the EDR technology, the assessability of Type 5 (lane change) accidents is expected to stay below the general level of assessability (Columns 3 and 4 in Table 3). The same columns prove that the assessability level of Type 7 (traffic lights) accidents is not enhanced by the introduction of EDR technology.

3.3 Forecast—EDR+ technology

The following step in the analysis aimed to explore the extent to which the availability of T_2data would further enhance the assessability of accidents. In this process, the assessability of a given accident type using data from $T_0$and T_2 systems was compared to the assessability of the complementary set without T_2 data, and the total set without T_2 data, respectively. Furthermore, it is also estimated how the assessment of accident types would improve if T_2 data were widely available. In this latter test, the assessability of a given accident type is compared to that of the complementary set and the total set provided that T_0 and T_2 data are available for each element of the sets.

In Table 4, Columns 1 and 3 show the *p* value for the comparison of the assessability of the given accident type set with T_2 data and that of the complementary set (without and with T_2 data, respectively). Columns 2 and 4 show the *p* value for the comparison of the assessability of the given accident type set with T_2 data and that of the total set (without and with T_2 data, respectively).

For each examined accident type, the inclusion of T_2 data would make assessability satisfactory compared to assessability of T_0 methods (cf. Columns 1 and 2 in Table 2). However, as the assessability of all accident

Table 3 The estimated assessability of accident types with T_1 data—*p* values of the Mann–Whitney Test—values below the significance level are indicated with an asterisk (*)

Accident type	1. Complementary set without EDR data	2. Total set without EDR data	3. Complementary set with EDR data	4. Total set with EDR data
1	0.9905	0.9892	0.6452	0.6397
2	0.9992	0.9996	0.555	0.5471
3	0.9999	0.9999	0.9954	0.9699
4	0.9939	0.9937	0.3884	0.3971
5	0.6849	0.8104	0.002481*	0.007259*
6	0.9999	0.9999	0.9091	0.8635
7	0.03809*	0.05073*	0.0009551*	0.00177*

Table 4 The estimated assessability of accident types with T_2 data—*p* values of the Mann–Whitney Test—values below the significance level are indicated with an asterisk (*)

Accident type	1. Complementary set without EDR + data	2. Total set without EDR + data	3. Complementary set with EDR + data	4. Total set with EDR + data
1	0.9993	0.9992	0.000001369*	0.00007869*
2	0.9999	0.9999	0.8097	0.7896
3	0.9999	0.9999	0.9135	0.8707
4	0.9999	0.9999	0.1303	0.1678
5	0.9999	0.9999	0.8169	0.7954
6	0.9999	0.9999	0.8369	0.8115
7	0.9999	0.9999	0.04746*	0.07278*

Table 5 Assessability of different accident types according to the level of available data—*p* values of the Wilcoxon Test

Accident type	1. Effect of the availability of EDR data (T_1) on assessability	2. Effect of the availability of EDR + data (T_2) on assessability
1	0.3002*	0.1352*
2	0.003158	2.13E-09
3	0.000233	2.287E-14
4	0.03634	0.0001338
5	0.01393	1.552E-09
6	0.0002826	2.576E-11
7	0.5296*	0.001293

Values over the significance level are indicated with an asterisk (*)

types increases if T_2 data are available, the assessability of types 1 and 7 prove to be lower than the average assessability of the whole set (cf. Columns 3 and 4 in Table 2). The reason for this is that some accidents belonging to these types cannot be fully reconstructed even if T_2 data were available for all participants.

3.4 Forecast—comparison of actual and future assessability by accident type

The next step of the analysis compared the assessability of a given accident type according to the three data category: (i) T_0; (ii) T_0+T_1; (iii) $T_0+T_1+T_2$. The two matched samples with non-normal distribution were compared using the Wilcoxon Test.

The results of these statistical test are given in Table 5. If the baseline assessability is not significantly lower than estimated assessability if T_1 or T_2 data are available, the values are underlined.

If data recording is expanded by the T_1 technology, the assessability of accident Types 1 and 7 does not improve significantly compared to the baseline case.

As far as accident Type 1 is concerned, these collisions can be assessed to a satisfactory degree even based on T_0 data. Consequently, for a significant increase in their assessability, extra information is required, which cannot be obtained by EDR systems. Such data could be collected by further individual data recording systems (e.g. a driver monitoring system).

Concerning accident Type 7, the EDR system does not record data that would significantly enhance the assessability of such collisions compared to the baseline case. However, owing to the GPS system, data collected by the EDR+ technology ensures the satisfactory assessability for this accident type.

3.5 Groupwise comparison of the assessability of accident types according to data recording technology

In the next step, the groupwise comparison of the assessability of accident types was carried out: (i) T_0; (ii) T_0+T_1; (iii) $T_0+T_1+T_2$. This comparison made it possible to rank the assessability of different accident types for a given data recording technology. In this case, the groupwise comparison of independent samples with non-normal distribution was carried out, thus the Kruskal–Wallis Test was applied.

As a multiple hypothesis tests were carried out, in order to diminish the probability of Type I error, the significance level of the test was determined using the Bonferroni correction. If the *p* value of the statistical test is lower than the corrected α ($p<\alpha_{corr}$), the H_1 hypothesis is accepted. By comparing all possible sample pairs, it can be determined which pairs display a significant difference.

Table 6 shows the comparison of accident types according to data recording technique:: (1) T_0; (2) T_0+T_1; (3) $T_0+T_1+T_2$.

