Analysis of the role of inattention in road crashes based on naturalistic on-board safety monitoring data

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Abstract

The general objective of the present analysis was to investigate the role of driver inattention in rear-end crashes and crossing path intersection crashes. To this end, a set of 133 naturalistic crashes (70 rear-end and 63 intersection crashes), obtained by means of the DriveCam on-board safety monitoring (OBSM) system, were analyzed based on a novel methodology for assigning and aggregating crash-contributing factors. The analysis focused on rear-end crashes where the OBSM-instrumented vehicle was striking a lead vehicle and crossing-path intersection crashes where the driver of the instrumented vehicle intended to proceed straight through the intersection. It was found that driver inattention, in particular driver distraction involving a diversion of gaze from the forward roadway, was the dominating factor contributing to the rear-end crashes. Although driver inattention also contributed to the intersection crashes, the patterns of contributing factors for this crash type were quite different compared to the rear-end crashes. In particular, in the intersection crashes, visual occlusion and insufficient selection of safety margins were identified as key contributing factors. Cognitively distracting activities that did not involve a diversion of gaze from the forward roadway, such as cell phone conversation, did not contribute frequently to avoidance failures for any of the crash types. The present results show that the role of driver inattention as a crash-contributing factor depends strongly on the type of crash. They also support previous findings from naturalistic driving studies that visual diversion from the forward roadway is the key mechanism by which inattention leads to rear-end crashes.

Introduction

Driver inattention is generally considered one of the most important factors behind road crashes (Dingus, Hanoswki and Klauer, 2011; Treat et al., 1977; Wang, Knipling and Goodman, 1996). However, despite extensive research efforts, there is still a limited understanding of *how* inattention contributes to road crashes. For example, how do different forms of inattention (e.g., visual-manual vs. auditory-vocal distraction, sleep-related impairments etc.) contribute and do these contributing mechanisms differ between crash types?

Traditional on-site crash analysis is of little help in answering these types of questions as it provides an incomplete picture on the events preceding the crash. However, recent naturalistic driving (ND) studies have greatly advanced our understanding of the pre-crash phase. Such studies have so far mainly focused on the statistical estimation of risk associated with different driver activities. The consistent finding is that the risk of being involved in a safety-critical event (e.g., a crash or near-crash) increases significantly during activities requiring the driver to take the eyes off the forward roadway (see, e.g., Dingus, Hanowski and Klauer, 2011). However, non-visual, purely cognitively loading, tasks, such as phone conversation, have not been found to be associated with increased risk in these studies (Dingus, et al., 2011; Fitch et al., 2013). A further general finding in recent ND studies is that safety-critical events are typically due to the *co-occurrence of inattention and an unexpected external event* (e.g., a lead vehicle suddenly braking; Dingus et al., 2006). However, existing ND studies have generally not addressed such underlying crash-contributing mechanisms in further detail. Moreover, these studies have involved relatively few crashes (typically in the range of 20-70 crashes) and have thus mainly used near-crashes and incidents as the basis for the statistical analysis.

This paper explores an alternative approach to ND analysis, making use of data collected from on-board safety monitoring (OBSM) devices used in commercial safety management programs. Rather than collecting continuous data, as in traditional ND studies, such devices record safety-critical events based on kinematic triggers. Due to commercial incentives, OBSM devices are typically installed in a much larger number of vehicles than is feasible in traditional ND studies, which enables the collection of large samples of detailed naturalistic crash and near-crash data. Hickman, Hanowski and Bocanegra (2010) conducted an analysis of the risks associated with driver distraction based on a sample of OBSM data, collected by means of the DriveCam system (see www.drivecam.com), which contained more than 2,000 crashes, 24,000 near-crashes, and 204,000 incidents. The results generally confirmed those obtained in ND studies that employed continuous data collection (e.g., Dingus et al., 2011; Fitch et al., 2013). One key advantage of using OBSM data is that the large samples of crashes allow for the selection of specific crash types for analysis. This enables a detailed analysis of factors contributing to specific crash/near crash types as well as the aggregation of cases in order to elicit common patterns of contributing factors. Habibovic et al. (2013) performed such an analysis of factors contributing to vehicle-pedestrian incidents at intersections based on Japanese OBSM data. However, this type of analysis has not yet been applied to crash data.

The present analysis focused on two types of crashes in event-triggered data obtained from the DriveCam OBSM system: 1) rear-end crashes where the OBSM-equipped vehicle (henceforth referred to as the Subject Vehicle, SV) was striking a leading Principal Other Vehicle (POV) and 2) crossing path crashes in intersections where the SV driver intended to proceed straight through the intersection and a POV encroached into the SV's path. Rear-end crashes account for about 33 % of all police reported crashes in the U.S. while crossing path intersection crashes account for about 21 % according to the National Automotive Sampling System (NASS)/General Estimates System (GES) data from 2010 and 2011 (Kusano and Gabler 2013). The general objective of the present analysis was to better understand to what extent, and how, driver inattention contributes to crash avoidance failures for these two crash types. More specifically, we were interested in the contributing roles of 1) inattention versus other contributing factors, 2) the roles of different forms of inattention, in particular driver distraction, and 3) the role of driver distraction involving the diversion of gaze from the forward roadway versus non-visual, purely cognitive, distraction. A further objective was to examine the nature of the external unexpected events (e.g., a stopped, braking or encroaching POV) that co-occurred with inattention in these crash types.

The present analysis focused specifically on factors contributing to the last-second failure to avoid the crash by means of braking and/or steering. Hence, “upstream” factors that led to the development of the safety-critical event in the first place (e.g., initial failures to pick up predictive information, such as a red traffic light or a traffic queue building up ahead), which may also be due to driver inattention, are not addressed in the present paper. Such upstream factors will be the subject of further analysis of the present dataset.

The analysis was based on a novel accident coding scheme, and an associated accident model, developed specifically for the detailed analysis of crash contributing factors in ND data. In particular, to analyze the role of different sub-categories of inattention, clear-cut definitions of these sub-categories are needed. To this end, an inattention taxonomy recently developed by a US-EU expert group (Engström et al., 2013) was applied.

