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Assessing safety critical braking events in naturalistic driving studies

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ABSTRACT

Naturalistic driving studies permit the study of driving behaviour during every day driving. Such studies have a long duration and rare events such as near-crashes and even crashes do occur during the period of the study. This fact gives an opportunity to study events that are otherwise difficult to find. However, the vast amount of data recorded within these naturalistic driving studies demands a huge amount of manual work to identify hazardous situations. This paper concerns the development and validation of a new method, based on critical jerk, to identify safety critical braking events during car driving. The method was compared with one of today's most used method, which is based on the longitudinal acceleration measure. Both methods were applied on near-crash data from the 100-car naturalistic driving study previously carried out by the Virginia Tech Transportation Institute (VTTI). The data included 637 near-crashes. The results from the analyses showed that the critical jerk method performed approximately 1.6 times higher overall success rate than the method based on the longitudinal acceleration measure. In addition, a positive correlation was found between driver's safety critical braking event and crash involvement. The conclusion is that the critical jerk method is capable of detecting safety critical braking events and may also be used for assessing high risk drivers.

1. Introduction

To perform analyses of hazardous situations in driving, naturalistic driving studies can be used as they enable analysis of driving behaviour in normal conditions as well as in critical situations, which are otherwise difficult to find and observe. However, one of the problems associated with naturalistic driving studies is that the identification of specific moments or behaviour is very time consuming due to the vast amount of recorded data. A range of different methods has been used in different studies with varying results, e.g. longitudinal acceleration, forward-time-to-collision and yaw rate, to mention a few.

Several classifications of hazardous situations exist depending on the kind of evasive manoeuvre, if any, performed by the driver, the severity grade of the situation and also whether or not other road users are involved. Dingus et al. (2006) used definitions as near-crashes, crash relevant events and proximity events, where near-crashes were of the highest severity, closest to crashes. A thorough description of all events is found in Dingus et al. (2006). Our study takes near-crashes where the driver had carried out an evasive braking action into consideration, i.e. safety critical braking events, while excluding near-crashes where braking is not part of the evasive manoeuvre or where another driver has performed the evasive manoeuvre.

Dingus et al. (2006) implemented seven different methods to detect different hazardous situations in naturalistic driving studies. It was found that the forward time-to-collision method had the best success rate of 56% in detecting near-crashes,

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but also a severely high false rate of 86%. The method that had best overall performance was the longitudinal acceleration method with a success rate of 45% and a false rate of 66%. Similar problems with low success rates were found by Mclaughlin, Hankey, and Dingus (2008) using acceleration as a marker for crashes and near-crashes when evaluating a collision avoidance system.

Thus, there is still a need for a method to be able to select the events of interest from a large database in a sufficiently effective manner.

1.1. Aim

The aim of this study is to validate a previously developed method (Bagdadi & Várhelyi, 2012) that uses jerk, i.e. the rate of change of acceleration, as the primary measure for detecting safety critical brake events where the driver had performed an evasive manoeuver, during car driving. Bagdadi and Várhelyi (2012) found that the proposed method was sensitive enough to distinguish between brake responses in situations with different severity grades.

The method is applied to a dataset originating from the 100-car naturalistic driving study (Dingus et al., 2006). A comparison of the success rate obtained by our method and the success rate obtained by using longitudinal acceleration, which showed the best overall performance in the original 100-car study (Dingus et al., 2006), is performed. Longitudinal acceleration is commonly used to measure certain traffic situations such as crashes and near-crashes in naturalistic driving studies or studies where kinematic vehicle data is gathered (McLaughlin et al., 2008; Nishimoto, Arai, Nishida, & Yoshimoto, 2001; Van Winsum & Brouwer, 1997; Van Winsum & Heino, 1996; Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008) and is thus considered to be a valid measure for comparison.

The second objective is to assess the relationship between crashes and hazardous situations for the individual drivers. Bagdadi and Várhelyi (2011) showed that drivers with an accident history were involved in more situations involving abrupt braking, indicating that such abrupt braking responses may be an indicator for the driver's involvement in hazardous traffic situations and accident proneness. Establishing the relationship between the numbers of crashes a driver is involved in with the frequency of critical jerks performed by the driver would facilitate the work of developing a method for studying indicators of risky driving.

