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REPORT

Combining Virtual CRASH and MADYMO to reconstruct motor vehicle collision dynamics and assess injury risk to occupants

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ABSTRACT
We evaluated Virtual CRASH motion output as input to MADYMO for assessing risk of injury to rear seat occupants of a vehicle involved in a three-vehicle collision. The vehicle accelerometer records captured by the vehicle's EDR served as a reference. We determined that Virtual CRASH can faithfully reproduce crash scene evidence and general vehicle motion, but it overestimates peak accelerations during impacts, which would lead to overestimating the risk of injuries. Although EDR records provide a reliable input for MADYMO, since they are only 0.3 s in duration and represent vehicle motion in the reference frame of the vehicle, their utility in reconstructing events following an impact is limited. We demonstrate the utility of combining Virtual CRASH with MADYMO to reconstruct the entire sequence of events during the collision and accurately assess the risk of injury to the rear seat occupants of the most damaged vehicle.

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Motor vehicle collision; virtual crash simulation; occupant dynamics; injury risk

Introduction

Motor vehicle crash simulation software such as PC-Crash and Virtual CRASH are frequently used to analyse collisions with pedestrians or cyclists [1–3]. However, there are few if any published studies in which such software packages alone are used to analyse the risk of injury to vehicle occupants in accidents involving two or more motor vehicles. In particular, Virtual CRASH can simulate the motion of vehicles during a crash based on initial conditions at the instant of impact [4,5], but since it does not provide any information about the dynamics of the vehicles' occupants it cannot be used to assess the risk or severity of injury to the occupants. A complementary software package, MADYMO, is frequently used to assess motor vehicle safety. MADYMO is able to estimate the forces and torques on the bodies of the vehicle's occupants [6–9] but requires vehicle movement time history as input. Furthermore, it is not designed to simulate ensuing vehicle motion from initial conditions.

MADYMO incorporates a physical model of the vehicle and its occupants. The occupant models represent connected body segments that experience forces and torques based on their linear and angular accelerations. The kinematics and dynamics of the body segments are used to compute a number of injury criteria from which probability of injury severity can be determined for each body segment in the model. The most significant limiting factor in using MADYMO is the requirement for an accurate time history of the vehicle movement. Acceleration recorded by the vehicle event data recorder (EDR) can provide relatively accurate linear acceleration of the vehicle centre of mass. However, the duration of the recorded data is limited to 0.3 s following impact and does not include any information about the orientation of the vehicle relative to the world or its angular motion.

Although Virtual CRASH simulations can be used to estimate the vehicle acceleration, assumptions such as a fixed centre of impact, single coefficient of restitution and simplified deformation geometry, limit the accuracy of acceleration estimates during the impact duration. Because EDR acceleration data represent an accurate record of the vehicle's accelerometer signals, they are much more reliable than the vehicle acceleration obtained from a Virtual CRASH simulation. However, post-impact vehicle motion may last considerably longer than the 0.3 s records available from EDRs. Acceleration from Virtual CRASH simulations could, therefore, be used to supplement EDR data during post-impact motion, particularly since accuracy may be less critical during this period given that acceleration will generally be much lower and, hence, the forces and torques on the vehicle occupants will be lower than during the impact duration. In addition, important data for injury analysis such as the orientation, angular velocity and acceleration of the vehicle are generally not available from EDRs but can be obtained from Virtual CRASH simulations.

Being able to combine evidence from sources such as EDRs, tire marks and/or vehicle rest positions with simulations of vehicle dynamics and occupant dynamics, would provide more reliable and accurate reconstruction of a collision and injury risk assessment than relying on a single source of evidence. We present a case of a three-vehicle collision in which such evidence was used to generate a Virtual CRASH simulation. The Virtual CRASH output was then

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combined with EDR data to serve as input for MADYMO for establishing the risk of injury to two rear seat occupants of a vehicle involved in a three-vehicle collision.

