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Skull Fractures in Fatalities Due to Motor Vehicle Collisions

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ABSTRACT: A retrospective analysis of 89 fatalities with skull fracture resulting from motor vehicle-pedestrian and various single passenger car frontal, side, rear and rollover collisions was done. Passenger compartment intrusion and occupant ejection were responsible for most, but not all, cranial fractures occurring in impacted motor vehicles. Victims of frontal collisions usually were unrestrained; however, a majority of individuals in cars hit by heavy trucks were wearing seatbelts. Vehicles involved in frontal crashes had crush profiles reflecting a barrier equivalent velocity (BEV) of at least 50 km/h (about 30/mph). In side impacts, most ejected occupants were unrestrained, whereas many of those intruded upon were belted. The minimum BEV calculated in these collisions approached 20 km/h (12 mph). The observation of a skull fracture intregrated with accident investigation (that is, determination of head contacts) was useful in the reconstruction of various collisions. Skull fracture patterns, as documented by autopsy, reflected certain kinematic trajectories described in motor vehicle-pedestrian frontal collisions.

KEYWORDS: pathology and biology, skull fracture, fatality, motor vehicle

Motor vehicle trauma is a common cause of skull fracture [*1*]. This injury is frequently observed by coroners/medical examiners and pathologists during the investigation of a motor vehicle related death. This study examined the factors responsible for skull fracture and the significance of this finding in various fatal motor vehicle collisions.

Methods

The University of Western Ontario (U.W.O.) Multi-Disciplinary Accident Research Team is part of a Canadian national network of university based teams, funded by Transport Canada, which investigate representative fatal and non-fatal motor vehicle collisions in a defined geographical area. Fatalities with associated skull fractures were analyzed using U.W.O. Team data (1984 to 1991) derived from the Passenger Car Study

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(PCS). This source provided information about the vehicle(s), the scene, collision circumstances, accident reconstruction and summarized the victims' injuries including their probable cause. Many cases were complemented by scene and vehicle photographs. Postmortem data was supplemented by a study of more detailed autopsy reports obtained from the centralized files of the Ontario Chief Coroner's Office. Skull fracture diagrams and radiology reports, if part of the autopsy file, were also analyzed during this review. Radiographs and postmortem photographs were unavailable.

Frontal (''head-on''), side (angle or T-intersection) and rear-end impacts between a passenger car and either another single car/light truck, heavy truck (>5000 kg or 11 000 lb) or fixed object were studied. Collisions involving either more than two vehicles or one fixed object were excluded. In general, the direction of the impacting force was within a 45° angle of the plane perpendicular to the crushed surface of the passenger car. Side collisions were divided into near-side, that is, occupant with skull fracture seated on same side as the collision and far-side, that is, injured occupant located opposite to the impact. Passenger car rollovers and pedestrian-motor vehicle frontal impacts were also assessed. Motorcyclists and bicyclists were not considered in this analysis.

Certain details, if known, were studied in all cases: age group (adult or child), head contact(s) following collision, survival time and method of skull fracture documentation (that is, either autopsy or external examination). In a given collision, a head contact point was determined by team investigators who correlated the likely initial head position with consequent head motion and deformation of a certain structure either within or outside the vehicle. This determination was supported by observing tissue and/or blood at the site of head impact. Also, skull fracture patterns, particularly if documented by diagram at autopsy, were studied. Regarding fatal motor vehicle occupants, other factors—occupant location, restraint system use, occupant ejection, passenger compartment intrusion and vehicle deformation extent (VDE)—were analyzed. VDE is one component of the Collision Deformation Classification, a code used to classify vehicle deformation due to impact [2]. The maximum degree of deformation is numerically designated (1 to 9) based on extent zones across either the length or width of the car depending on the type of collision (either frontal/rear or side respectively) (see Figs. 1 and 3). The code also includes parameters such as force direction, area of damage and type of damage distribution (for example, wide versus narrow impact area).