Method

Crash scenarios

As mentioned above, the present analysis focused on two crash types: 1) read-end (SV striking) and 2) crossing path in intersections (SV going straight). The selection of crash events was conducted by viewing the video recordings of the crashes and applying the following criteria: 1) selection of specific sub-scenarios (see below), 2) the driver should not wear sunglasses, and 3) the speed of the SV should be higher than 15 km/h at the start of the evasive maneuver or the moment of crash impact. The latter criterion was imposed in order to exclude low-speed stop-and-go rear-end crashes which are less interesting from a road safety perspective. Furthermore, only crashes with adult SV drivers (no teen drivers) where included in the study.

For the rear-end scenarios, the following additional criteria were applied: 1) the POV should remain in the same lane from the beginning of the event until the crash, and 2) heavy vehicles (trucks and buses) were prioritized. This resulted in a sample of 70 rear-end crashes that occurred between October 4, 2011 and March 1, 2012. 53 crashes occurred in the U.S. and 17 in Africa (South Africa, Nigeria, Zambia, and Zimbawe). In 26 cases (37 %), the SV was a passenger car, in 16 cases (23 %) the SV was a bus and in the remaining 28 cases (40 %), the SV was a truck. 64 (91 %) of the SV drivers were males. The crash times were distributed over the 24 hours, with peak at 6 to 8 AM.

The intersection scenarios were divided into a set of sub-types, as illustrated in Figure 1. An additional criterion applied for the selection of intersection scenarios was that the camera view should correspond to the SV driver’s view from the beginning of the recording until the start of the avoidance maneuver (or, in the absence of an avoidance maneuver, the crash). This criterion implies that crashes where the POV was visible to the driver before it was visible in the OBSM video were discarded, regardless of whether the driver had actually seen the POV or not. This resulted in 63 intersection crashes that occurred between October 26, 2011 and February 28, 2012.

58 occurred in the U.S. and five in Africa (a lack of GPS data for some events made it difficult to identify the country or state, although the continent, i.e., the U.S. or Africa, could always be determined with certainty based on the video). The distribution of scenario sub-types is given in Figure 1. In 32 of the intersection crashes (51 %), the SV was a passenger car, in 19 cases (30 %) a bus and in 12 cases (19 %) a truck. In 54 (86 %) of the intersection crashes, the SV driver was male, and in nine cases (14 %) female. The distribution of the time of day was generally similar as for the rear-end crashes with a peak around 6 to 8 AM.

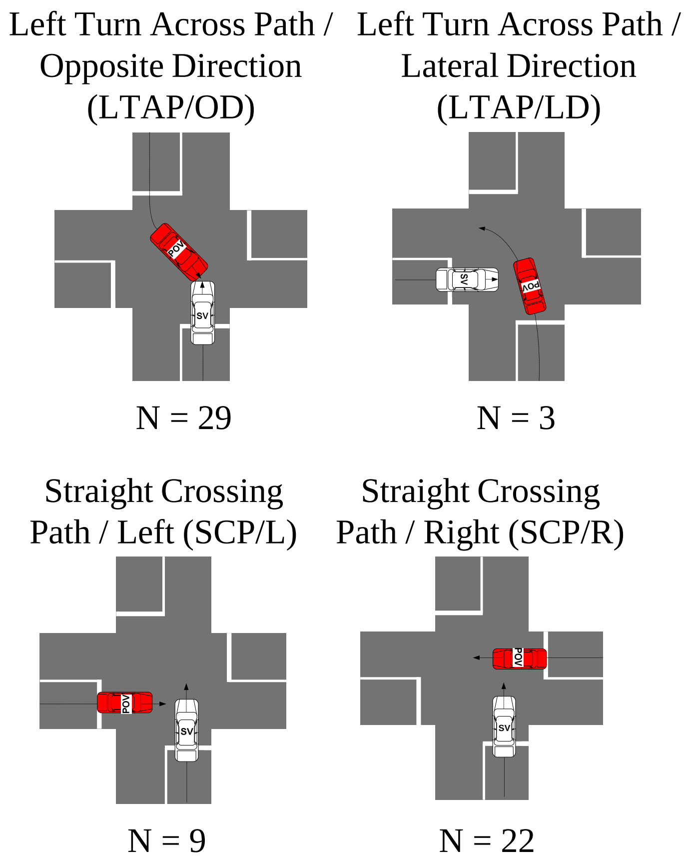

Figure 1. The four sub-types of the intersection scenarios crashes (N = 63). The white vehicle represents the SV and the red vehicle the POV

The DriveCam OBSM data

DriveCam offers a commercial service primarily aimed at commercial vehicle fleets, (e.g., logistics companies and bus fleets). The service includes the installation of an OBSM device that records safety-critical events based on kinematic triggers. This data is then used to coach drivers towards a safer and more efficient driving style in the context of a behavior-based safety management program (see www.drivecam.com). DriveCam currently has OBSM devices installed in over 120,000 vehicles, primarily in the U.S. and South Africa.

The data used in the present analysis consists of 1) forward scene video, 2) driver/cabin video, 3) lateral and longitudinal acceleration, 4) vehicle ground speed (based on Global Positioning System, GPS, data), and 5) global position (GPS-based). The OBSM device records data 8 s before and 4 s after the kinematic trigger point. GPS is collected at 1Hz and the other data at 4Hz.

Data reduction

Two types of data reduction were performed: 1) event coding of variables related to the entire crash event and 2) manual video annotation of time series data. The data reduction scheme was based on that used in the 100-car ND study (Dingus et al., 2006), but adapted for present purposes. The data reduction was performed by a trained analyst at DriveCam (the fourth author). The event coding included a *narrative*, describing how the event played out in text along with information traditionally coded in accident analysis (e.g., SV and POV vehicle types, road and intersection type, lighting conditions, SV driver gender and driver activity). The manual time series annotation involved frame-by-frame video analysis of 1) *POV width* on the screen as measured by ruler (using a single computer with a constant image size), 2) *POV turn onset*, 3) *POV brake light onset*, 4) *visual occlusion of the POV* (three levels: fully occluded, partially occluded or not occluded), 5) *visual behavior* (including eye closure), 6) *visual eccentricity* and 7) *the onset of the driver's physical reaction* (when driver reacted to the event by either face or posture changes).