Materials and methods

A loaded Chevrolet Silverado pulling a loaded Big Tex trailer hit the rear of a Chevrolet Cruze, which was following a Porsche Cayenne. Figure 1 shows the final positions of the vehicles following the collision. EDR data from the Cruze indicated that it was moving at 30 km/h when it sustained an initial impact producing forward acceleration that increased its speed by 67 km/h. The Cruze was following the Cayenne as a precaution since the Cayenne was on a spare tire. It can, therefore, be reasonably assumed that the Cayenne was travelling at the same speed as the Cruze. Based on EDR data recorded 0.5 s prior to impact, the Silverado was travelling at 113 km/h. Longitudinal and lateral acceleration of the Cruze were recorded at 0.002 s intervals by its EDR for 0.3 s from the time of impact. The Cruze sustained a second impact somewhat later, according to its EDR data. Since the Cruze sustained both rear-end damage and front-end damage, whereas the Silverado sustained only front-end damage and the Cayenne sustained only rear-end damage (Figure 2), it can logically be assumed that the second impact registered by the Cruze EDR was a front-end collision with the Cayenne. The final positions of the Cruze and the Cayenne were consistent with this assumption.

Tire marks were clearly evident in photos taken at the scene of the accident. However, given that there were four separate units involved in the crash (Silverado, Big Tex trailer, Cruze and Cayenne), each with four or more wheels, attributing tire marks to specific units involved some uncertainty. The approach taken in attempting to resolve the tire marks, was to work backwards from the final positions of the Cruze and Cayenne to the initial tire marks associated with braking of the Silverado prior to impact with the Cruze. It was not possible to resolve all of the tire marks, particularly since some may have been left by following vehicles attempting to avoid colliding with the Cayenne or by emergency vehicles which responded to the accident. Nevertheless, the tire mark analysis suggested that the Cruze underwent a rotation of at least 400°, i.e. more than one complete rotation between the first impact and coming to rest in its final orientation (Figure 3). In addition, the tire mark analysis established positions for the Silverado and Cruze at the instant of impact and the position of the Cayenne when it was hit from the rear.

The Cruze EDR data provided only two 0.3 s separated segments of information about its motion during the collision and no information about its orientation in the world reference frame. To fill the gap between the EDR data segments and to provide information about the orientation of the Cruze during the collision, a Virtual CRASH simulation was carried out. The longitudinal velocity of the Silverado and the centre of impact coordinates were adjusted in the Virtual CRASH simulations to obtain an output that met all of the following criteria: 1) the travel path of the Cruze after impact agreed with the tire mark analysis; 2) the travel path of the Cruze produced an impact with the Cayenne that agreed with the front-end damage to the Cruze and rear-end damage to the Cayenne; 3) the impact between the Cruze and the Cayenne resulted in motion of the two vehicles post-impact that agreed with their final positions; 4) the Silverado and Big Tex trailer avoided contact with the Cayenne; 5) the Big Tex trailer grazed the concrete median, consistent with the black marks found on the concrete median. Inputs to Virtual CRASH included the mass of the vehicles, the vehicle dimensions, the velocities of the vehicles just prior to impact, braking input for the Silverado, the centre of impact and the orientation of the vehicles at impact.

EDR acceleration data during the 0.3 s intervals after each impact were rotated by the Cruze yaw angle, provided from the Virtual CRASH output, so that they were represented in the coordinates of the world reference frame. Virtual CRASH velocity output was used to create the acceleration time history for the Cruze in the interval following the EDR data from the first impact until the onset of the second impact. Virtual CRASH produced velocity information at 10 ms intervals, i.e. 100 Hz. To match the EDR sampling rate, the Virtual CRASH velocity was resampled at 500 Hz using the *resample* function in Matlab. The resampled velocity was then low-pass filtered with a 100 Hz Butterworth filter using the *filtfilt* function in Matlab.

Figure 1. Resting positions of the three vehicles involved in the collision.