1.2. Safety critical braking events

In order to properly assess a single driver's behaviour and their crash involvement, it is important that only relevant events are analyzed. Otherwise, other drivers' behaviour might be incorrectly superimposed onto the original driver's assessment. Using near-crashes as a surrogate measure for crashes does not fulfil this requirement as a near-crash is defined as:

> *"Any circumstance that requires a rapid, evasive manoeuvre by the subject vehicle,* ***or by any other vehicle, pedestrian, cyclist, or animal, to avoid a crash****. A rapid, evasive manoeuvre is defined as steering, braking, accelerating, or any combination of control inputs that approaches the limits of the vehicle capabilities."* (Dingus et al., 2006).

This definition indicates that it is sufficient that any driver, or animal, performs an evasive action in order for the event to be classified as a near-crash, superimposing the occurrence of a near-crash on "our" driver under observation. Thus, a new surrogate measure for crash, i.e. the safety critical braking event, is therefore suggested, defined as:

> *"Crashes or situations that requires a sudden, evasive manoeuvre to avoid a hazard or to correct for unsafe acts performed by the driver himself/herself or by other road users."*

Although there are several different kinds of evasive manoeuvres, safety critical braking events in specific refer to events where braking was the primary evasive manoeuvre.

This proposed surrogate measure assumes that all situations in which the driver performs critical driving manoeuvres could be seen as a failure in the traffic system and thus decrease the overall traffic safety.

A critical driving manoeuvre is caused by a sudden necessity for the driver to perform an evasive manoeuvre. The manoeuvre is often characterized by an abruptness in the manoeuvre related to the often very short reaction time available. Although the available reaction time may be different in different cases it is assumed that in a situation where the driver need to act abruptly the reaction time is less than preferred by the driver and it is thus argued that the driver did not plan for the performed action. Although drivers always need to be aware of the limits of their driving capabilities (Fajen, 2005) drivers' perception and expectations may cause the drivers to misinterpret a traffic situation and thus cause a hazardous situation to arise. The most common crash type in vehicle accidents are rear end striking, which most often occurs in situations that should be easy for the driver to handle (Lee, Llaneras, Klauer, & Sudweeks, 2007). One reason why this kind of crashes occurs more frequently than other kinds is that the driver did not expect any hazard and did not allow for a sufficient time margin to the lead vehicle. Thus the driver was perhaps not aware of his/hers limits of driving capabilities or took a conscious risk. Hazardous situations force the drivers to behave in a way that most likely is different from how they prefer to drive, thus further study of driving behaviour during these situations could facilitate the development of driver behavioural models or discrete choice models.

1.3. Limitations

Even though it is important to have a sufficiently high success rate of detecting critical situations, it is also important to reduce the false rate as much as possible. However, a false rate analysis has not been possible due to two reasons. First, the data set that has been made available from the 100-car study contained only time series data from the near-crashes and crashes and not from any crash relevant events with lower severities or any of the baseline periods. Second, a direct comparison would be misleading as the definitions of what is regarded as an in-valid near-crash and in-valid safety critical braking event differ.

According to the definition of a near-crash, a situation in which the driver performs an evasive manoeuvre for any other reason than to avoid a crash is regarded as an in-valid near-crash and is not, per definition, correlated to crashes or crash involvement. However, in addition to situations where a hazard is apparent and a risk of crash exists there are also situations concerning unsafe acts, or erroneous driving behaviour, such as slips and lapses, mistakes or violations of traffic rules, which affect the traffic safety in a negative way even though no other road user are present. An example of this is when the driver is about to run a red light or a stop sign, but realizes this at the last second and performs necessary evasive manoeuvre (Reason, 1990).

These situations are considered to hazardous, and could under the "right" circumstances result in a crash if the driver does not perform the evasive manoeuvre.

Other situations may be perceived as hazardous by the driver and thus performs an evasive manoeuvre, which could turn out to be a "false alarm", e.g. the driver thinks he/she sees a child or an animal about to cross the road, but it turns out to be nothing, or just a shadow. These situations are likely to be deemed as safety critical events, perhaps erroneously, depending on how the drivers' intentions in the specific situations are to be valued in safety research. Unfortunately, these kind of events are not easily recognized in driving studies and drivers might be required to give feedback about the specific event. An assessment of potentially hazardous situations could unfold valuable knowledge about unsafe acts, such as lapse of attention, and contribute to the assessment of traffic safety. However, this is not within the scope of this article.