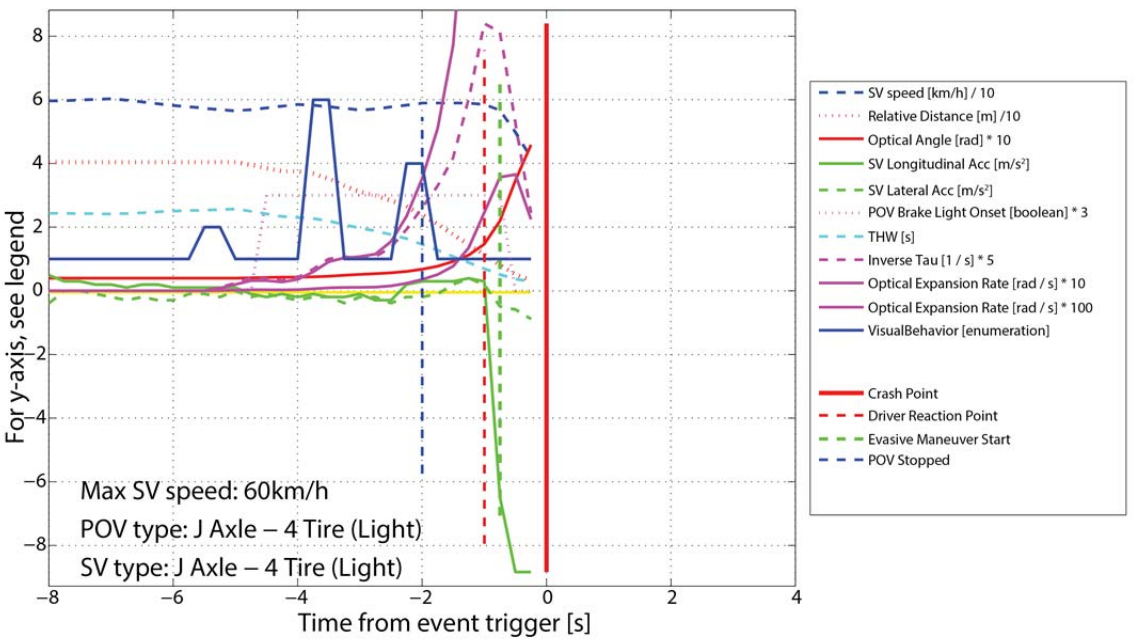

Figure 2 Example of a time-history plot used to support the analysis of crash-contributing factors. The four bottom legend entries represent the vertical lines, marking points in time. The number and mathematical operator to the right of some of the legend entries indicate the scaling applied to enable the fitting of all measures into one plot.

The time series sensor data and manually annotated time series data was further processed to obtain variables related to POV optical expansion and range between the SV and the POV. This involved camera calibration, image rectification, and various other forms of signal processing (for details see Bärgman et al., 2013). After the data had been processed and all relevant variables derived, plots were made for each crash event to support the qualitative analysis of crash-contributing factors further described below. An example plot is given in Figure 2.

Methodology for the analysis of crash-contributing factors

Crash-contributing factors were analyzed for each crash based on a novel coding scheme. The coding scheme provides operational definitions of key contributing factors and a tree-structure linking the different factors. Application of the coding scheme to a safety critical event thus results in a tree-structure of contributing factors, in a similar vein as the DREAM methodology (Habibovic et al., 2013; Wallén-Warner et al., 2008). These tree structures were then aggregated across events in order to elicit common patterns of contributing factors (see Figure 5 and Figure 6)

The coding scheme was derived from a general accident model illustrated in Figure 3. The central idea behind this accident model is that a normal driving situation evolves into a crash avoidance situation due to the *co-occurrence* of 1) one or more factors related to failures in the driver's control of safety margins and 2) a *precipitating factor*. Factors related to safety margin control failures are broadly divided into a) driver inattention (e.g., driver distraction), b) insufficient safety margins (e.g., close following behind a lead vehicle), and c) environment/vehicle factors (e.g., adverse visibility conditions and mechanical vehicle failures). A precipitating factor is here defined as *the state of environment or event that, given a co-occurring failure in the control of safety margins, brings about the incident, near-crash or crash*.

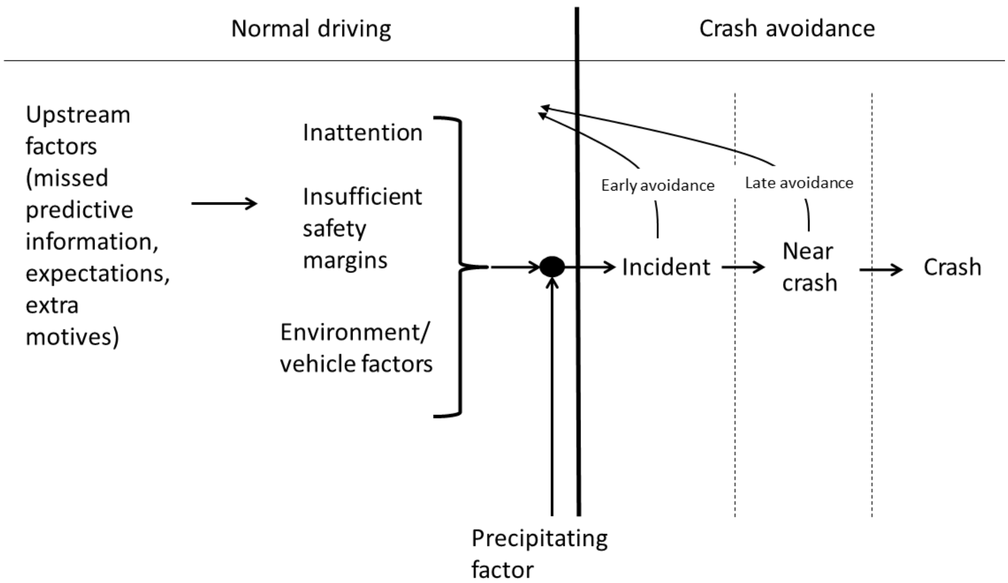

Figure 3 General accident model

The contributing factors in the coding scheme are grouped into three general categories:

1. *Avoidance failure:* This group represents factors characterizing the avoidance failure that led to the crash. Avoidance failures are divided into two general types: 1) a lack of avoidance maneuver and 2) insufficient time for the avoidance maneuver to be successful. Insufficient time available may, in turn, be due to the initial adoption of insufficient safety margins and/or due to a delayed initiation of the avoidance maneuver. The initiation of the avoidance maneuver is considered as delayed by a contributing factor (e.g., driver distraction) if the presence of that factor led to a later avoidance reaction than would have been the case if the factor had not been present.
2. *Factors contributing to avoidance failures:* This group contains factors related to safety margin control failures that contributed directly to an avoidance failure. Following the accident model outlined above, these factors are divided into three sub-categories: a) driver inattention (further detailed below), b) insufficient safety margins, and c) environment/vehicle factors. While insufficient safety margins contribute directly to insufficient time available, inattention and environmental/vehicle factors contribute mainly to delayed or lacking avoidance maneuvers.
3. *Precipitating factor:* This group represents the precipitating factor that induced the safety-critical events by co-occurring with one or more of the factors in the previous group. In the present crash scenarios, the precipitating factor always involved a stopped, slowly moving, braking or encroaching POV.

Of particular importance for the present analysis was the categorization of inattention. The present conceptualization and categorization of inattention was directly based on the driver inattention framework and taxonomy recently developed by a US-EU Working Group on Driver Distraction and HMI (Engström et al., 2013; see Figure 4). The four general sub-categories of inattention are defined below (see Engström et al., 2013, for further details):

Insufficient attention

- *Sleep-related attentional impairment*: The driver’s allocation of resources to activities critical for safe driving does not match the demand of these activities due to factors related to sleep regulation.
- *Insufficient attentional effort*: The driver’s allocation of resources to activities critical for safe driving does not match the demand of these activities due to an inability of the driver to mobilize sufficient attentional effort.

Misdirected attention

- *Incomplete selection of safety-critical activity:* The driver allocates sufficient resources to one or more activities critical for safe driving, or believed by the driver to be critical for safe driving, while the resources allocated to other activities critical for safe driving do not match the demands of these activities.

- *Driver distraction:* The driver allocates resources to a non-safety critical activity while the resources allocated to activities critical for safe driving do not match the demands of these activities.

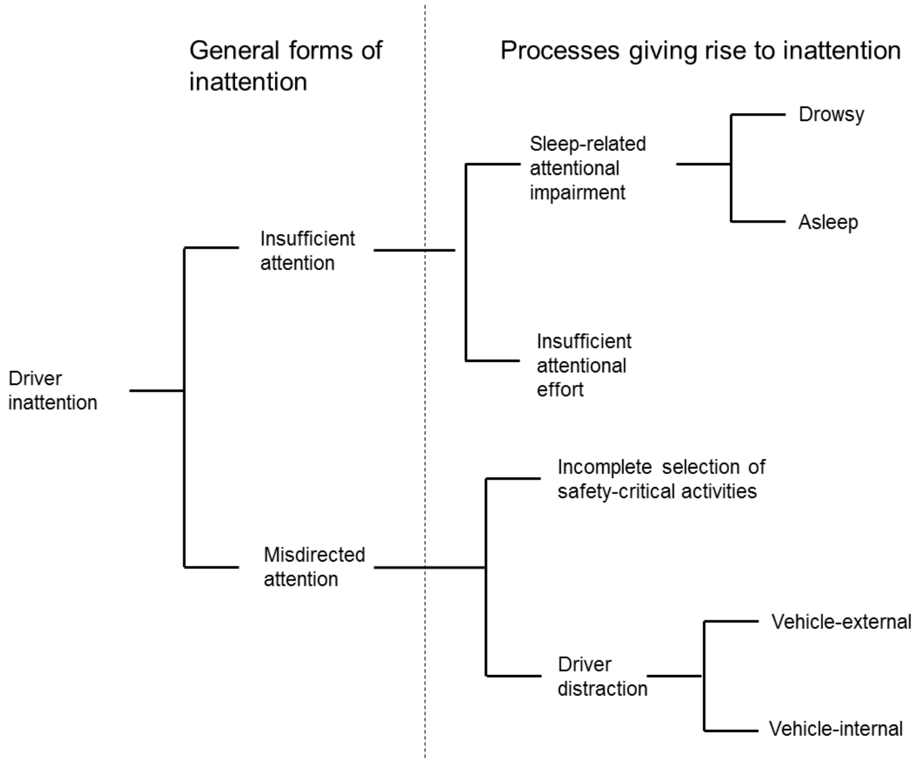

Figure 4. Inattention taxonomy (Engström et al., 2013)

The coding started with the avoidance failure and then worked backwards towards the factors directly contributing to the failure, and the precipitating factor. Only factors judged by the analyst to actually contribute to the crash were coded. A factor was judged to contribute if the absence of the factor would have led to a different outcome of the event (i.e., crash avoidance or reduced crash impact). Thus, the mere presence of a factor did not qualify it as a contributing factor.

Once the data reduction and processing was completed, two principal analysts applied the coding scheme to each individual event. The coding was mainly based on the reduced event and time series data, as well as snapshots of the forward road scene obtained from the crash videos. In addition, the crash video recordings were re-examined in order to resolve remaining open issues. Refinement of the coding scheme and clarification of the categorization by examples was iteratively performed until a final version was agreed upon. One analyst (the first author) carried out an initial coding of the rear-end crashes and another analyst (the second author) initially coded the intersection cases. The analysts then examined each other's initial coding and the final result was based on consensus within the analysis team.

Results

Rear-end crashes

The aggregated chart of contributing and precipitating factors for all 70 rear-end crashes is shown in Figure 5. The numbers on the links indicate the number of cases for which each factor contributed to another factor or the crash. In reading these charts, it should be noted that many of the contributing factors are not mutually exclusive and thus may co-occur in a specific crash. Hence, the numbers on the links for one group of factors do not necessarily sum up to the total number of crashes.