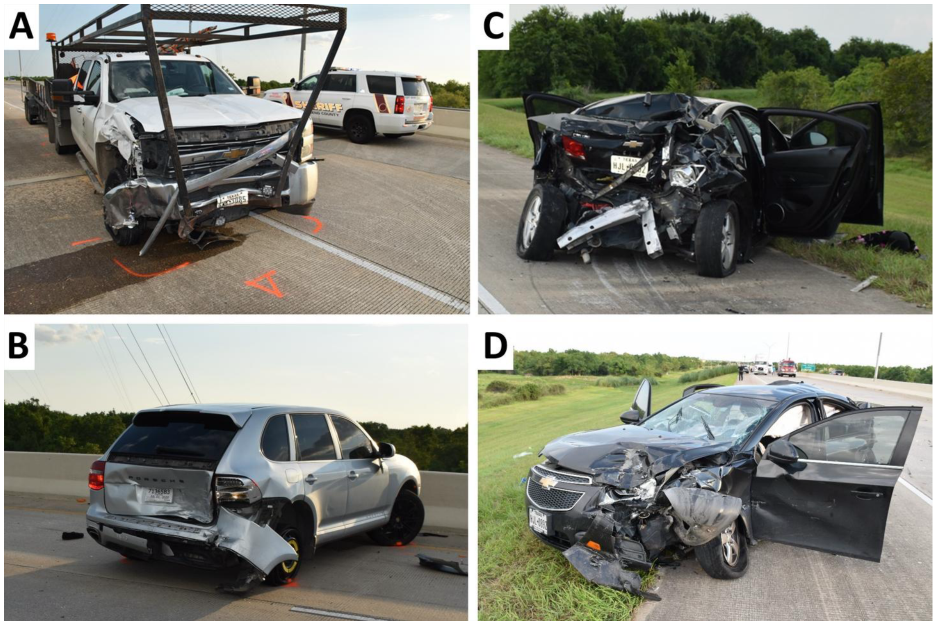

Figure 2. A. Front-end damage to chevrolet silverado B. Rear-end damage to porsche cayenne C. Rear-end damage to chevrolet cruze D. Front-end damage to chevrolet cruze.

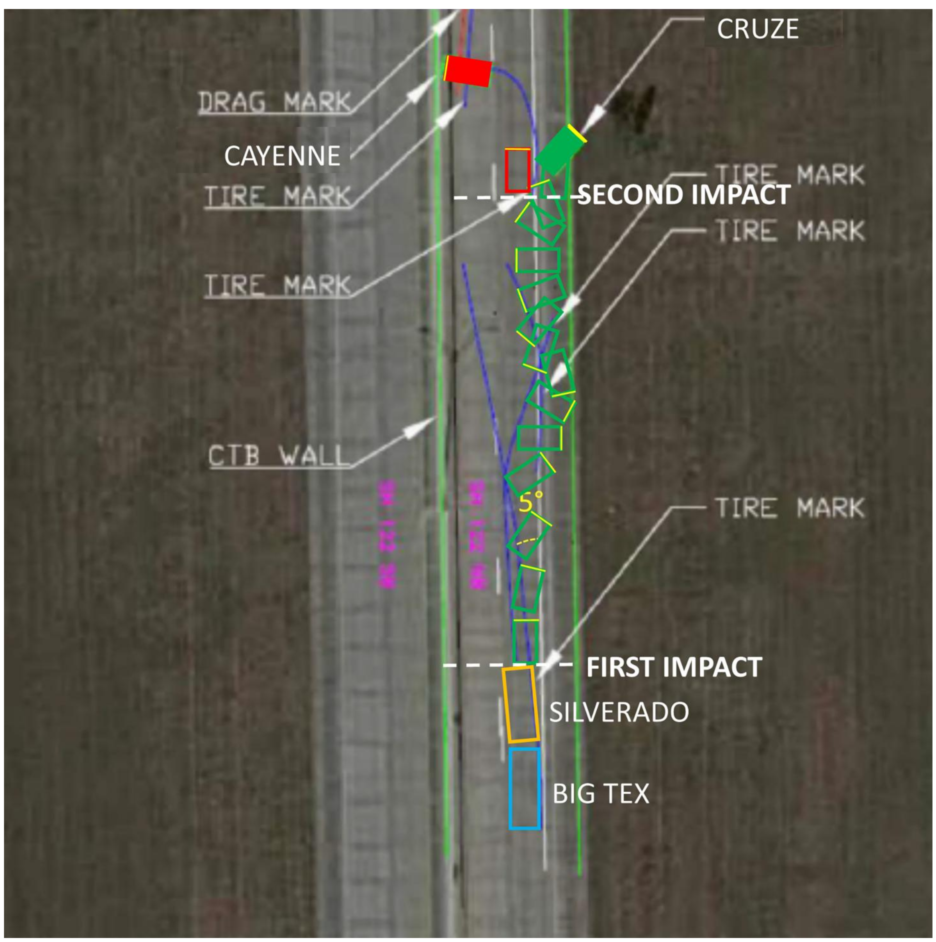

Figure 3. Tire mark analysis showing the reconstructed travel path of the cruze (green rectangles) and the positions of the silverado (orange rectangle) and cayenne (red rectangle) at the time of the first and second impacts, respectively. Filled rectangles show the rest positions of the cruze and cayenne. Yellow line segments indicate the front end of the vehicle.