2. Method

2.1. The naturalistic driving study data set

2.1.1. Participants

The 100-car naturalistic driving study data set, thoroughly described in (Dingus et al., 2006), contains driving data for 109 participants, ranging in age from 18 to over 55 (43 female, 66 male), who commute to and from the Washington, DC metro area.

2.1.2. Data description

The time series data set from the 100-car study contains data recorded during the registered near-crashes and crashes, beginning at approximately 40 s before the event and lasting approximately 20 s after the event. It also includes data from various sensors, typically radar, accelerometers, GPS, various detection systems for detecting side obstacles and an incident box for the driver to report incidents.

The 100-car study data set includes a total of 761 near-crash events identified manually. Near-crashes in which no evasive manoeuvre is carried out by the driver, or carried out by another road user and cases where swerving or acceleration is the primary action, totally 124 cases, are excluded from further analyses. The remaining 637 near-crashes, performed by 93 drivers are included in this study. Table 1 shows the distribution of the sample of observed near-crashes by driver reaction.

The acceleration data that is necessary for our analyses to compare the two methods, i.e. the longitudinal acceleration of braking manoeuvres and the critical jerk, had a sampling frequency of 10 Hz.

Table 1
Near-crashes distributed by driver reaction.

Event	Manoeuvre type	Included	Excluded
Near-crash	Braking with/without swerving	637	
	Swerving only		69
	Accelerating with/without swerving		5
	No action/missing		48
	Total	637	124
Crashes	Braking with/without swerving	28	
	Swerving only	12	
	No action	27	
	Missing		1
	Total	67	1

2.2. Procedure

Our proposed method of detecting critical jerks (Bagdadi & Várhelyi, 2012) uses a set of algorithms to analyse the level and characteristics of the change in acceleration rate. To be able to unambiguously detect safety events, it is necessary to filter out the noise to such an extent that the fluctuations of the derivatives are minimized. For that purpose, a second order Savitzky-Golay filter is used to improve the signal-noise ratio. The calculation of the rate of change of the acceleration is done simultaneously using the Savitzky-Golay polynomial differentiation method, from which the measure of a peak-to-peak value of the jerk is obtained. By determining the threshold of the jerk value to correspond to what has been found in traffic conflict analyses (Bagdadi & Várhelyi, 2012) a critical jerk measure is defined.

Events involving such an abrupt braking response that it creates a critical jerk, i.e. exceeding a certain predefined threshold of what is concerned to be a critical jerk, are classified as safety critical braking events.

2.2.1. Analysis of detection of safety critical braking events in naturalistic driving studies

The performance of our method is compared with the performance of the method based on the measure of longitudinal acceleration, which is one of the most commonly used methods of detecting near-crashes and also one of the best performing methods in the original 100-car study.

Bagdadi and Várhelyi (2012) showed that for situations where the driver, at initial speeds of 50 km/h and 70 km/h, had approximately 1.5 s to carry out the braking manoeuvres, the mean value of the rate of change in acceleration was 1.0 g/s (95% confidence interval 0.8–1.2). In traffic conflict studies, a time window of 1–1.6 s at speeds of 50–70 km/h is often found in serious conflict situations (Hydén, 1987; Svensson, 1998). Thus, for this study the value of 1.0 g/s is chosen as the threshold for our method. In addition, a sensitivity analysis is also conducted to test the change in the success rate when the threshold is set to 0.8 g/s and 1.2 g/s.

The critical jerks in the time series data for the 637 near-crashes are calculated for each event using Matlab. The statistical analysis is performed in SPSS.

2.2.2. Assessment of the relationship between involvement in safety critical braking events and crashes

This assessment concerns the relationship between the number of safety critical braking events and the number of crashes the driver is involved in. A Poisson regression is used to examine the impact on the expected number of crashes with an increased number of critical jerks. The initial regression model includes gender and age group dummy variables to see if any effect on the expected number of crashes exists. In addition, differences in the involvement in crashes as well as in safety critical braking events between gender and age groups are also tested with non-parametrical statistical tests, i.e. Kruskal–Wallis and Mann–Whitney tests.