From Figure 5 it is clear that inattention was the dominating contributing factor in the rear-end crashes presently analyzed. 52 of the 70 rear-end crashes (74 %) involved at least one form of inattention as a contributing factor. Besides inattention, the main contributing factor in the rear-end crashes was close following, which contributed in 18 cases (26 %). Only in three of these cases did close following co-occur with inattention which indicates that drivers typically do not divert attention from the road when intentionally adopting a short following distance. When following closely, the drivers usually reacted quickly to the braking lead vehicle but were unable to bring the vehicle to a stop due to short following distance. Interestingly, 16 of the 18 close following cases involved heavy vehicles (i.e., trucks or buses) for which the maximum deceleration achieved was relatively low (<5 m/s^2). Environment-related factors contributed in 16 rear-end crashes (23 %). Mechanical vehicle failures were coded in two cases, both related to failures of the braking systems (where the maximum achieved deceleration was less than 2.5 ms/s^2 even though the driver seemed to have attempted to brake to maximum).

The most common *precipitating* factor in the rear-end crashes was when the POV braked in a following situation due to a braking or stopped road user ahead (25 cases; 36 %). In 19 cases (27 %), the POV braked to yield at an intersection. In 12 cases (17 %), the SV encountered a stopped or slowly moving POV, in six cases (9 %) the POV braked for no apparent purpose, in 4 cases (6 %) the POV braked to exit a main road and in the remaining four cases (6 %) the POV braked to merge into an adjacent lane.

The most common avoidance failure mechanism was a delayed braking and/or steering avoidance maneuver leaving insufficient time for the avoidance maneuver to be effective once initiated (45 cases; 64 % of all crashes). For the rear-end crashes, the delay was most often the result of inattention, which contributed in 42 of the 45 (93 %) crashes which involved a delayed reaction. In 13 of these cases, environment factors also contributed. Only in three cases was the delay solely due to environment factors. In 10 cases, all involving driver inattention, no avoidance maneuver was initiated prior to impact. There were 15 cases where the crash did not involve a delayed or missing reaction, but was rather solely due to insufficient time available for the maneuver to be effective. The great majority of these cases were due to the initial adoption of a too short headway (i.e., close following) when the POV suddenly braked (in 3 cases, the insufficient time available was due to both close following and a delayed reaction).

Of the four general inattention types, driver distraction was the most frequent, contributing to the crash in 30 cases (43 % of all rear-end crashes). Table 1 shows the distribution of the distraction cases into four sub-types defined based on 1) the location of the distracting object (vehicle-internal or vehicle-external) and 2) whether the distracting task involved a diversion of gaze from the forward roadway. Vehicle-internal distraction was about twice as common (20 cases) as vehicle-external distraction (9 cases). Furthermore, all but one of the distraction cases involved a diversion of gaze from the forward roadway. This shows that purely cognitive distractions, such as conversation on the phone or with a passenger, hardly contributed at all to avoidance failures in these rear-end crashes.

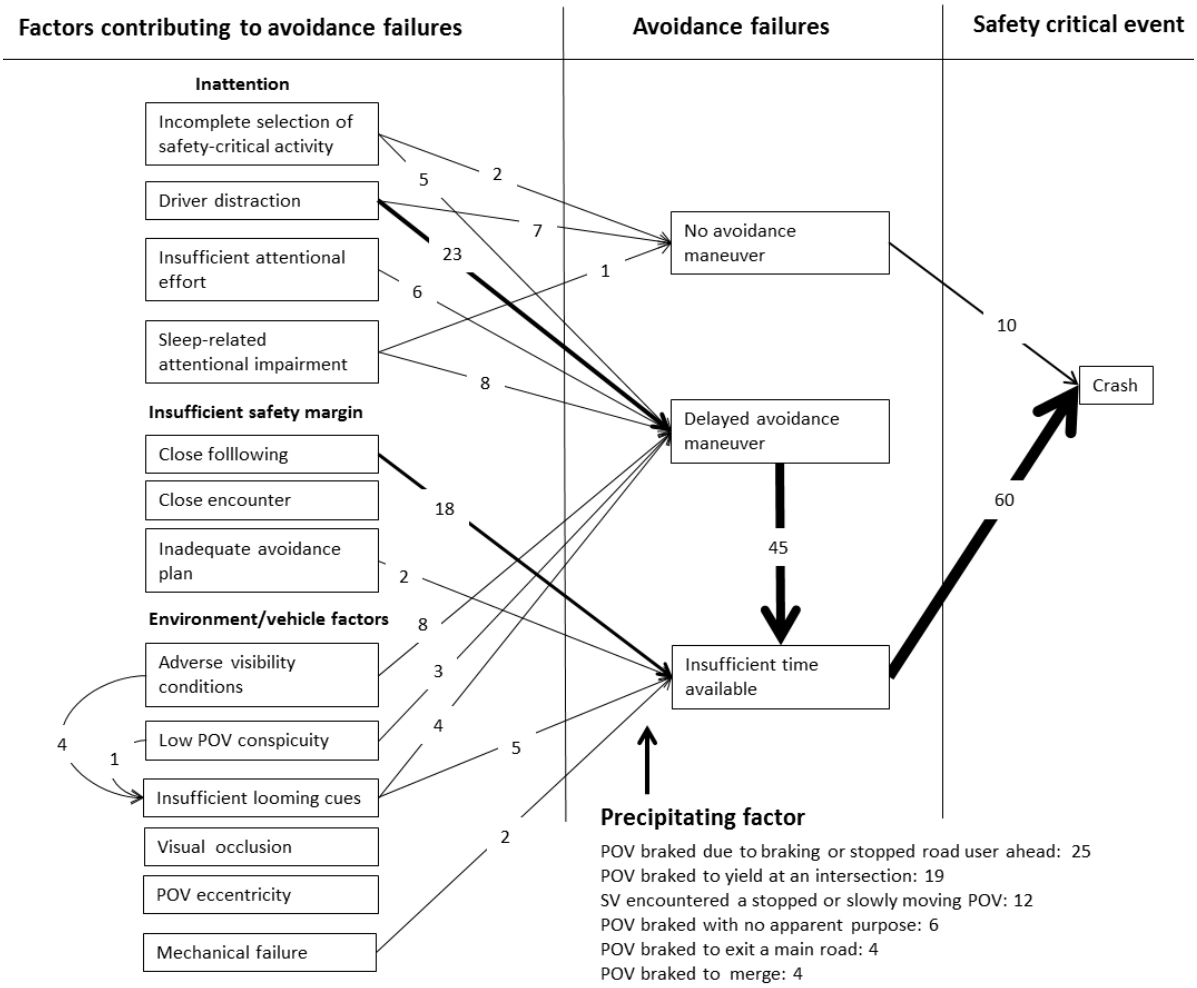

Figure 5. Aggregated chart of contributing and precipitating factors for the rear-end crashes (N = 70)