The filtered velocity was differentiated to obtain acceleration. The acceleration derived from Virtual CRASH was also used to create the acceleration time history following the EDR data for the second impact until the Cruze came to rest. In this way, the EDR acceleration together with the interpolated Virtual CRASH acceleration were combined to create an acceleration time history for the entire duration of the Cruze motion that served as input to MADYMO for assessing the risk and severity of injury to the two rear seat occupants of the Cruze. MADYMO incorporated a model of the Cruze in which seats and pillars were represented by ellipsoids with the size and weight scaled to the specifications of the Cruze. The size of the seats in the MADYMO model were adjusted to match the size and position of the seats in the Cruze. The rear seat occupants of the Cruze were 4-year old and 8 year-old males. Hybrid III dummy models were scaled to the height and weight of the occupants to determine injury risk. Linear and angular head accelerations for the occupants were obtained from the MADYMO output.

Results

In order to obtain Virtual CRASH output which matched the evidence, as shown in Figure 4, it was necessary to set the initial linear velocity of the Silverado was to 121 km/h with the centre of pressure located 35 cm to the left of the rear-centre of the Cruz and 44.4 cm above the road. The Virtual CRASH simulation indicated that the Cruze did not come to a stop until 4.2 s after being hit from the rear by the Silverado.

The peak x-acceleration (parallel to the road) during the first impact in the Virtual CRASH simulation was 2284 m/s^2 (233 g) compared to 276 m/s^2 (28 g) recorded by the Cruze EDR (Figure 5A). The duration of the first impact, based on the x-acceleration, was approximately 0.11 s in the Virtual CRASH simulation compared to approximately 0.15 s for the EDR data. Despite the large difference in the peak acceleration, the x-force impulse, i.e. the area under the x-acceleration graph multiplied by the mass of the Cruze, only differed by approximately 8.3% for the 0.3 s after the onset of the impact, i.e. it was slightly higher when calculated from the EDR data than from the Virtual CRASH simulation. In the second impact, the peak x-acceleration was negative, −608 m/s^2 (-62 g) for the Virtual CRASH simulation compared to −275 m/s^2 (-28 g) for the EDR data. The duration of the second impact, based on the x-acceleration was approximately 0.16 s in the Virtual CRASH simulation compared to approximately 0.14 s for the EDR data. Again, despite the large difference in peak acceleration, the x-force impulse only differed by approximately 10%, i.e. it was slightly higher when calculated from the EDR data than from the Virtual CRASH simulation.

The y-acceleration during the first impact was initially positive but quickly became negative in both the Virtual CRASH simulation and EDR data (Figure 5B). The peak positive y-acceleration was 9.89 m/s^2 (1.01 g) in the Virtual CRASH simulation compared to 9.30 m/s^2 (0.95 g) recorded by the EDR. The y-acceleration rapidly became negative and primarily remained negative for the duration of the first impact. The peak negative y-acceleration in the Virtual CRASH simulation was −10.9 m/s^2 (-11.1 g) compared to −54.3 m/s^2 (-5.54 g) recorded by the EDR. The y-force impulse calculated from the Virtual CRASH simulation was only about 20% of that calculated from the EDR data, i.e. the Virtual CRASH y-force impulse was much lower. During the second impact, the peak y-acceleration in the Virtual CRASH simulation was −10.9 m/s^2 (-11.1 g) compared to −2.82 m/s^2 (-0.29 g) for EDR data. The y-acceleration for the EDR data was close to zero for most of the duration of the 0.3 s record, such that the calculated y-force impulse was close to zero whereas the y-acceleration in the Virtual CRASH simulation remained negative and, therefore, created a y-force impulse that was approximately 66 times the y-force impulse calculated from the EDR data.

The angular acceleration determined by Virtual CRASH was relatively low, with a magnitude less than 0.07 rad/s^2 throughout the entire rotational motion of the Cruze (Figure 5C). There was a negative peak of −0.059 rad/s^2 during the first impact, which initiated clockwise rotation of the vehicle, and a positive peak of 0.068 rad/s^2 during the second impact, which stopped the clockwise rotation. However, for most of the rotation the angular acceleration was near zero, indicating that the Cruze rotated at a relatively constant angular velocity.