The statistical analysis is performed in SPSS.

3. Results

3.1. Detection of safety critical braking events in naturalistic driving studies

The hazardous situations classified as near-crashes recorded in the 100-car study are categorized by the type of incident. Table 2 shows the distribution of near-crashes included in this study. The most common incident type is rear-end striking (59%) followed by sideswipes (19%) and incidents where other vehicles are cutting in either by crossing the road or by lane changing very close to the subject vehicle (10%).

Near-crashes categorized as "Other" involve obstacles or objects in the roadway, single vehicle situations or if the driver had backed into an object or parked vehicle.

In the present analysis, both longitudinal acceleration and our proposed method are applied to the data set of 637 near-crashes. The analysis shows a success rate of 54.2% using the longitudinal acceleration method with a threshold of 0.6 g. Our method, using a threshold value of 1.0 g/s, applied to the data set of 637 near-crashes shows a success rate of 86%, see Table 3.

Table 2
Distribution of near-crashes by incident type.

Incident type	Frequency	Percentage (%)
Rear-end striking	373	59
Sideswipe	119	19
Cutting-in vehicle	64	10
Rear-end struck	35	5
Other	18	3
Vulnerable road user or animal	15	2
Road departures	13	2
Total	637	100

Table 3
Success rate by the longitudinal acceleration method and by our (critical jerk) method.

Method	Detected (total amount)	Success rate (%)
Negative longitudinal acceleration (threshold = 0.6 g)	345 (637)	54.2
Critical jerk (threshold = 1.0 g/s)	548 (637)	86.0

Table 4
Incident type of the detected near-crashes.

Incident type	Longitudinal acceleration		Critical jerk	
	Number	Per cent	Number	Per cent
Rear-end striking	257 (373)	68.9	347 (373)	93.0
Sideswipe	33 (119)	27.7	85 (119)	71.4
Cutting-in vehicle	23 (64)	35.9	55 (64)	85.9
Vulnerable road-user or animal	11 (15)	73.3	15 (15)	100
Other	10 (18)	55.5	16 (18)	88.8
Rear-end struck	9 (35)	25.7	22 (35)	62.8
Road departures	2 (13)	15.4	8 (13)	61.5
Total	345 (637)	54.1	548 (637)	86.0

Table 5
Short description of an excerpt of road departures and rear-end struck situations missed by both methods.

Road departures
Subject driver is going through an intersection and nearly hits the median post intersection
Subject driver is looking at his laptop located in the passenger seat at the same time as talking to a passenger. The vehicle drifts over the white line to the right edge of the road, just before a driveway
Subject driver is driving on a one way roadway when a vehicle in the right lane tries to change into the left lane and then parallel park. The other vehicle almost sideswipes our subject driver. The subject driver swerves to the left to avoid being hit
Rear-end struck
Subject vehicle is slowing down for a slower lead vehicle. The following vehicle must suddenly apply his brakes to keep from hitting the subject's vehicle
Subject driver is slowing down to a stop because he sees a person with a baby stroller on the sidewalk on the left side of the street; a following vehicle rapidly approaches, nearly hitting the subject vehicle in the rear
Subject vehicle is slowing down for a stopped lead vehicle. The following vehicle must suddenly brake to keep from hitting the subject's vehicle
The subject vehicle is in a line of stopped traffic. The lead vehicle moves forward and then stops. The subject vehicle does as well. The following vehicle is distracted and must stop suddenly to avoid hitting the subject's vehicle

Deeper analyses of the detected events show that both methods perform best on rear-end striking incidents, with 68.9% and 93% of the events found with longitudinal acceleration and our method, respectively. Road departures are the most difficult type of incident to detect, with a success rate of 15.4% and 61.5% for longitudinal acceleration and our method, respectively, see Table 4. Note that each incident type is independent regarding the number of events detected; thus, the percentages cannot be added together.

A contextual analysis of the near-crashes classified as road departure shows that in almost all cases the drivers seems to drift towards the curb, nearly hitting it. Typically in near-crashes classified as rear-end struck the subject driver performs a normal, non-critical, brake action, which forces the driver of the car behind, which perhaps is following too closely, to brake hard or swerve to avoid an accident. Table 5 shows an excerpt of the different situations.