Cases where the avoidance reaction was delayed or lacking due to attention being allocated to other safety critical activities (i.e., incomplete selection of safety critical activities) contributed to the crash in seven cases (10 %). These safety-critical activities typically involved monitoring other vehicles and checking the mirrors before changing lane. Sleep-related attentional impairment contributed to crashes in nine cases (13 %). In five of these, the driver was judged as sleepy (e.g., exhibited long eye closures) and in four cases the driver was asleep at the wheel.

Finally, insufficient attentional effort was coded as a contributing factor in six cases (9 %). This factor was coded in situations where the SV driver had his/her eyes on the road, but it was judged the driver could have reacted earlier if s/he had mobilized additional attentional effort. In these cases, the drivers were judged to be relaxed and not involved in any attentionally demanding (driving or non-driving related) tasks. However, it should be noted that cases coded in this category could possibly involve non-observable forms of cognitive distraction such as daydreaming.

Table 1. Distribution of distraction sub-types for the rear-end crashes

Distraction type	**Number of crashes**	**Percentage of distraction crashes**
a. Vehicle-external distraction, no gaze diversion	0	0 %
b. Vehicle-external distraction, gaze diversion	9	30 %
c. Vehicle-internal distraction, no gaze diversion	1	3 %
d. Vehicle-internal distraction, gaze diversion	20	67 %
Sum	**30**	**100 %**

In summary, the present analysis suggests that the most common mechanism behind rear-end crashes is the co-occurrence of an off-road glance and an unexpected event, most often a lead vehicle braking unexpectedly in a following situation. This typically leads to a severe delay in responding to the closing vehicle, thus eventually leaving insufficient time for the avoidance maneuver to be successful.

Intersection crashes

The aggregated chart of contributing and precipitating factors for all 63 intersection crashes is shown in Figure 6.

Inattention contributed to 24 of the 63 intersection cases (38 %), which is substantially less than for the rear-end crashes (where inattention contributed to 74 % of the crashes). Rather, the main factor contributing to these types of intersection cases was a close encounter, which was coded in 53 cases (84 %). In the present coding scheme, a close encounter refers to a situation where the driver intentionally selected and pursued a path that did not leave sufficient room for a successful avoidance of the crash (e.g., the POV suddenly encroaches into the SV's path). In the present cases, this typically occurred in scenarios where the SV driver had (or believed s/he had) the right of way and entered the intersection on the assumption that the other road users would yield.

The third main contributing factor behind the intersection crashes was visual occlusion (26 cases, 41 %). The majority of these cases (69 %) involved visual occlusion by dynamic external objects, such as waiting or parked vehicles at the intersection. Visual occlusion due to static external objects (e.g., buildings, hills etc.) was coded in 27 % of the occlusion cases.

The most common precipitating factor, present in 47 of the intersection crashes (74 %) was when the POV encroached into the SV driver's path (turning across or entering straight across) road when the SV driver had the right of way. In 12 cases (19 %), the POV had the right of way. For the remaining cases (N = 4, 6 %), neither the SV nor POV had the right of way (e.g., both ran a red light).