The Virtual CRASH linear and angular acceleration output was used as input to MADYMO to assess the risk of injury to the two rear seat occupants of the Cruze. Since the EDR acceleration data was assumed to be accurate, whereas the Virtual CRASH simulation was based on a number of simplifying assumptions, the linear acceleration recorded by the Cruze EDR during the first and second impacts replaced the Virtual CRASH linear acceleration during the corresponding 0.3 s intervals. Transition between the EDR acceleration data for the first impact and the Virtual CRASH acceleration data involved linear interpolation from the time when the EDR acceleration effectively reached zero until 0.2 s from the end of the EDR record (as seen in Figure 5A). This was done because the Virtual CRASH acceleration during the impact did not return to zero as quickly as the EDR acceleration.

The MADYMO analysis showed that the peak head acceleration for both rear seat occupants occurred during the first impact. The resultant peak linear head acceleration experienced by the left rear seat occupant was approximately 2700 m/s^2 (275 g), creating a HIC of 5417, which was well above 99% probability for severe head injury (AIS $\geq$ 4). The resultant peak linear head acceleration of the right rear seat occupant (Figure 6) was approximately 1200 m/s^2 (122 g), creating a HIC of 589, which represents less than 50% probability of serious head injury (AIS $\geq$ 3). The resultant peak angular head acceleration experienced by the left rear seat occupant (Figure 7) was approximately 17,500 rad/s^2 and the resultant peak angular acceleration experienced by the right rear seat occupant was approximately 16,000 rad/s^2. Based on established head injury criteria, these peak accelerations indicated risk of severe to critical head and neck injury to both rear seat occupants during the first impact. In contrast, head accelerations were much lower during the remaining motion of the Cruze, including the second impact, resulting in negligible risk of additional injury.

Discussion

The Virtual CRASH simulation was able to generate vehicle motions consistent with evidence from the scene of the