Analyses of the context of rear-end struck incidents that were detected by our method but not by the longitudinal acceleration method shows that the driver had performed an evasive manoeuvre to avoid a hazardous situation in contrary to those rear-end struck incidents that were not detected, where the driver had slowed down and stopped in a controlled manner. Table 6 shows an excerpt of the detected rear-end struck incidents.

3.1.1. Sensitivity analysis of the threshold value of the critical jerk method

A sensitivity analysis of the success rate where the threshold value is set differently shows that an increased threshold value would lead to a lower success rate, and most probably to a lower level of false alarms as well. Two alternative levels of thresholds are tested, 0.8 g/s and 1.2 g/s, corresponding to the 95% confidence levels found by Bagdadi and Várhelyi (2012). The analysis shows that a 20% increase to 0.8 g/s in the threshold decreases the success rate by 9% and, correspondingly, a decrease of 20% to 1.2 g/s increases the success rate by a similar amount, 9%, see Table 7.

Corresponding sensitivity analyses of the longitudinal acceleration method, with a 20% change in threshold values, i.e. threshold set at -0.72 g and -0.48 g, show a decrease of 38% and an increase of 41% in success rate, respectively, see Table 8.

Table 6
Short description of an excerpt of road departures and rear-end incidents that are detected by our (critical jerk) method but not by the longitudinal acceleration method.

Rear-end struck
The lead vehicle slows and stops and the subject's vehicle must do the same. The following vehicle must suddenly slow and stop to avoid hitting the subject's vehicle
Lead vehicle decelerates and appears to come to a stop while the subject driver is looking left. Subject driver brakes and decelerates. The following vehicle almost hits the subject vehicle in the rear
Subject driver is driving around a curve and does not see the stop light. The driver must suddenly stop and steer to the left. The following vehicle must quickly stop to avoid hitting the subject's vehicle
Subject driver uses signal to indicate a turn into the right lane. A vehicle from the far right lane moves into the lane the subject driver intends to change into. Subject driver brakes suddenly and the following vehicle nearly hits the subject vehicle in the rear

Table 7
Sensitivity analysis by testing alternative threshold values for the critical jerk method.

Threshold values	Detected (total)	Success rate (%)	Change in success rate
Critical jerk = 1.0 g/s	548 (637)	86	–
Critical jerk = 0.8 g/s	595 (637)	93	9% increase
Critical jerk = 1.2 g/s	496 (637)	78	9% decrease

Table 8
Sensitivity analysis by testing alternative threshold values for the longitudinal acceleration method.

Threshold values	Detected (total)	Success rate (%)	Change in success rate
Acceleration = −0.60 g	345 (637)	54	–
Acceleration = −0.72 g	214 (637)	34	38% decrease
Acceleration = −0.48 g	487 (637)	76	41% increase

3.2. Relationship between involvement in hazardous situations and crashes

The 100-car study data set includes a total of 68 crashes of which 67 are used in this study due to missing data in one case. In 28 (42%) of the crashes the driver uses braking as the primary evasive manoeuvre, in 12 (18%) cases swerving is the manoeuvre and in 27 (40%) cases there are no evasive manoeuvres. The crashes are categorized by the type of incident. The most common crash type is road departure (34%) followed by rear-end striking (21%) and crashes where the driver crashes into fixed objects (21%), see Table 9.

Crashes categorized as "Other" involve objects or obstacles on the roadway and single vehicle crashes, or if the driver backs into an object or parked vehicle.

The relationship between the driver's crash and near-crash involvement within the 100-car study has been analysed previously by Guo, Klauer, Hankey, and Dingus (2010). However, in that study all types of crashes and near-crashes were included in that analysis as part of the analysis was to find environmental factors correlating with the occurrence of near-crashes. In the present analysis only near-crash events where the driver had performed an evasive manoeuvre, identified as a critical jerk, are included, which means, for instance, that events where another driver had performed the evasive manoeuvre, e.g. rear-end striking near crashes, and situations where the evasive manoeuvre was not critical enough to cause a critical jerk are excluded from further analysis. This resulted in 548 critical jerks, conducted by 88 drivers, to be included in the analysis.