For T_0, there is stochastic dominance between samples 3–5 and 3–7; i.e. the values for elements randomly selected from the population characterized by the

Table 6 Groupwise comparison of the assessability of accident types for various data recording technologies—the *p* values of the Kruskal–Wallis Test—values below the significance level are indicated with an asterisk (*)

Accident type pairs	1. *p*-value T_0	2. *p*-value T_1	3. *p*-value T_2
x_1–x_2	0.08912	0.8055	0.00482*
x_1–x_3	0.6153	0.6777	7.9E-05*
x_1–x_4	0.2141	0.6221	0.1551
x_1–x_5	0.05644	0.04283	0.00386*
x_1–x_6	0.08328	0.8381	0.002*
x_1–x_7	0.06371	0.03524	0.3315
x_2–x_3	0.01947	0.2682	NaN
x_2–x_4	0.8842	0.7592	0.1888
x_2–x_5	0.2987	0.03554	NaN
x_2–x_6	0.4851	0.4917	NaN
x_2–x_7	0.2894	0.01461	0.09945
x_3–x_4	0.07346	0.1865	0.06308
x_3–x_5	0.00129*	0.00042*	NaN
x_3–x_6	0.04488	0.7461	NaN
x_3–x_7	0.00538*	0.00082*	0.01981
x_4–x_5	0.5128	0.06554	0.1775
x_4–x_6	0.5055	0.3517	0.1482
x_4–x_7	0.6038	0.01463	0.7397
x_5–x_6	0.07678	0.00477*	NaN
x_5–x_7	1	0.02732	0.09097
x_6–x_7	0.06393	0.00545*	0.06989
α_{corr}	0.007143		

Table 7 Pairwise comparison of the assessability of accident types for various data recording technologies—the *p* values of the Mann–Whitney Test

Accident type pairs	1. *p*-value traditional data	2. *p*-value EDR data	3. *p*-value EDR + data	4. Relation between accident type pairs
x_1–x_2	–	–	0.003029	$x_1 < x_2$
x_1–x_3	–	–	0.001556	$x_1 < x_3$
x_1–x_5	–	–	0.002424	$x_1 < x_5$
x_1–x_6	–	–	0.001248	$x_1 < x_6$
x_3–x_5	0.0005099	0.00001499	–	$x_3 > x_5$
x_3–x_7	0.002868	0.0001956	–	$x_3 > x_7$
x_5–x_6	–	0.002497	–	$x_5 < x_6$
x_6–x_7	–	0.002959	–	$x_6 > x_7$

samples will be different. For T_1, significant difference was found between four pairs: 3–5, 3–7, 5–6, and 6–7.

As for T_2, for several pairs (2–3, 2–5, 2–6, 3–5, 3–6, 5–6) the value of *p* is not a number (NaN): for samples with equal elements, in the mathematical formula of the statistical test the denominator will be 0. Thus, no difference can be supposed between them. In practice, these accident types become fully assessable in the T_2 case.

3.6 Comparison of sample pairs with stochastic dominance

Pairwise comparisons were carried out between those pairs that proved to display stochastic dominance with the aim to explore the relations between such pairs of accident types. If the *p* value of the statistical test is lower than α ($p < \alpha = 0.05$), the H_1 hypothesis is accepted.

Table 7 gives the results of the pairwise comparison of accident types: (i) T_0; (ii) $T_0 + T_1$; (iii) $T_0 + T_1 + T_2$.

The test results prove the following.

- Incase T_1, Type 3 (turning vehicle) is more assessable than Types 5 (lane change) and 7 (traffic lights).
- In case T_1, Types 3 (turning vehicle) and 6 (rear-end) would be more assessable than Types 5 (lane change) and 7 (traffic lights).

Table 8 Groupwise comparison of the change in assessability of accident types according to data recording techniques—*p* values of the Kruskal–Wallis Test

Accident type pairs	1. *p* value traditional—EDR change	2. *p* value traditional – EDR + change	3. *p* value EDR—EDR + change
x_1–x_2	0.2553	0.00316*	0.091
x_1–x_3	0.3931	0.01472	0.2115
x_1–x_4	0.2925	0.03525	0.1172
x_1–x_5	0.5173	0.00404*	0.00052*
x_1–x_6	0.1936	0.00103*	0.1936
x_1–x_7	0.2367	0.05703	0.02451
x_2–x_3	0.4477	0.01947	0.2682
x_2–x_4	0.9238	0.7336	0.8803
x_2–x_5	0.5932	0.2987	0.03554
x_2–x_6	0.9323	0.4851	0.4917
x_2–x_7	0.0297	0.6833	0.0679
x_3–x_4	0.4894	0.1943	0.4296
x_3–x_5	0.977	0.00129*	0.00042*
x_3–x_6	0.33	0.04488	0.7461
x_3–x_7	0.0452	0.0606	0.00762
x_4–x_5	0.6091	0.2967	0.02236
x_4–x_6	0.9673	0.9284	0.6437
x_4–x_7	0.04399	0.6791	0.05512
x_5–x_6	0.508	0.07678	0.00477*
x_5–x_7	0.1084	0.6523	0.1829
x_6–x_7	0.01633	0.3254	0.02969
α_{corr}	0.007143		

Values below the significance level are indicated with an asterisk (*)

- In case T_2, most accident types would be better assessable that Type 1 (destabilization).