Velocity at impact was either estimated (pedestrian and rollover deaths) or calculated in certain frontal, side and rear collisions, when data was available, as Barrier Equivalent Velocity (BEV). BEV is the velocity that reflects a particular crush profile in a vehicle crashed into a fixed barrier. BEV is useful as a measure of collision severity, for comparison of collision types and in predicting the potential for injury. Campbell explored the relationship between vehicle crush and velocity change [3]. Following the determination of a linear relationship between impact speed and vehicle crush derived from frontal impact crash tests on 1971 to 1974 General Motors cars, a number of commercial computer programs have been devised which calculate the velocity change from crush measurements [4–6]. BEV is determined by equating the pre-impact kinetic energy with the post-impact crush energy [7].

$$\text{BEV} = \sqrt{\frac{2 \times \text{crush energy}}{\text{vehicle mass}}}$$

The crush energy is computed using measurements of vehicle deformation (crush), principal direction of impacting force and pre-determined vehicle stiffness values. Crush is measured at six equidistant intervals perpendicular to the original undeformed plane according to a certain protocol [8]. The direction of force is determined from vehicle

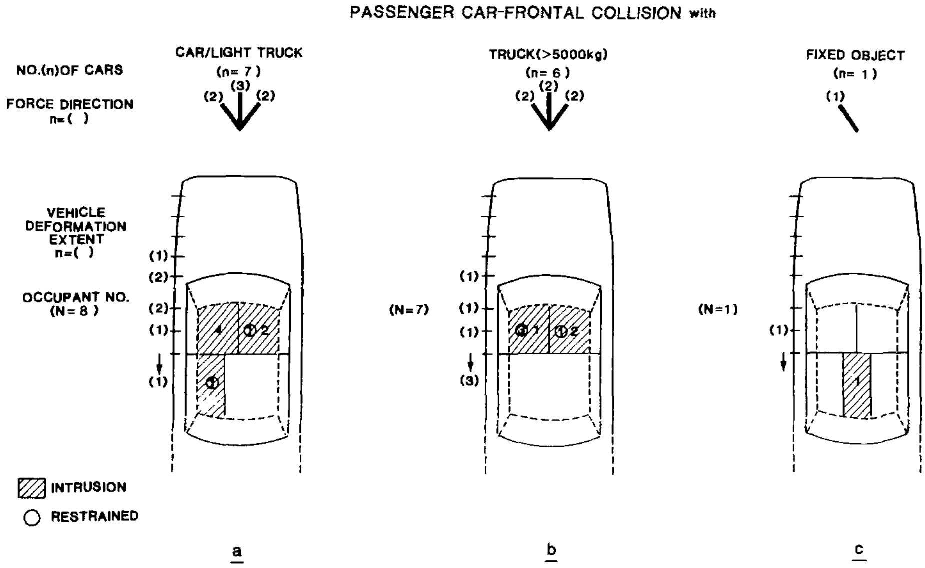


FIG. 1—*Passenger car—frontal collision with:* a) *car/light truck,* b) *heavy truck and* c) *fixed object.*