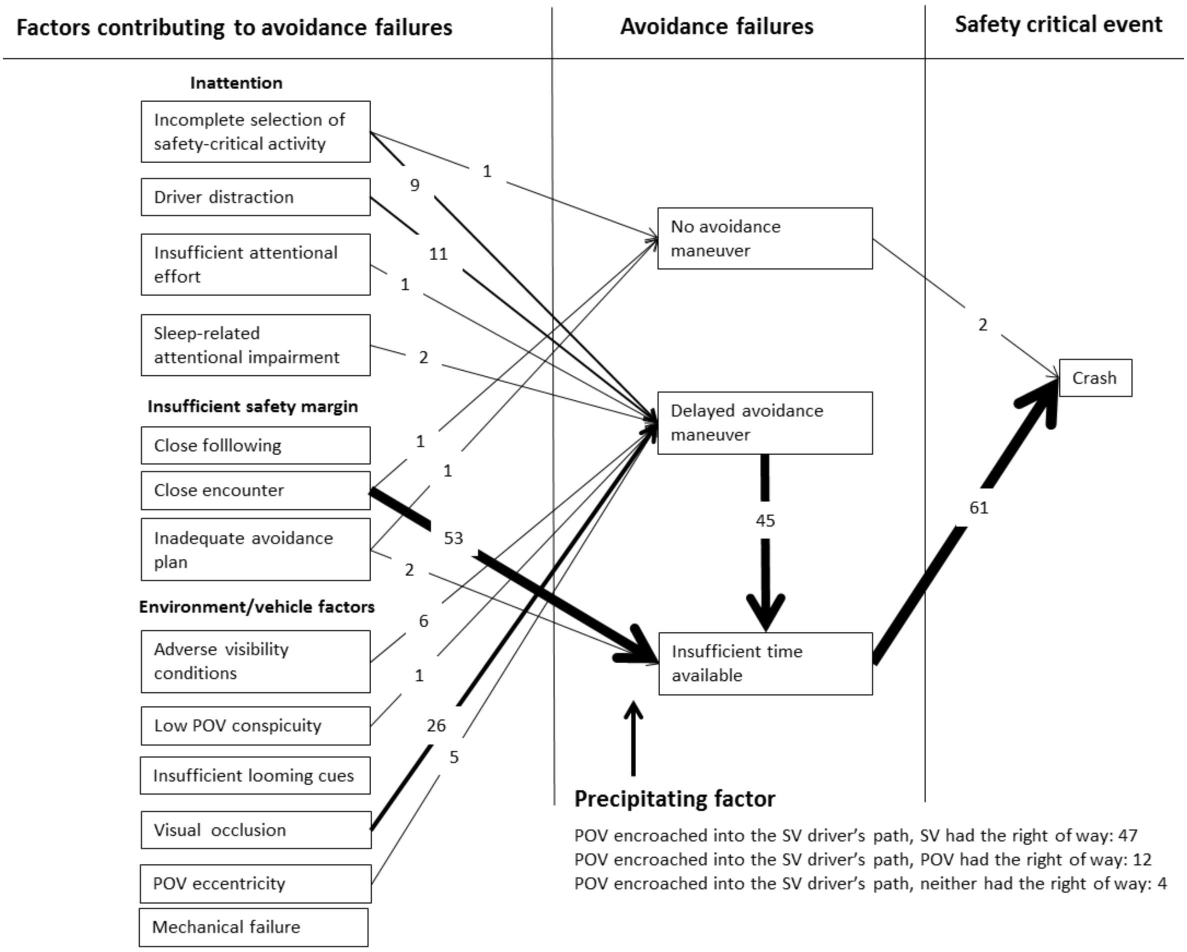

Figure 6. Aggregated chart of contributing factors for the intersection crashes (N = 63)

As shown in Figure 6, 45 of the intersection crashes (71 %) involved a delayed avoidance maneuver which led to insufficient time available to avoid the crash. The delay was typically due to inattention and/or visual occlusion. There were only two intersection cases where the SV driver did not initiate any avoidance maneuver prior to the crash. However, the insufficient time available was also often due to a small selected initial safety margin to the POV (i.e., a close encounter, 53 cases). In the majority (36) of these cases (68 %), the insufficient time was due to a close encounter combined with a delayed reaction. In 8 cases (15 %), the insufficient time was solely due to a delayed reaction and in 17 cases (32 %) the time was insufficient solely due to a close encounter.

Of the four inattention sub-categories, driver distraction (11 cases, 17 % of all intersection crashes) and incomplete selection of safety critical activities (i.e., attention being allocated to other safety critical activities; 10 cases, 16 %) were the dominating inattention factors contributing to 21 out of the 24 (88 %) inattention-related intersection cases. Sleep-related impairments were infrequent and only contributed in two cases. Of the 11 cases involving distraction, five were coded as vehicle-internal- and six as vehicle-external distractions. In all 11 distraction cases, the gaze was diverted from the forward roadway. Thus, as for the rear-end crashes, purely cognitive distraction does not seem to contribute frequently to avoidance failures in these types of intersection crashes.

Incomplete selection of safety critical activities typically involved cases where the POV approached from the right-hand side of the intersection, but the SV driver, having the right of way, looked towards vehicles approaching from the left-hand side or focused attention on the forward roadway thus failing to detect the POV approaching from the intersecting road.

As noted above, the SV driver had the right of way in 47 (74 %) of the present intersection crashes. It may be suggested that inattention would be more common as a factor contributing to avoidance failures in situations where the driver failed to yield. Indeed, of the 16 intersection crashes where the SV driver failed to yield, some form of inattention was involved in 9 cases (56 %). For the 47 cases where SV driver had the right of way, inattention contributed in 15 cases (32 %). It should be noted, however, that the present analysis only included factors contributing directly to avoidance failures (i.e., delayed or missing reactions to the POV). It is likely that inattention also played a key role in upstream failures such as missing a red light or failing to detect a stop sign, but these aspects were not addressed in the present analysis.

To conclude, in a typical intersection crossing path crash, the vehicle that intends to go straight (the SV in the present analysis) has the right of way and enters the intersection based on the assumption that other vehicles will yield. Another vehicle then fails to yield and suddenly encroaches into the SV's path, leaving insufficient time for the SV driver to avoid the crash. In addition, the reaction of the SV driver to the encroaching vehicle is often delayed due to visual occlusion, driver distraction involving gaze diversion or visual scanning of the road scene towards a different location than that of the encroaching vehicle.

Discussion

The general objective of the present analysis was to better understand to what extent, and how, driver inattention contribute to crash avoidance failures in two types of crashes: 1) rear-end crashes and 2) intersection crossing path crash scenarios where the SV driver intended to proceed straight through the intersection. The results indicate that inattention is the dominating factor behind rear-end crashes, in line with existing ND studies (e.g., Dingus et al., 2006). Also in line with Dingus et al. (2006), the key underlying mechanism was a delay in the initiation of the braking/steering avoidance maneuver due to a diversion of gaze from the forward roadway that co-occurred with the lead vehicle initiating braking. The visual diversion was most often related to driver distraction, that is, attention is diverted towards a non-safety critical activity. Sleep-related impairment was also a relatively common factor contributing to rear-end crashes.

However, it should also be noted that 26 % of the rear-end crashes were attributed to factors other than driver inattention. Closer examination revealed that the majority of these cases involved heavy vehicles that followed too closely behind the POV given its limited braking capacity. Thus, in these crashes, the driver generally reacted fast to the braking POV, but was still unable to avoid the crash due to insufficient time to bring the vehicle to a stop. This result indicates that close following is mainly a problem for heavy vehicles with limited braking capacity and, hence, an unusually long stopping distance.