3.7 Groupwise comparison of the change in assessability of accident types according to data recording techniques

Groupwise comparison makes it possible to rank accident types according to the extent of change in assessability for a given data recording technology. Thus, independent samples with non-normal distribution were compared by the Kruskal–Wallis Test, combined with Bonferroni correction, in order to minimize the probability of Type I error during the multiple hypothesis test.

Table 8 shows the comparison of accident types according to data recording technique:: (i) T_0; (ii) T_0+T_1; (iii) $T_0+T_1+T_2$.

Data in Column 1 prove that if EDR data are introduced alongside data recorded by traditional techniques, changes in assessability do not significantly differ for the different accident types.

As for Column 2, if even EDR+data are available, the change in assessability compared to that if only traditionally recorded data are provided, significantly differs for some pairs: stochastic dominance is witnessed for pairs 1–2, 1–5, 1–6 and 3–5.

As regards the change in assessability between the cases with EDR and EDR+technology (Column 3), stochastic dominance is present in pairs 1–5, 3–5, and 5–6.

3.8 Comparison of sample pairs with stochastic dominance

For the next test, only those pairs were considered in which the previous test found stochastic dominance in order to reveal the relation between those accident types. The independent samples with non-normal distribution were compared using the Mann–Whitney Test. If the p value for the statistical test proves to be lower than $\alpha=0.05$, the H_1 hypothesis is accepted.

Accident types are compared according to data recording technique in Table 9: Column 1 depicts the estimated change in assessability if T_1techniques are introduced; Column 2 shows results for $T_0+T_1+T_2$ compared to T_0; while Column 3 illustrates the estimated change in assessability between cases with T_1 and T_2 data.

The following statements can be made based on the above results.

- If EDR data are made available, the change in assessability of no accident type is significantly bigger than that of any other accident type.
- If EDR+data are available, the change in assessability compared to traditional data recording techniques is significantly bigger for Types 2, 5 and 6 than for Type 1. Furthermore, the change for Type 5 is significantly bigger than for Type 3.
- The change in assessability is significantly bigger for Type 5 than for Types 1, 3 and 6.

4 Conclusion

This study compared the levels of assessability of various road accident types with a series of statistical tests. The presented framework also makes it possible to examine how the assessability is expected to improve by the introduction of modern data recording technologies. Besides, our method contributes to the identification of the adequate data recording technology to achieve the required level of assessability.

The assessability of seven road accident types for forensic accident reconstruction was explored, using data from a collection of 124 real accidents in Hungary. Four assessability levels were established, and 7 accident types were set up. In addition to comparing the assessability of the various types, it was also estimated how assessability would change if data from new technologies (EDR; and EDR+, i.e. technology used by autonomous vehicles) were available.

Table 9 Pairwise comparison of the change in assessability of accident types according to data recording techniques, compared to traditional and EDR technologies

Compared accident type pairs	1. *p* value traditional—EDR change	2. *p* value traditional—EDR+ change	3. *p* value EDR—EDR+ change	Accident type pairs—results
x_1–x_2	–	0.001834	–	$x_1 < x_2$
x_1–x_5	–	0.002288	0.0003094	$x_1 < x_5$
x_1–x_6	–	0.0006014	–	$x_1 < x_6$
x_3–x_5	–	0.0003691	0.00004055	$x_3 < x_5$
x_5–x_6	–	–	0.002497	$x_5 > x_6$

The *p* values of the Mann–Whitney Test

The results prove that accident assessability considerably improves if EDR technology is applied in addition to traditional data recording technologies. If EDR+ data are also present, the assessability of each accident type would be satisfactory. As the assessability of each accident type grows owing to the EDR+ data, the assessability of accidents in Type 1 (roadway departure) and 7 (at traffic lights) does not reach the average. The reason for this is that some of the accidents in these sets could not be fully assessable (i.e. Level 4) even if EDR+ data were present.

Our evaluation proved that even if modern data recording technologies are applied, the assessability of accidents involving roadway departure (Type 1) and of accidents at traffic lights (Type 7) does not improve significantly compared to the case when only traditional data recording is used, as only information beyond data recorded by modern technologies could ensure full assessability (e.g. the physiological parameters of the drives for roadway departure).

In the next step, the groupwise comparison of the assessability of accident types was carried out according to various data recording techniques. The aim of this test was to rank the assessability of accident types for each data recording technology.

It is impossible to rank all accident types, as significant differences in assessability were found only for certain relations.

Finally, the groupwise comparison of the change in assessability for each accident type was completed to rank accident types according to the change in their assessability due to the introduction of modern technologies. This change did not prove to be significant for any type if only EDR technology is introduced. However, the inclusion of EDR+ data showed a lower change in assessability for roadway departure (Type 1) for other accident types. Furthermore, the assessability change for Type 5 (lane change) accidents in the EDR+ and EDR comparison is significantly higher than for several other accident types.

In conclusion, the above analyses proved that the assessability of some roadway accident types significantly differs from that of other types if only traditional authorized data recording technologies are applied (T_0). This evaluative analysis supports the assumption that if modern data recording technologies (EDR, EDR+) widely spread (cases T_1 and T_2, respectively), the assessability of all accident types will increase. However, for some accident types full assessability cannot be reached. In order to enhance the assessability of these accident types, further data recording devices and techniques should be introduced. When choosing new methods, it is advisable to take into consideration how the application of the novel devices would affect the assessability of accidents. These effects vary according to device and accident type. The introduction of proper data recording technologies could enhance these methods' level of usefulness to society.