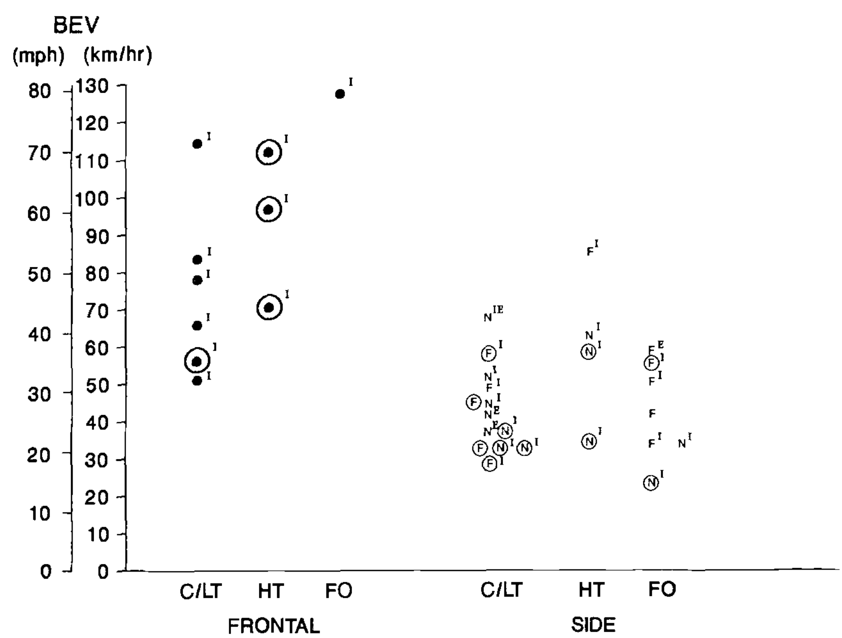


FIG. 2—*Barrier equivalent velocity (BEV) in various frontal and side collisions. Car/light truck (C/LT). Heavy truck (HT). Fixed object (FO). Restrained (open circle). Intrusion (I). Ejection (E). Near-side impact (N). Far-side impact (F).*