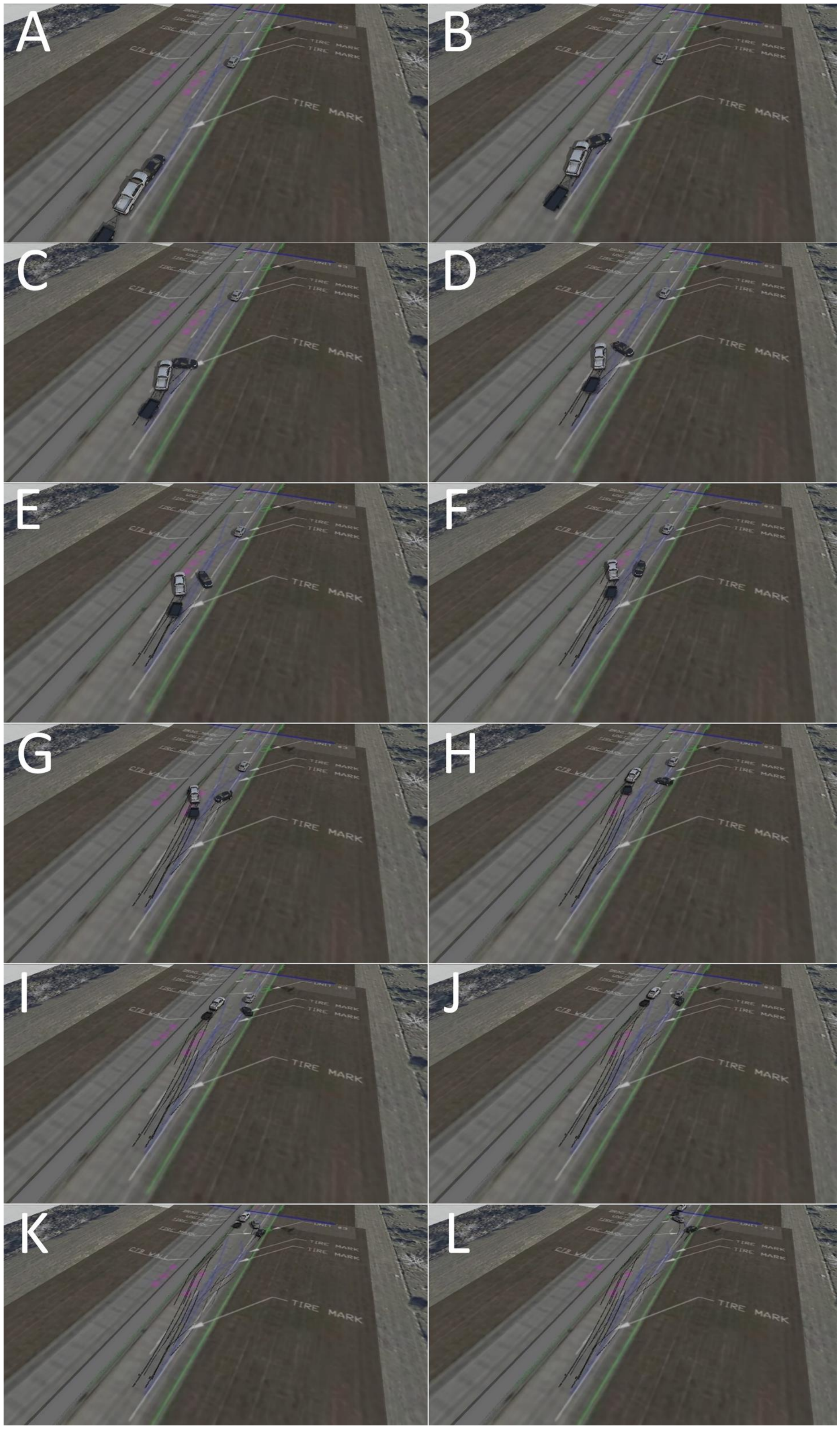

Figure 4. Sequential images from the Virtual CRASH simulation (A-L) starting from the first impact until reaching the rest position of the Cruze and Cayenne after the second impact.

collision. In particular, the force impulse associated with the first impact explained the severe damage to the rear of the Cruze and the damage to the front left of the Silverado. The rotation of the Cruze after the first impact generally matched the path determined from the analysis of the tire marks. It is also consistent with the Cruze striking the rear of the Cayenne at the approximate location of the second impact, as documented in the certified crash record. The orientation of the Cruze was such that the front left of the Cruze impacted the rear of the Cayenne to the left of centre,

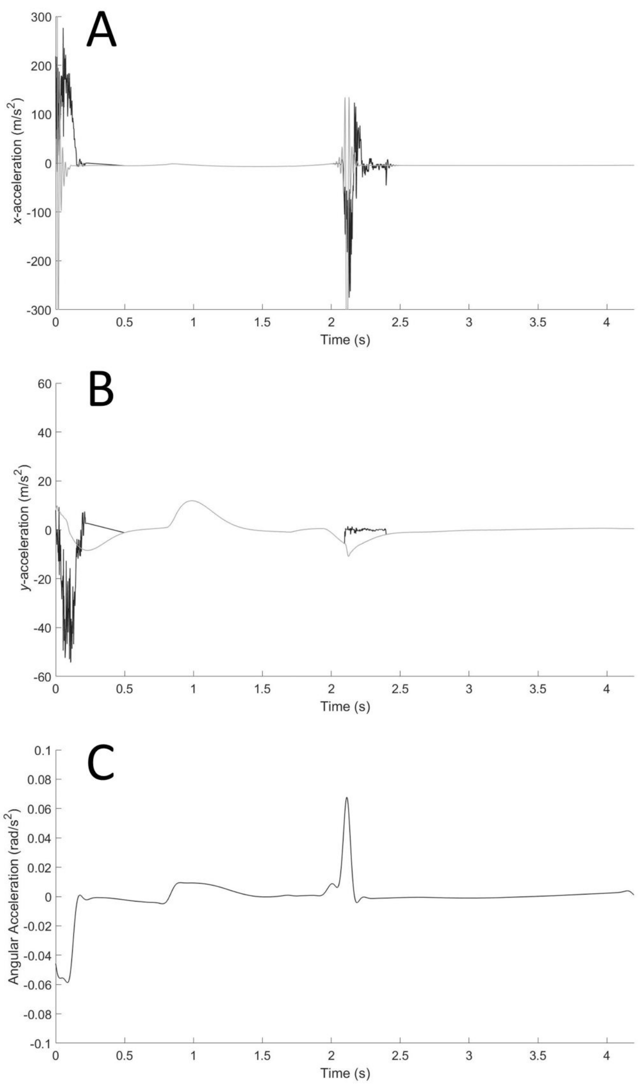

Figure 5. A. Cruze centre of mass acceleration in the *x*-direction from the virtual CRASH simulation (grey line; peaks are off scale) and from the EDR (black line) B. Cruze centre of mass acceleration in the *y*-direction from the virtual CRASH simulation (grey line) and from the EDR (black line) C. Cruze angular acceleration from the virtual CRASH simulation.