In order to reach the appropriate assessability level of the examined seven types of accidents, in five cases, the traditional data recording technologies used today and, in some cases, the increasingly widespread EDR data recording technology are sufficient. At the same time, for Types 5 and 7, not even the EDR data recording technology can ensure adequate assessability; and in some cases, technologies beyond EDR+ would be necessary to achieve adequate assessability.

This research assumed that all the vehicles involved in a given accident were equipped with the same data recording technology. Thus it would be an important to examine those cases where the data recording technology of the vehicles is different since this difference may result in differences between the assessability of the accident forms.

For accidents involving highly automated vehicles, the use of EDR+ data recording technology is essential to ensure adequate assessability. Furthermore, with the further increase of the level of automation and the emergence and spread of autonomous systems, new types of accidents will result in the development and use of new analysis and data recording methods.

Appendix 1

Sample accidents

Below, each of the above categories is illustrated by a real accident which can be regarded as a typical example of the given category. In the descriptions, only relevant accident data are given, and personal data or any information referring to personal data are not shared.

Destabilization, roadway departure

The sample collision happened in a crossing with traffic signs. The driver driving on the main road noticed that the vehicle obliged to give way had dangerously entered the main road. The driver of the vehicle on the main road (blue) steered left, right and left again, and thus the vehicle got destabilized. Consequently, the vehicle drifted to the left-side crash barrier. The reconstructed accident is shown in Fig. 10.

Data serving as a basis for accident reconstruction were obtained in the traditional way. In cases similar to this one, in addition to the above reconstruction of the accident, it is also necessary to know the movements of the vehicle from the side road (red), both in space and

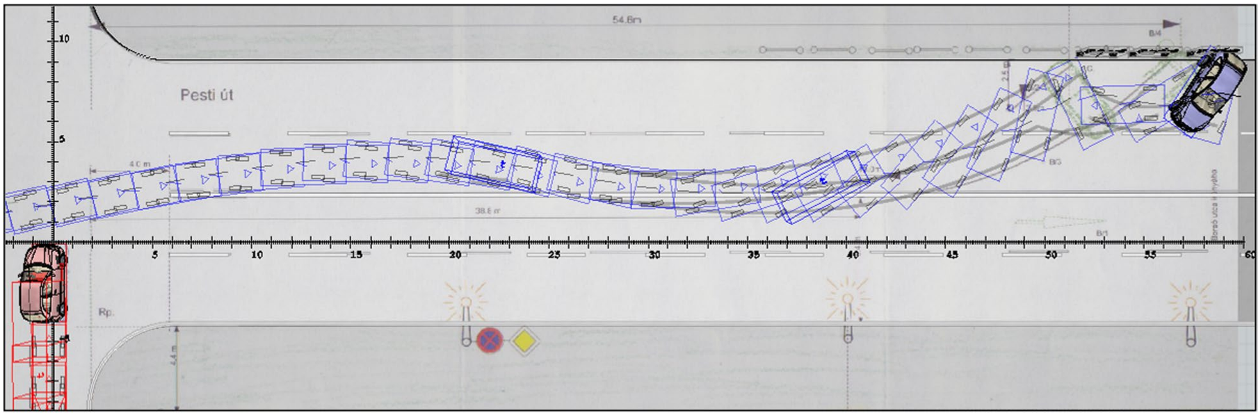

Fig. 10 Sample accident 1—destabilization

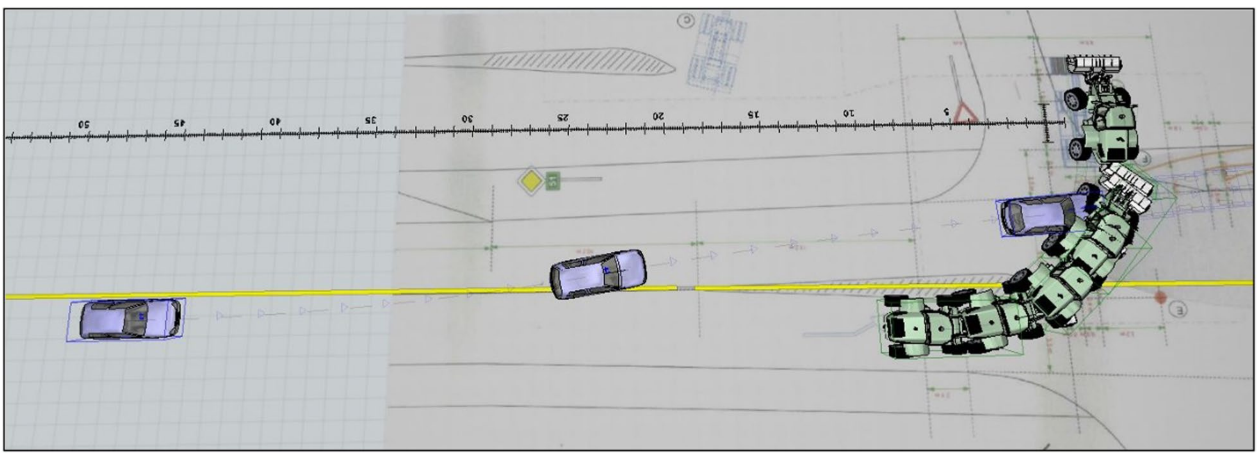

Fig. 11 Sample accident 2—collision of a vehicle turning left and another one overtaking it

time. Thus, it must be known when and how far the red car entered the crossing. The critical question is whether the avoidance manoeuvre was justified or not. In several cases, when traditional data recording methods are used, no such information is available. Consequently, the assessability of the accident is only Level 1.