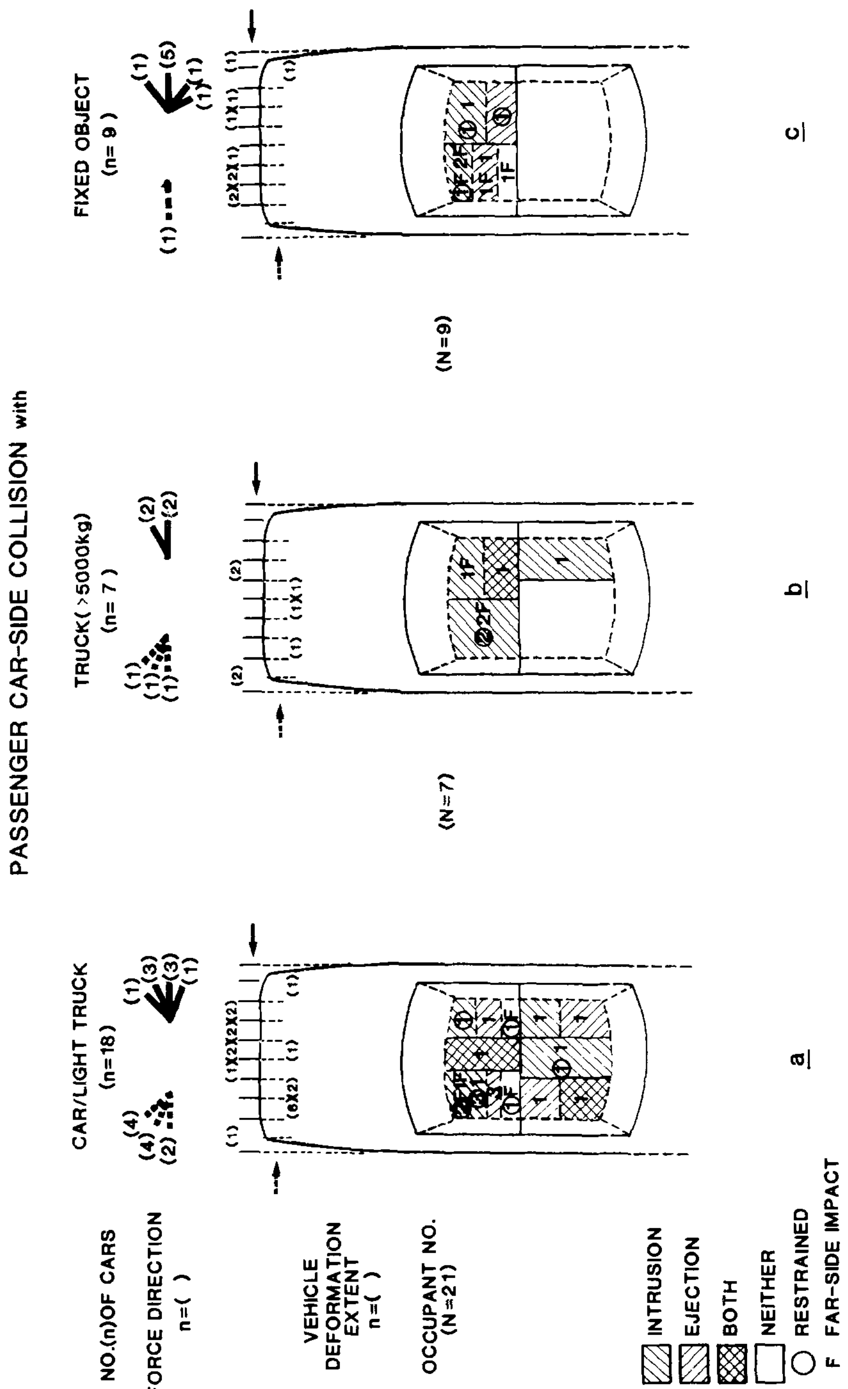


FIG. 3—*Passenger car—side collision with:* a) *car/light truck,* b) *heavy truck and* c) *fixed object.*

and scene inspection. Frontal, side, and rear end stiffness values have been calculated from staged crash tests of different vehicles. In our study, BEV values were eliminated in any side impact involving a rigid axle. The BEV results in these cases were apparently low because part of the collision energy was transmitted along the relatively non-deforming axle and not into the less stiff passenger compartment. ''Sideswipe'' collisions were not included in the study because of the difficulty in BEV determination in these glancing impacts.

Results

From 1984 to 1991, 247 passenger car collisions causing 300 fatalities were referred to the U.W.O. Team. Skull fractures were documented in about one-half of the victims (n = 148; 128 impacts).

There were 89 deaths (30% of total fatalities) with skull fractures, including seven children (aged four months to twelve years), observed in 82 impacts (33% of total fatal collisions) that fulfilled the criteria outlined in the methods. A total of 74 (83%) of the victims were dead at the scene, the remainder dying within 24 hours. The cause of death was due to either craniocerebral or multiple trauma. An autopsy was done in 58 cases (65% overall autopsy rate). The autopsy rate varied: drivers—78% (32/41; 12 of those 15 restrained); other occupants—38% (12/32; 2 of those 10 restrained) and pedestrians—88% (14/16).

Frontal Collisions (Fig. 1)

A total of 16 deaths (eight drivers) were observed in 14 collisions. At least 14 were dead at the scene. Ten autopsies were done. In these cases, the skull fracture was either massive or basal. In only one autopsy report (an unrestrained right front passenger in a vehicle hit by another car) was the skull fracture documented by diagram. There were two cases (collisions with heavy trucks) which had radiology reports.

With Car/Light Truck (Fig. 1*a*)

Eight deaths (four drivers) occurred in seven impacts. Two individuals, a right front passenger and a four-month-old left rear passenger, were restrained. Skull fracture was caused by passenger compartment intrusion in all cases. Head contacts were determined in three cases: A-pillar (two deaths) and the front header. Three of the drivers and one passenger were autopsied.

With Heavy Truck (Fig. 1*b*)

Seven deaths (four drivers) occurred in six collisions and four of the victims (including three drivers) were restrained. Intrusion was a factor in causing skull fracture in all cases. Head contacts were determined as due to either part of the intruding vehicle (for example, bumper) which usually tore off the car roof (involved in four of the five deaths) and the car interior (for example, steering assembly) in two cases. Autopsies were done on all the drivers and one passenger.

With Fixed Object (Fig. 1*c*)

One death (an unrestrained rear passenger) was observed in an impact with a bridge abutment. Intrusion was responsible for the skull fracture observed at autopsy. Head contact occurred with a roof pillar support.

VDE

In almost all types of collisions (13 cases), the vehicle deformation extent was at or beyond the level of the passenger car windshield (that is, ≥5).