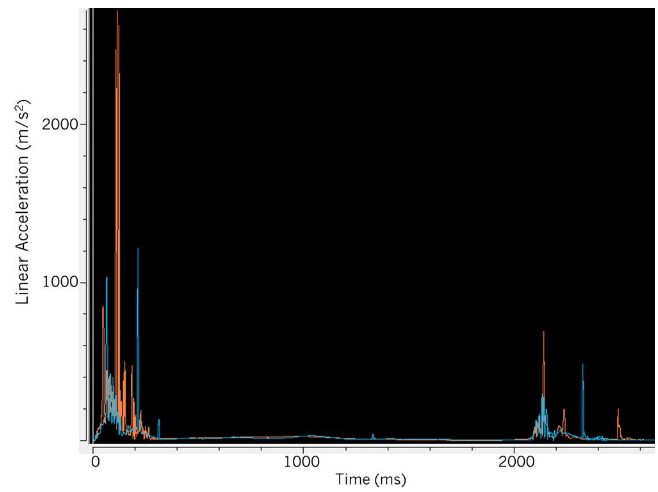

Figure 6. Head linear acceleration records from MADYMO with the red line representing the left side rear seat occupant and the blue line representing the right side rear seat occupant.

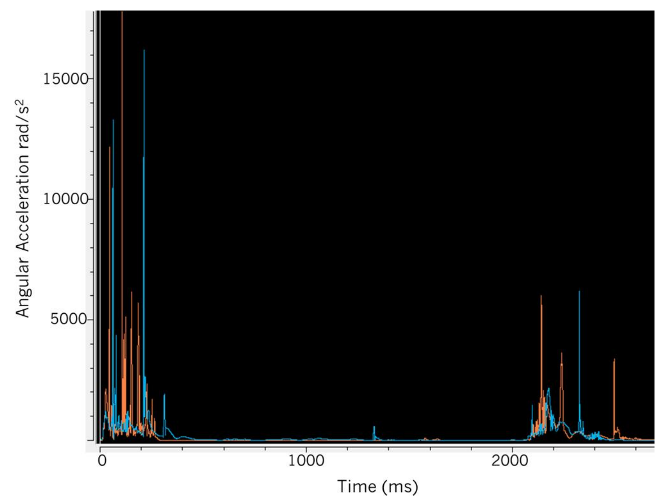

Figure 7. Head angular acceleration records from MADYMO with red line representing the left side rear seat occupant and the blue line representing the right side rear seat occupant.

consistent with the damage to the front left of the Cruze and the rear of the Cayenne (Figure 2). Furthermore, the Silverado and Big Tex trailer were able to pass by the Cayenne before the Cayenne veered into the left lane and the Cayenne stopped moving before contacting the concrete median barrier, avoiding damage to the front of the vehicle. Given the consistency of the Virtual CRASH simulation with the evidence from the accident scene, the angular motion predicted by the Cruze simulation was presumed to be valid and, therefore, sufficiently accurate to be used as input to MADYMO for simulating the effect of the collision on the occupants of the Cruze.

However, since the Virtual CRASH simulation is based on simplifying assumptions about the mechanics of two colliding vehicles, which treat each vehicle as a rigid body with a single coefficient of restitution, whereas vehicles have complex geometries and are constructed from a variety of materials with very different mechanical properties, the acceleration recorded by the EDR provided a more accurate representation of the dynamics during the impact than the Virtual CRASH simulation. The Virtual CRASH simulation indicated that the duration of the sequence of events from the first impact to the final rest position of the Cruze and Cayenne encompassed 4.2 s. Since the two 0.3 s records from the Cruze EDR comprised less than 15% of the duration of the event, the EDR data provided only a fraction of the total vehicle movement following impact and, furthermore, did not include any information about the orientation of the vehicle relative to the world or its angular acceleration. Therefore, it would not have been possible to reconstruct the entire collision event based on EDR data alone, even though the EDR data was more accurate than the Virtual CRASH simulation. The Virtual CRASH simulation was able to fill the large gaps in the event to provide a complete time history of the vehicle motion.