If the vehicles had been equipped with an EDR system, the determinability of the accident cause and thus the assessability of the accident would not have changed significantly. The reason for this is that it is necessary to know how the two vehicles moved compared to each other in time to be able to determine the exact reason of the accident. This is only possible if EDR+data are available, which would ensure a Level 4 assessability for this accident type.

Collision of a vehicle turning left with a vehicle overtaking it

In the sample accident, the car (blue) intended to overtake the construction vehicle (green) which was turning left, and the car crashed into it. The reconstructed collision is shown in Fig. 11

.

Data serving as a basis for accident reconstruction were obtained in the traditional wayTo determine the cause of the accident, it is also required to find out which driver started the manoeuvre earlier in a way that it could be noticed by the other driver. Thus, the position of the overtaking vehicle must be known for the moment when the construction vehicle started to turn left: was it visibly already in the overtaking position, or was it approaching the vehicle to be overtaken in its own lane?

Traditional data recording techniques generally provide sufficient data for the reconstruction of the collision. However, vehicle movements before the collision can only partially be determined. Consequently, these type

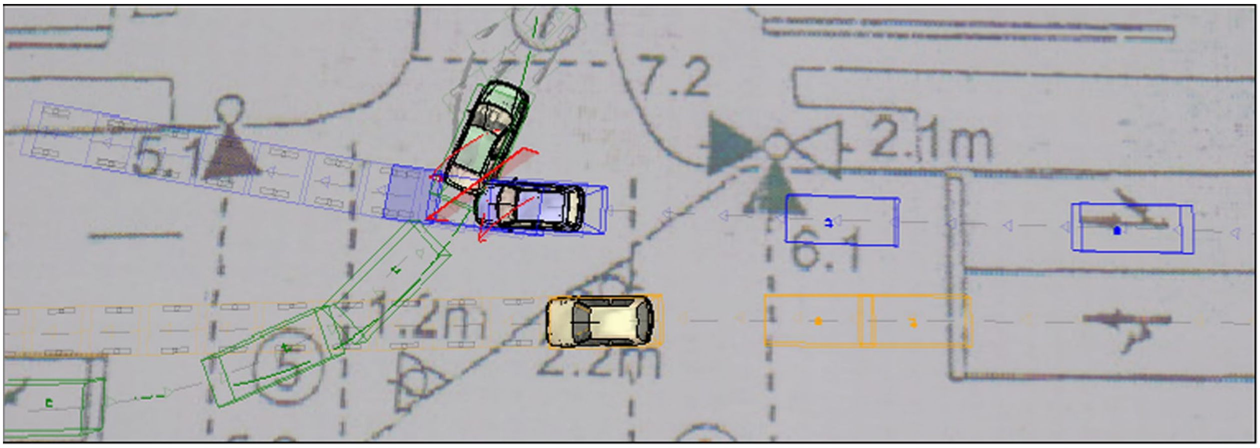

Fig. 12 Sample accident 3—collision of a vehicle turning left and a vehicle going straight

of accidents generally belong to the Level 1 assessability category.

In the presence of EDR data, the track of the vehicles prior to the crash can be calculated. What is more, EDR + technology is able to record the exact route. Consequently, the availability of EDR data enhance assessability, while the use of the EDR + technologies could result in Level 4 assessability.

Collision of a turning vehicle with a vehicle driving straight

In the sample accident, a car going straight (blue) crashed into a car turning left (green). Figure 12 shows the reconstructed collision.

Data serving as a basis for accident reconstruction were obtained in the traditional way. Traditional data recording techniques generally provide sufficient data for the reconstruction of such a collision. Consequently, the assessability of accidents in this category is typically Level 3 or higher.

If the vehicles are equipped with EDR or EDR + systems, the movement of vehicles and their relative position can be determined more accurately, and thus the movement processes of the accident can be fully and accurately reconstructed. Therefore, the assessability of the accident could reach Level 4.

Head-on collision

The accidents in this category happened when one of the vehicles went over to the opposite lane (Fig. 13).