BEV (Fig. 2)

Values were available in ten collisions: car/light truck (six cases, range 51.0 to 114.7 km/h or 31.7 to 71.2 mph, average 74.7 km/h or 46.4 mph), heavy truck (three collisions, range 70.5 to 112 km/h or 43.8 to 69.6 mph, average 93.3 km/h or 57.9 mph) and fixed object collisions (127.6 km/h or 79.2 mph).

Side Collisions (Fig. 3)

A total of 37 fatalities (21 drivers) were studied in 34 impacts; 33 were dead at the scene; 23 autopsies were performed. The fractures typically involved the base of the skull. There were no post-mortem reports supplemented by a diagram of the skull. One case (collision with a car) had a filed radiology report.

With Car/Light Truck (Fig. 3*a*)

A total of 21 deaths (including three middle seat passengers, one of whom was a restrained three-year-old) were seen in 18 impacts (near-side = 13 deaths including seven drivers, three of whom were restrained; far-side = five deaths including four drivers, three of whom were restrained). Seven of the ejected victims (one also intruded upon) were in near-side collisions. None were restrained. Head contacts by ejected individuals were with either the other vehicle (for example, hood edge, 2/5 cases) or the ground (two cases). Intrusion alone was responsible for skull fracture in six other near-side impacts. Four of these occupants were restrained (including a 12-year-old right front passenger). The victim's head contacted either the other vehicle (for example, hood edge—three cases) or the car interior (for example, pillar—three cases). Of the five far-side collisions, intrusion usually by a pillar support was implicated in causing skull fracture in three victims. Two of these included restrained drivers. (VDE values in these cases were four and six.) Neither intrusion nor ejection were assessed as factors in the two other deaths. An 18-year-old restrained male driver's head hit the opposite roof pillar (BEV = 43.0 km/h or 26.7 mph; VDE = 5). A 76-year-old right front passenger hit the instrument panel after slipping out of the chest portion of his seatbelt (BEV = 33.3 km/h or 20.7 mph; VDE = 3). His driver, a 47-year-old restrained man, was intruded upon by the hood edge of the incoming vehicle.

Autopsies were performed on eight (of eleven) drivers and six (of ten) passengers.

With Heavy Truck (Fig. 3*b*)

Seven deaths occurred in a similar number of collisions (near-side = four deaths including two restrained drivers, other occupants unrestrained; far-side = three fatalities including two drivers, none of victims belted). Intrusion was a factor in all cases. One right front occupant was also ejected in a near-side collision. Head contacts known in two near-side and two far-side collisions were either within the car (roof, pillar support) or the other vehicle (one near-side crash).

Autopsies were performed on two (of four) drivers and one passenger.

With Fixed Object (Fig. 3c)

Nine fatalities were observed in an equal number of impacts, usually with trees or utility poles (four cases each). Among far-side collisions, either intrusion (three drivers, one restrained) or ejection (one unrestrained driver) was a factor in causing most of the skull fractures. Head contacts due to intrusion were in the car (roof, roof pillar). The ejected victim hit the ground. Neither factor was implicated in a fifth case, a 28-year-old unrestrained driver whose car hit a utility pole on the passenger side (BEV = 42.9 km/h or 26.6 mph, VDE = 1). Car interior contacts were observed. Either intrusion (two deaths, two right front passengers, one restrained) or ejection (two deaths, one restrained right front passenger and an unrestrained driver) was responsible for skull fracture in the four near-side collisions. Three of the victims contacted the fixed object, two by intrusion; the other could have struck a roof pillar while being ejected.

Autopsies were performed on five (of six) drivers and one passenger.

VDE

The degree of deformation, in about $^2/_3$ of all types of impacts (car/light truck—14 cases; heavy truck—four cases; fixed object—three cases) was up to the center of the passenger compartment (that is, ≤ 5).

BEV (Fig. 2)

Values were available in 23 impacts: with car/light truck (twelve cases, two victims in same car, range 29.6 to 69.4 km/h or 18.4 to 43.1 mph, avg. 43.3 km/h or 26.9 mph); with heavy truck (four cases, range 34.5 to 86.6 km/h or 21.4 to 53.8 mph, avg. 60.8 km/h or 37.8 mph) and with fixed object (seven cases, range 22.5 to 59.9 km/h or 14.0 to 37.2 mph, avg. 43.1 km/h or 26.8 mph).