Table 9
Distribution of crashes by incident type.

Crash incident type	Frequency	Percentage
Road departures	23	34
Rear-end striking	14	21
Other	14	21
Rear-end struck	11	16
Sideswipe	3	5
Vulnerable road-user or animal	1	1.5
Cutting-in vehicle	1	1.5
Total	67	100

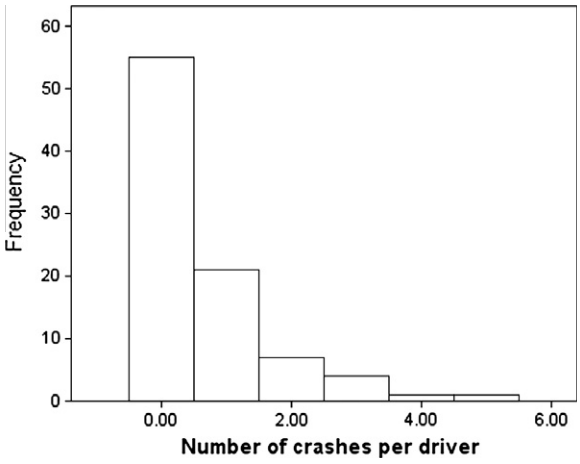

Fig. 1. Distribution of crashes among the drivers.

In addition, the eleven (11) rear-end struck crashes, where the subject driver had been hit by another vehicle coming from behind, suggesting that the other driver had failed to perform an evasive manoeuver are also excluded from further analysis concerning the relationship of a driver's involvement in hazardous situations and crashes.

The remaining 56 crashes were caused by 34 drivers: 21 were involved in one crash, 7 in two crashes, 4 in 3 crashes, one in 4 crashes and one in 5 crashes. The other 54 drivers were not involved in a crash, see Fig. 1.

The distribution of critical jerks among drivers for crash involved drivers and non-crash involved drivers are shown in Fig. 2.

The characteristics of the critical jerks are shown in Table 10 divided by drivers with and without crash involvement.

A Poisson regression analysis was carried out to analyse the relationship between the number of crashes the driver was involved in during the trial, and the number of critical jerks the driver had performed. Gender and age of the drivers were also included in the model to ensure that any potential effect would be accounted for. The drivers were divided into three age groups, 18–24, 25–44 and 45+ years.

The model setup was as follows:

$$y_i \sim \text{Poisson}\ (\lambda_i)$$

$$\log(\lambda_i) = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_5 X_{5i}$$

where y_i is the number of crashes; λ_i is expected number of crashes; X_{1i} is number of critical jerks for driver i; X_{2i} is gender of driver i, X_{3i}–X_{5i} is age group of driver i (18–24, 25–44 and >44 respectively), and β_0–β_5 is the regression parameters.

Neither gender nor age showed any statistical significant effects and they have been excluded from the model. The final model fitting parameters are $\beta_0 = -1.0$ and $\beta_1 = 0.06$ (p-value < 0.001). The model shows that for each increase of critical jerk the driver performs, the expected accident involvement increases by a factor of 1.1 (exp0.06).