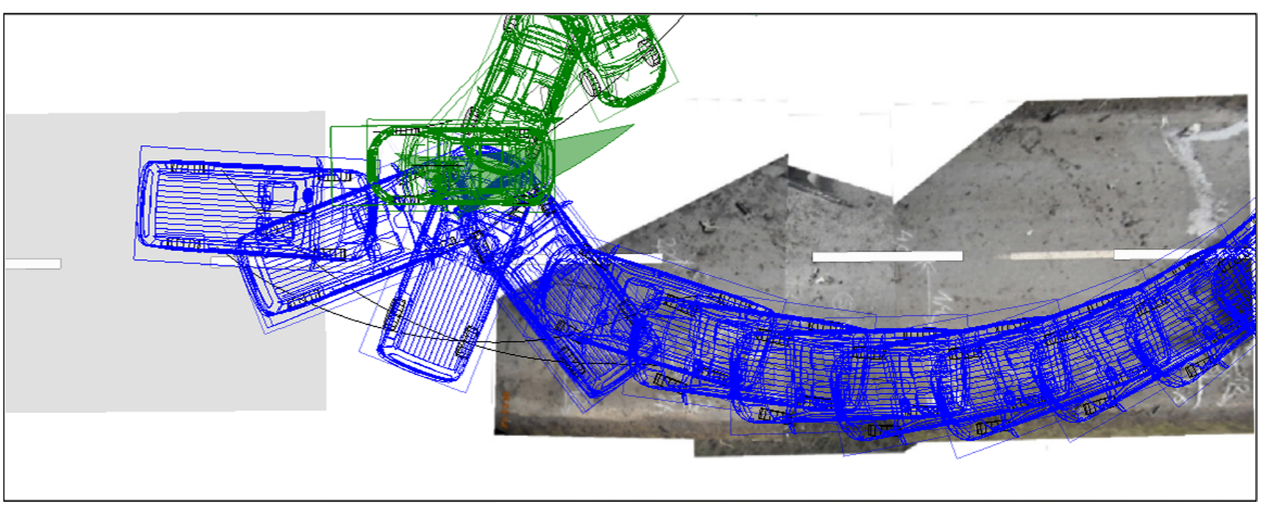

Fig. 13 Sample accident 4—head-on collision

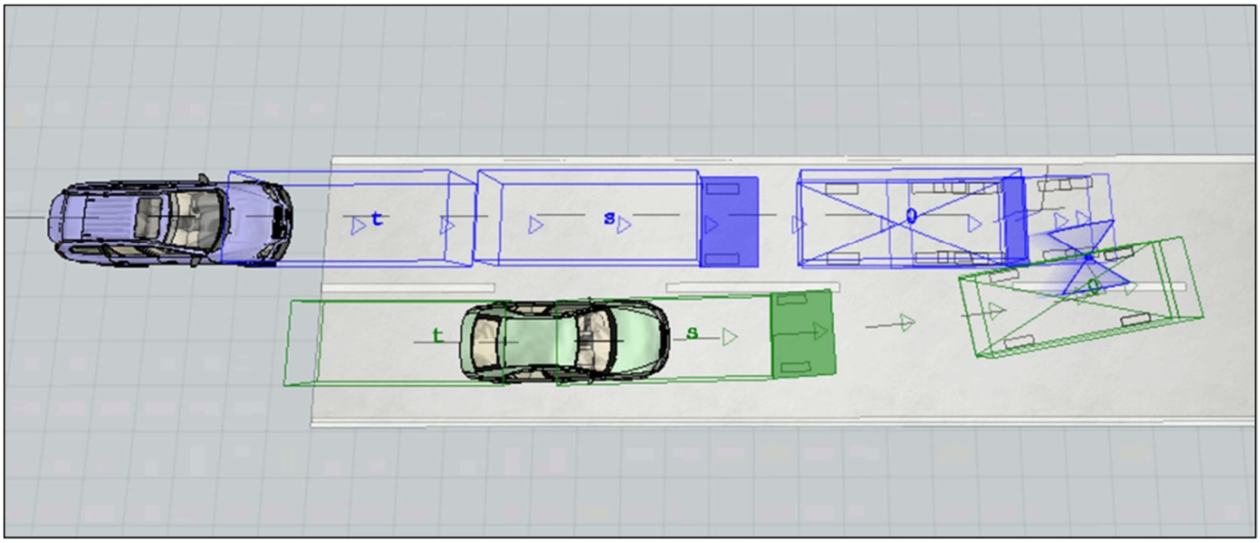

Fig. 14 Sample accident 5—lane change

Data serving as a basis for accident reconstruction were obtained in the traditional way. In order to reveal the causes of the accident, it is necessary to determine in which lane the collision happened, and which driver went over to the opposite lane and how. Thus, it is also necessary to determine the track of each vehicle prior to the crash.

Traditional data recording techniques generally provide sufficient data for the reconstruction of the collision. However, vehicle movements before the collision can only partially be determined. As a result, the assessability of accidents in this category is usually Level 1 or 2.

EDR data make it possible to calculate the route of the vehicles before the collision. If EDR + technology is applied, the exact route is recorded. As a result, the availability of EDR data improve assessability, while data recorded by EDR + technologies could enhance assessability to Level 4.

Lane change

This category contains accidents in which at least one of the vehicles changed lanes either immediately before the collision or during the accident process (Fig. 14).

Data serving as a basis for accident reconstruction were obtained in the traditional way. It is necessary to determine whether the lane change manoeuvre of one vehicle could be noticed by the other driver within or outside of the stopping distance. To achieve this, in addition to the reconstruction of the collision process, it is also necessary to determine the track of each vehicle prior to the crash.

Traditional data recording techniques generally provide sufficient data for the reconstruction of the collision. However, vehicle movements before the collision can only partially be determined. As a result, the accident process usually cannot be reconstructed or can only partially be reconstructed. Consequently, the assessability of accidents in this category is usually Level 1 or 3.

The track of the vehicles before the crash can be calculated if EDR data are given. Moreover, the exact route can be recorded by EDR+ technology. Thus, while the availability of EDR data enhance assessability, with the application of the EDR+ technologies Level 4 assessability might be reached.

Backing/rear-end collision

This category comprises those accidents in which at least one of the vehicles was backing or one vehicle crashed into the other one from the back, going in the same direction (Fig. 15).

Data serving as a basis for accident reconstruction were obtained in the traditional way. In such cases, it is also necessary to determine the track of each vehicle prior to the crash.