Although the acceleration derived from the Virtual CRASH simulation during the impacts had a significantly different profile than that recorded by the EDR, the *x*-force impulse calculated from the Virtual CRASH simulation was very similar to the x-force impulse calculated from the EDR data for both impacts. However, the y-force impulse calculated from the Virtual CRASH simulation was considerably different from that calculated from the EDR data for both impacts. It is likely that the accelerometer recording the linear acceleration of the Cruze was not located at the centre of rotation of the vehicle, which would, therefore, have resulted in the angular acceleration of the Cruze contributing to the linear acceleration recorded by the Cruze EDR. Given that the initial angular acceleration of the Cruze was in the clockwise direction, it would have contributed primarily to negative y-acceleration, which could account for the larger negative y-force impulse during the first impact. In the case of the second impact, the angular acceleration was positive. In this case, given the orientation of the Cruze at the time of the second impact, the angular acceleration would have contributed primarily to positive y-acceleration. If the y-acceleration of the centre of mass of the Cruze was negative, as determined from the Virtual CRASH simulation, then a positive contribution from the angular acceleration would have reduced the magnitude of the negative y-acceleration, recorded by the EDR and, thereby, reduced the negative y-force impulse during the second impact. However, since the location of the accelerometer relative to the centre of rotation of the Cruze is unknown, it is not possible to establish whether the magnitude of the y-acceleration produced by the effect of angular acceleration of the Cruze would have been sufficient to explain the entire discrepancy between the force impulses calculated from the Virtual CRASH simulation and the EDR data.

The MADYMO analysis determined that only the first impact produced a significant risk of head injury. This is logical given the difference in momentum between a loaded Silverado pulling a loaded Big Tex trailer and the Cruze compared to the difference in momentum between the Cruze and the Cayenne. It is also evident in comparing the damage to the Cruze sustained from the rear-end impact compared to the front-end impact. It is interesting that a relatively low angular acceleration was able to account for the rotational motion of the Cruze determined from the tire mark analysis. This indicates that the change in linear velocity of the Cruze following the impact was much more likely to result in head injury than the change in angular velocity. Although MADYMO provides HIC values, these are based on linear acceleration and relate mainly to injuries such as skull fracture. Traumatic brain injuries such as diffuse axonal injury have been more closely linked to angular acceleration [10]. Nevertheless, since MADYMO provides both linear and angular head acceleration the risk of traumatic brain injury can be readily assessed with MADYMO. Furthermore, the predicted head injuries from the MADYMO simulation closely matched the hospital records of the injured children.

The Virtual CRASH simulation determined that the impact between the Cruze and the Cayenne occurred at approximately 2.1 s following the onset of the impact between the Silverado and Cruze. Assuming that the Cruze and Cayenne were travelling at the same speed prior to the first impact and that the speed of the Cruze increased by 67 km/h after the first impact, as implied from the Cruze EDR, then the Cruze would have travelled approximately 39 m between the first and second impacts. The certified crash record indicated that the distance between the first and second collisions was 134 feet, i.e. 40.8 m. Thus, the distance between impacts in the Virtual CRASH simulation differed by only 4% from the certified crash record.

The analysis of the three-vehicle collision reported here, indicates that peak acceleration values derived from Virtual CRASH during impacts considerably overestimate the true peak accelerations, although the force impulses appear to be relatively accurate. This suggests that the primary utility of Virtual CRASH is in reconstructing the motion following impact as opposed to accurate representation of the dynamics during impact. Virtual CRASH output cannot be relied on for analysis of injury risk since the risk would be greatly overestimated. However, being able to use the EDR data to represent the dynamics of the impact and Virtual CRASH to represent the motion following the complex interaction dynamics of the impact can provide more complete analysis than can be achieved from EDR data alone and more accurate analysis than can be achieved from the Virtual CRASH output alone.

Summary

The objective of this investigation was to demonstrate the utility of combining several methodologies to obtain a more complete description of the dynamics of motor vehicle collisions than is available from a single methodology on its own. The investigation began with the EDR data, assumed to be the ground truth and built upon it, adding missing information by interpreting other available evidence, i.e. tire marks, and performing a Virtual CRASH simulation to obtain a more complete record of the vehicle dynamics. The results demonstrate that there are limitations to the accuracy of the Virtual CRASH simulation during the brief force impulse created during impact, where complex vehicle deformations likely differ from Virtual CRASH assumptions. For this reason, it is more accurate to use EDR data as input to MADYMO during the interval of the force impulse, rather than the output of Virtual CRASH. On the other hand, as we have attempted to demonstrate, Virtual CRASH output provides realistic vehicle dynamics after completion of the force impulse, i.e. the vehicle motion predicted by Virtual CRASH was consistent with the evidence from tire marks.

Disclosure statement

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