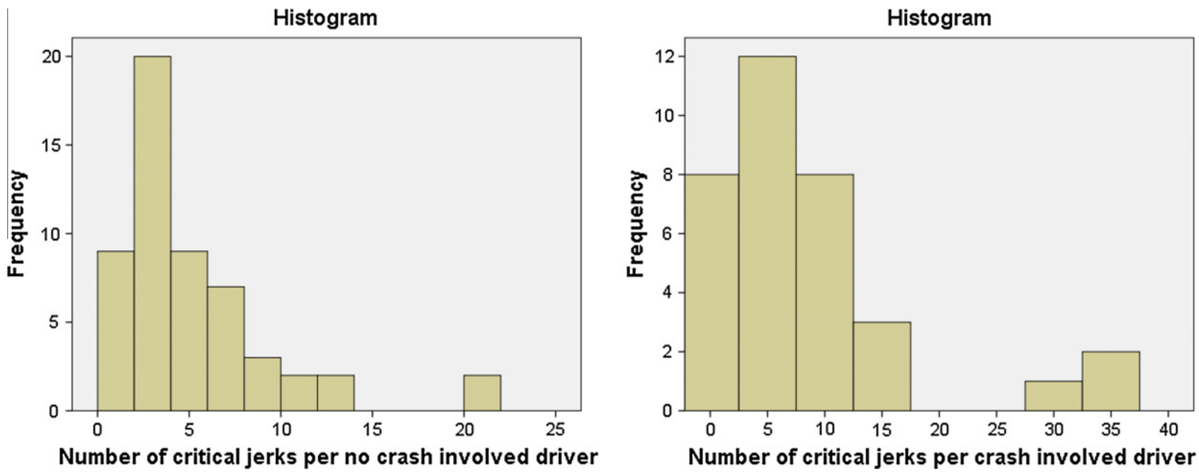

Fig. 2. Distribution of critical jerks among the (left) non-crash involved drivers and (right) crash involved drivers.

Table 10
Mean values of critical jerks for crash involved drivers and non-crash involved drivers by gender and age groups.

	No crash involvement	Crash involvement	Total
Female drivers			
Number	18	16	34
Mean critical jerks	4.8	11	7.5
S.D.	4.5	11	8.5
Male drivers			
Number	36	18	54
Mean critical jerks	4.8	6.6	5.4
S.D.	4.4	7.3	5.5
Age group 1 (18–24)			
Number	15	16	31
Mean critical jerks	6.1	11	8.7
S.D.	5.5	6.9	8.1
Age group 2 (25–44)			
Number	19	13	32
Mean critical jerks	4.8	6.9	5.7
S.D.	4.7	9.7	7.1
Age group 3 (45–64+)			
Number	20	5	25
Mean critical jerks	3.8	3.8	3.8
S.D.	2.7	4.8	3.1

Even though neither age group or gender showed any statistical significant effects on the expected number of crashes, according to the Poisson regression model, a non-parametric Kruskal–Wallis test was conducted to evaluate the differences in crashes between the three age groups (18–24, 25–44 and >44) or gender. The Kruskal–Wallis test showed that there is a statistical significant difference between at least two of the age groups, ($H(2, N = 88) = 7.2$, $p = 0.027$). Follow-up Mann–Whitney tests were conducted to evaluate pairwise differences among the groups. The results show that 18-24 year old drivers were involved in more crashes than drivers above 44 years of age (mean rank 18–24 yr = 33, >44 yr = 23, $U = 252$, $p = 0.010$). No statistical significant difference was found between 18–24 year old drivers and 25–44 year old drivers or between 25–44 year old drivers and drivers above 44 years of age. No statistical significant difference was found between genders.

Regarding the number of safety critical braking events the drivers were involved in, a non-parametric Kruskal–Wallis test was conducted to evaluate the differences between the three age groups (18–24, 25–44 and >44) or gender. The Kruskal–Wallis test showed that there is a statistical significant difference between age groups, ($H(2, N = 88) = 9.9$, $p = 0.007$). Follow-up Mann–Whitney tests were conducted to evaluate pairwise differences among the three age groups.

The results indicate that 18–24 year old drivers conducted significant more critical jerks than 25–44 year old drivers (mean rank 18–24 yr = 37, 25–44 yr = 27, $U = 339.5$, $p = 0.030$). Similarly, the results show that 18–24 year old drivers were involved in more safety critical braking events than drivers above 44 years of age (mean rank 18–24 yr = 34, >44 yr = 21, $U = 204$, $p = 0.002$). No statistical significant difference was found between 25–44 year old drivers and drivers above 44 years of age or between genders.

4. Discussion

Our proposed method (critical jerk) performs statistically significantly higher success rates compared to the longitudinal acceleration method for detecting near-crashes; our method shows an almost 1.6 times higher detection rate (86% versus 54%). Certain types of near-crash situations are more difficult to detect than others for both methods, especially road departures and situations where the driver is in conflict with a following vehicle, denoted as rear-end struck incident type. However, our method performs better than the longitudinal acceleration method in both of these types of situations as well, with approximately 4 times better success rate for detecting Road departures (62% versus 15%) and 2.4 times better success rate for detecting Rear-end struck (63% versus 26%).