With traditional data recording techniques, vehicle movements before the collision can only partially be determined. As a result, the accident process usually cannot be reconstructed or can only partially be

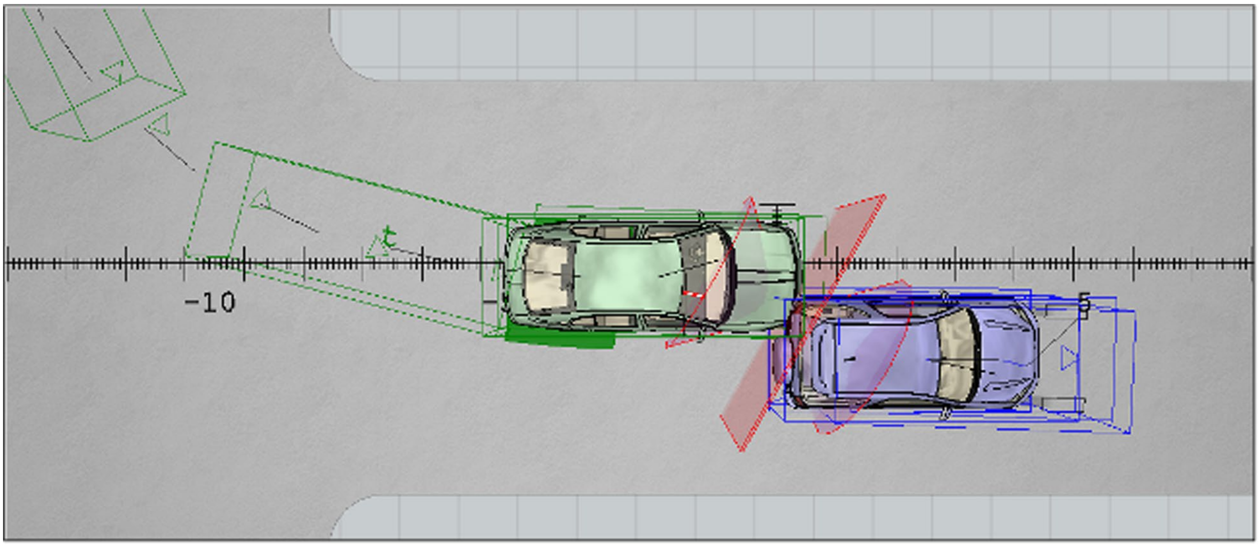

Fig. 15 Sample accident 6—rear-end collision

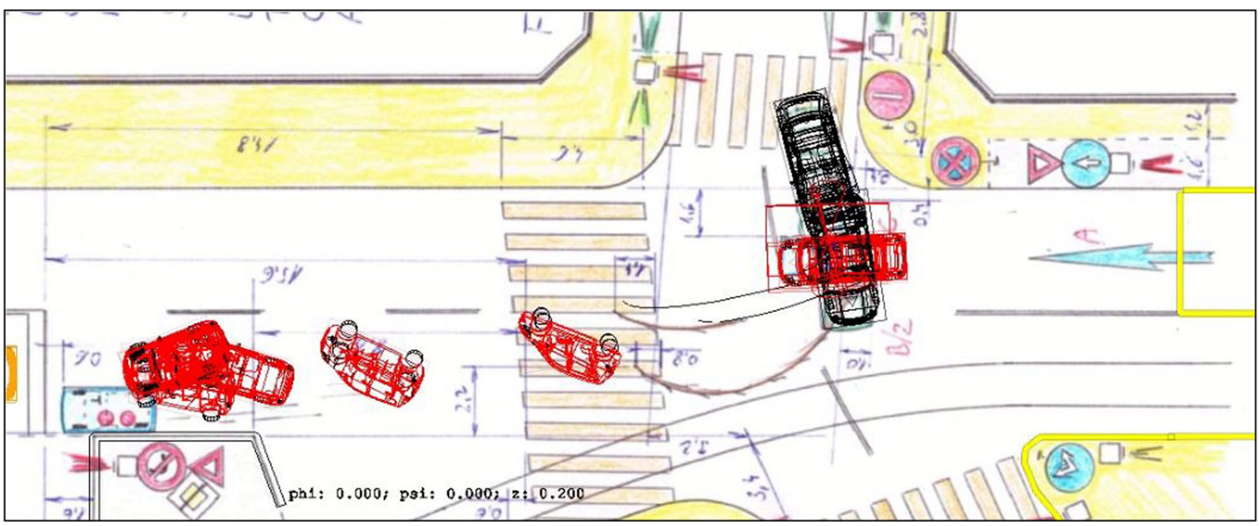

Fig. 16 Sample accident 7—collision at traffic lights

reconstructed. Consequently, the assessability of accidents in this category is usually Level 1 or 3.

EDR data would make it possible to calculate the vehicle routes prior to the collision. EDR + technology is capable of recording the route precisely. As a consequence, assessability may be improved by using EDR technologies, while EDR+ technologies could enhance the accuracy of assessability to Level 4.

Traffic lights

The collisions in this category happened in crossings with traffic lights, and it was a question what colour the lights were for the vehicles immediately before entering the crossing (Fig. 16).

With traditional data recording techniques, both the accident process can be reconstructed and the vehicle movements before the collision can be determined. However, in order to be able to determine liability, the real colour of the traffic lights immediately before the crash must be known. Consequently, the assessability of accidents in this category is usually Level 2 or 3.

Even if the vehicles are equipped with an EDR system, the cause of this accident type cannot be determined more accurately; thus, assessability would not change considerably compared to that of accidents recorded with traditional techniques. The reason for this is that it is crucial to determine what sign the traffic lights showed for the accident parties. This is only made possible if EDR+ data are available, which could result in Level 4 assessability.

Acknowledgements
The authors are grateful for the support of HAS Bolyai scholarship. The research was supported by the Ministry of Innovation and Technology NRDI Office within the framework of the Autonomous Systems National Laboratory Program.