For the intersection crashes analyzed here, driver inattention contributing directly to avoidance failures was less prevalent than in the rear-end cases. Still, inattention contributed to a relatively high number of cases (38 %). In contrast to the rear-end cases, driver distraction was not the dominating inattention sub-category. Incomplete selection of safety critical activity was almost as frequent as distraction and typically involved incomplete visual scanning of the intersection (see, e.g., Summala and Räsänen, 2000; Werneke and Vollrath, 2012, 2013, for related findings). Moreover, in the intersection crashes, visual occlusion, mainly due to other vehicles in the intersection, contributed to delayed avoidance maneuvers to a similar degree as did inattention. Another key mechanism was the acceptance of a small safety margin when passing through the intersection based on a strong expectation that other vehicles will yield (i.e., close encounter). However, it should be emphasized the present analysis was only concerned with drivers that intended to go straight through the intersection, who, in the majority of the present crash scenarios (74 %), had the right of way. Inattention may be expected to be a more prevalent factor in scenarios where the observed driver failed to yield. This is supported by the present finding that inattention contributed to avoidance failures in 56 % of the 16 crashes where the SV driver failed to yield (as opposed to 32 % when the SV driver had the right of way). This can be further investigated in future studies by specifically selecting intersection crashes where the OBSM-equipped vehicle did not have the right of way. It would also be interesting to investigate to what extent inattention contributes more upstream to the yielding failure itself (e.g., running a red light or a stop sign), an issue not addressed in the present analysis.

A general conclusion from the present analysis is thus that inattention contributes to crashes in different ways depending on the type of crash scenario, and most likely also depending on which vehicle in the scenario that is the object of analysis.

An important further implication of the present analysis is that purely cognitive distraction (e.g., induced by conversations on the phone or with a passenger) does not appear to be a factor frequently contributing to avoidance failures, at least not for the crash scenarios and drivers analyzed here. Distraction not involving gaze diversion from the forward roadway was only coded as contributing in one (rear-end) crash. This general result is in line with recent ND studies (e.g., Dingus et al., 2011; Fitch et al., 2013), and further extends these results to a larger sample of real crashes.

It should be stressed, however, that the lack of baseline data (i.e., data segments that do not involve a safety-critical event) in the present analysis precludes any direct estimation of crash risk. It is thus, in theory, possible that the low prevalence of cognitive distraction in the present crash data is due to a general reluctance of the present driver population to engage in such activities. However, recent studies have estimated that drivers today talk on the cellphone about 5 to 10 % of their driving time (see review in Fitch et al., 2013). Thus, if purely cognitive distraction due to cell phone conversation is a major factor contributing to crash avoidance failures, its prevalence in the present crash data would have been expected to be much higher. It may be objected that the fact that the crash-involved drivers in the present study participated in a safety management program would have made them less willing than the general driver population to engage in cell phone conversation (see Hickman et al., 2010 for a general discussion of this potential source of bias). While this may be true to some extent, the present drivers were clearly still very prone to engage in other, visual-manual, vehicle-internal, distracting activities.

Another possible objection is that purely cognitive distraction is difficult to identify solely based on video data. However, while this may be the case for certain forms of cognitive distraction (e.g., daydreaming), activities such as cell-phone- or passenger conversation are easily detectable from video. Moreover, when, in the present analysis, delayed or lacking avoidance reactions were not attributed to gaze diversion, the avoidance failure was generally explained by another factor such as sleep-related impairment or environmental factors (e.g., occlusions and adverse visibility conditions). The present results thus strongly suggest that purely cognitively loading activities do not directly contribute to avoidance failures by delaying avoidance reactions to critical events. However, it is still possible that cognitive distraction may play a role more upstream in the chain of events that led to the crash, for example by inducing failures to pick up relevant predictive information. This will be addressed in future analysis of the present dataset.

However, some further general caveats should be mentioned. First, it is unclear to what extent the present crash sample represents the general population of rear-end and intersection crossing path crashes in the U.S. and African countries represented in the data set. As already mentioned, one particular potential source of bias is that the present crash-involved drivers participated in a safety management program.

Second, in the present analysis, each case was initially coded by a single analyst and the final coding was the result of a consensus between this analyst and a second analyst who checked each case. However, the second analyst did not code the cases from scratch and, thus, no proper inter-rater reliability analysis could be conducted. Such an analysis is clearly an important topic for future work. Furthermore, this study represents the first application of the present coding scheme and, hence, cross validation between studies is not yet possible.

Third, the influence of substances, such as alcohol, is very difficult to determine solely based on video recordings. Hence, such contributing factors are most likely underreported in the present analysis.

Fourth, the present video frame rate of 4Hz clearly implies some limitations of the driver behavior analysis. In particular, blinks normally last between 0.1-0.4 seconds (Schiffman, 2001). It is thus likely that many short blinks were not captured by the video and the potential role of blinking as a crash-contributing factor may hence be underestimated in the present analysis. Moreover, some glances shorter than 0.25 seconds may have been missed in the present analysis. However, off-road glances in this range are relatively rare during driving (see, e.g., Rockwell, 1988) and thus this limitation is probably not too critical. The low sampling rate also limits the accuracy of the avoidance maneuver onset estimation. While this makes it difficult to measure small delays in braking/steering responses, the delays relevant for crash avoidance are normally in the range of seconds. Hence, the 4 Hz sampling rate should generally be sufficient for the type qualitative analysis conducted here.

In conclusion, OBSM crash data offers an extremely rich source of information for studying the detailed mechanisms behind road crashes, and the initial results presented here only scratch the surface of what can be analyzed in such datasets. One key topic for future work is the analysis of more upstream factors that lead to inattention or insufficient safety margins in the first place, such as expectations, extra motives and missed predictive information (where inattention could also be expected to contribute to failures to pick up predictive information). Further analysis will also explore combinations of factors in further detail. Another interesting topic is to conduct the type of analysis presented here also on near-crashes and investigate to what extent their patterns of contributing factors differ from crashes. Moreover, although the present paper focused on qualitative analysis, the present data also offers interesting possibilities for quantitative analysis, for example of drivers' reactions to visual cues such as looming and turn onsets. Furthermore, if the OBSM device is programmed to randomly sample baseline events, quantitative risk estimation similar to that conducted for continuous ND data could be performed (such an analysis was conducted by Hickman et al., 2010, although the baseline segments in this study were not randomly sampled but consisted of kinematically triggered, non-safety relevant, events). Finally, a very interesting area for further research would be to combine the present type of analysis with interviews with the crash-involved drivers (as traditionally conducted in in-depth crash analysis; e.g., Wallén-Warner, 2008). This would, in particular, provide useful complementary information on upstream factors that led to the crash, such as driver expectations and motives.

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