Near-crash situations involving vulnerable road-users, rear-end striking and crossing vehicles are situations that are very well detected by the critical jerk conducted by the driver. These kinds of near crashes are characterized by the need of the driver to make the evasive manoeuvre, in contrast to the "rear-end struck" situations where the evasive manoeuvre is performed by the following vehicle. In cases, where the driver recognizes the potential hazardous situation very late, or even after the fact that the hazard has materialized, an abrupt evasive manoeuvre is often needed to avoid a crash, causing higher rates of change in acceleration, i.e. high levels of jerk.

An important note is that although the driver brakes to avoid a crash with, for instance, a vulnerable road-user or a crossing vehicle at an intersection, the relatively low speed that is common in these situations decreases the maximum possible deceleration of the vehicle as a response to the braking manoeuvre. Consequently, the longitudinal acceleration method does not recognise these events as critical. Thus, a key difference between our method and the longitudinal acceleration method is the sensitivity for the vehicle's speed at the onset of braking. While the longitudinal acceleration method is sensitive to both high and low vehicle speeds, due to limitations in the vehicle's braking capacity and the physical law of movements, our method is capable of detecting abrupt braking responses irrespective of vehicle speed (Bagdadi & Várhelyi, 2012).

A sensitivity analysis determines how sensitive a method is to slight changes in the settings, here the choice of the threshold value. It also reflects the sensitivity to systematic variations in the data set, which is quite common between different data sets gathered with different methods. Although the threshold value is increased and decreased by 20%, i.e. a change of 0.20 g/s, of the original setting for our method, the change in its success rate does not exceed 10%.

This is to be compared to a 20% change, i.e. a change of 0.12 g, of the threshold of the longitudinal acceleration method, which results in an increase and decrease of 41% and 38%, respectively. By raising or lowering the threshold of critical jerk more or less abrupt brake actions respectively are detected by our method. However, a slight change of the threshold should not cause a very large change of detected events as this would cause a higher uncertainty of whether the number of detected events is trustworthy or not.

The frequency of critical jerks performed by each driver during the 100-car study correlates with the number of crashes he/she was involved in, and a Poisson regression model shows that the expected number of accidents a driver is involved in increases by a factor of 1.1 ($p < 0.001$) for each additional critical jerk the driver conducts. This could be compared with previous findings where the probability of an accident involvement increases by a factor of 1.13 for each additional critical jerk (Bagdadi & Várhelyi, 2011). Similar results are found by Guo et al. (2010) when examining the relationship between all near-crashes and crashes; i.e., an increase of the crash frequency by a factor of 1.23 for each near-crash the driver is involved in. However, by including all near-crashes, Guo et al. (2010) disregard the effect of incorrectly superimposing other drivers' behaviour onto the original driver's assessment.

Our study only includes near-crashes where the driver had carried out an evasive braking action, into consideration, i.e. safety critical braking events, while excluding near-crashes where the other driver had performed the evasive manoeuvre, in order to show a relationship between drivers' involvement in safety critical braking events and crashes, rather than between the occurrence of near-crashes and crashes.

The fact that 18–24 year old drivers were involved in more crashes than drivers above 44 years of age and younger drivers (18–24 years old) conduct more critical jerks than both 25–44 year old drivers and drivers older than 44 years indicates the consistency between crashes and our "critical jerk" method as a surrogate measure for crashes. No statistically significant differences were found between 25–44 year old drivers and drivers above 44 years of age or between genders.

5. Conclusions

Studying driver behaviour is important for understanding the mechanism of accident causation. However, behavioural studies have difficulties in collecting the necessary data especially pertaining rare-event situations such as crashes or near-crashes. Similarly, studying erroneous behaviour such as lapses of attention or distraction could also give further understanding of the mechanism behind a specific behaviour and facilitate the development of e.g. driver education or information campaigns targeting specific attitudes or behaviour in car driving.

The method proposed in this paper endeavours to vastly improve the collection of data from rare-events and thus facilitates further development and improvement of driver behaviour models by improving the availability of data that is recorded in large driving studies. Furthermore, the proposed method may also be used to determine the characteristics of drivers' evasive manoeuvres in any situation, facilitating the work of driver behavioural models and the understanding of drivers' perception of their action boundaries (Fajen, 2007). However, further research and development are needed to incorporate both longitudinal and lateral manoeuvres in the method, which is a necessity for the analysis of evasive manoeuvres other than braking.

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