Author contributions
GV: Methodology, Software, Data curation, Writing, Original draft preparation, Visualization. ÁT: Conceptualization, Validation, Reviewing and Editing, Supervision, Investigation. All authors read and approved the final manuscript.

Funding
Open access funding provided by Budapest University of Technology and Economics.

Declarations

Competing interests
The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

Received: 12 December 2022 Accepted: 23 May 2023
Published online: 05 June 2023

References

1. Anciaes, P., Jones, P., Mindell, J. S., & Scholes, S. (2022). The cost of the wider impacts of road traffic on local communities: 1.6% of Great Britain's GDP. *Transportation Research Part A: Policy and Practice, 163*, 266–287.
2. Bonferroni, C. E. (1936). Statistical theory of classification and calculation of the probability. *Publication of the R Institute Superiore of the Science of Economy and Commerce of Florence, 8*, 3–62.
3. Boole, G. (1847). *The mathematical analysis of logic, being an essay towards a calculus of deductive reasoning*. Macmillan.
4. Chand, A., Jayesh, S., & Bhasi, A. B. (2021). Road traffic accidents: An overview of data sources, analysis techniques and contributing factors. *Materials Today: Proceedings, 47*, 5135–5141.
5. Council of the EU. (2017). Valletta Declaration on Road Safety. https://eumos.eu/wp-content/uploads/2017/07/Valletta_Declaration_on_Improving_Road_Safety.pdf (Downloaded: 14 May 2022)
6. Delhaye, E. (2006). Traffic safety: Speed limits, strict liability and a km tax. *Transportation Research Part A: Policy and Practice, 40*(3), 205–226.
7. EC – European Commission. (2020). Next steps towards 'Vision Zero': EU road safety policy framework 2021–2030. Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/https://doi.org/10.2832/261629 (Downloaded 14 May 2022)
8. Fernández Llorca, D., & Gómez, E. (2021). Trustworthy Autonomous Vehicles. EUR 30942 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/120385. JRC127051
9. Haque, M. O., & Haque, T. H. (2018). Evaluating the effects of the road safety system approach in Brunei. *Transportation Research Part A: Policy and Practice, 118*, 594–607.
10. Jankó, D. (2019). A 2021–2030 közötti évekre tervezett EU közlekedésbiztonsági akcióprogram irányelvei, célkitűzései és ezek hazai elfogadhatósága. *Közlekedéstudományi Szemle, 69*(6), 56–65.
11. Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American statistical Association, 47*(260), 583–621.
12. Liu, S., Zhang, Z. J., & Yu, Z. H. (2022). Research on liability Identification System of Road Traffic Accident. *Journal of Computers, 33*(1), 215–224.
13. Ma, Q., Huang, G., & Tang, X. (2021). GIS-based analysis of spatial–temporal correlations of urban traffic accidents. *European Transport Research Review, 13*(1), 1–11.
14. Mann, H., & Whitney, D. (1947). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Annals of Mathematical Statistics, 18*(1), 50–60.
15. Mu, R., & Yamamoto, T. (2019). Analysis of traffic flow with micro-cars with respect to safety and environmental impact. *Transportation Research Part A: Policy and Practice, 124*, 217–241.
16. Nachar, N. (2008). The Mann-Whitney U: A test for assessing whether two independent samples come from the same distribution. *Tutorials in Quantitative Methods for Psychology, 4*(1), 13–20.
17. Pilet, C., Vernet, C., & Martin, J. L. (2021). Estimated crash avoidance with the hypothetical introduction of automated vehicles: A simulation based on experts' assessment from French in-depth data. *European Transport Research Review, 13*(1), 1–8.
18. Pinter, K., Szalay, Z., & Vida, G. (2021). Road accident reconstruction using on-board data, especially focusing on the applicability in case of autonomous vehicles. *Periodica Polytechnica Transportation Engineering, 49*(2), 139–145.
19. Rúa, E., Comesaña-Cebral, L., Arias, P., & Martínez-Sánchez, J. (2022). A top-down approach for a multi-scale identification of risk areas in infrastructures: Particularization in a case study on road safety. *European transport research review, 14*(1), 1–18.
20. Seidl, M., Edwards, M., Hynd, D., McCarthy, M., Livadeas, A., Carroll, J., Martin, P., Edwards, A., Huysamen, K., Radcliffe, J., Pistak, K., Appleby, J. (2021). General Safety Regulation: Technical Study to Assess and Develop Performance Requirements and Test Protocols for Various Measures Implementing the New General Safety Regulation, for Accident Avoidance and Vehicle Occupant, Pedestrian and Cyclist Protection in Case of Collisions. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (European Commission). Publications of the European Union.
21. Vida, G., & Török, Á. (2022). The impact of accident data recording technology on liability issues. Mendeley Data, V1. https://data.mendeley.com/datasets/hw6ft7jzcb/1. (Downloaded: 14 January 2022)
22. Wang, X., Qu, Z., Song, X., Bai, Q., Pan, Z., & Li, H. (2021). Incorporating accident liability into crash risk analysis: A multidimensional risk source approach. *Accident Analysis & Prevention, 153*, 106035.
23. Wilcoxon, F. (1992). Individual comparisons by ranking methods. In S. Kotz & N. L. Johnson (Eds.), *Breakthroughs in statistics* (pp. 196–202). Springer.
24. WHO (World Health Organization). (2018). Global status report on road safety 2018: summary (No. WHO/NMH/NVI/18.20). World Health Organization. https://www.who.int/publications/i/item/9789241565684 (Downloaded: 14 January 2022).