Rear-End Collisions

Two children, a seven-year-old and a restrained eight-year-old, were rear seat passengers in a car hit by a truck. Their heads hit the intruded roof. The BEV was 85.9 km/h (53.3 mph). An autopsy was not performed on either child.

Roll-Over Collisions

Eighteen deaths (twelve drivers) occurred in 17 cases, all estimated at high speed ($\geq$100 km/h or 60 mph). Fifteen were dead at the scene. Eleven autopsies were performed, ten on drivers. Three cases were supplemented by skull diagrams.

Car roof intrusion following two cases of vehicle rollover into either a tree or utility pole caused skull fracture in three people (two drivers, one restrained and a belted right front occupant). Autopsies were performed on both drivers. One had extensive "crushing" of the skull but the other was described as having a fracture of the right temporal bone. Neither case was documented by a skull diagram. Fifteen victims (ten drivers, two of whom were restrained) were either partially or completely ejected. None of the passengers were belted. Events leading to the ejection of drivers were determined by vehicle and scene investigation (Fig. 4). Head contacts observed as a consequence of the rollover were noted in the car interior (for example, roof, pillar support) and either on the vehicle exterior (roof) or ground following partial or complete ejection through the window. Most of the sustained fractures were described as "severe," "multiple" or "crushing" and involved the entire skull; (autopsies performed on eight drivers and one passenger);

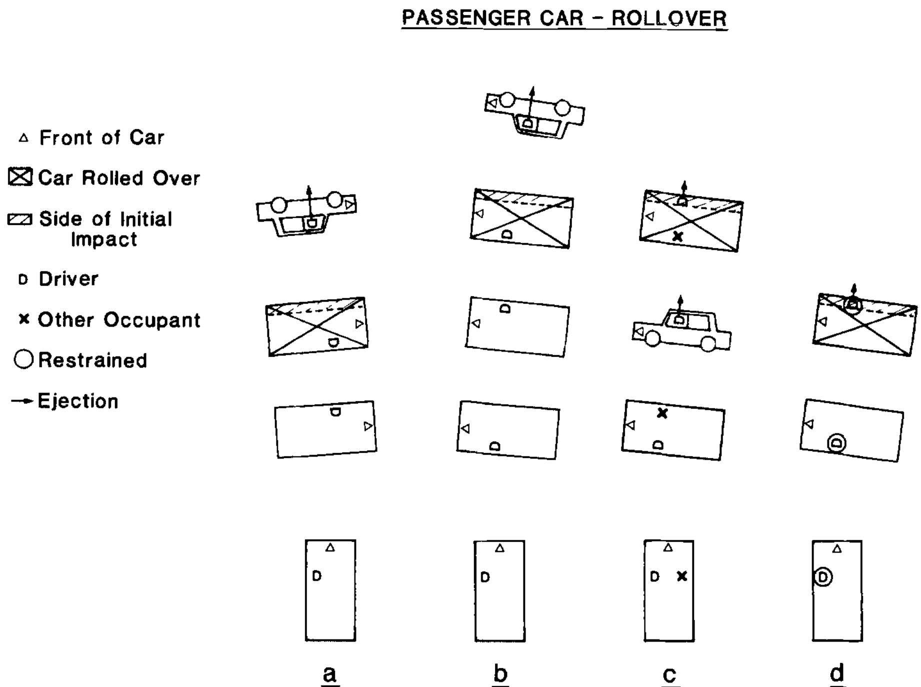


FIG. 4—*Observed rollover events leading to ejection of driver. Estimated speeds ≥100 km/h (about 60 mph).*

a) *Driver, unrestrained and sole occupant. Clockwise rotation. Initial impact of rolled car on passenger side. Driver ejected through left front window (3 cases).*
b) *Driver, unrestrained and sole occupant. Counter-clockwise rotation. Driver shifted to passenger side. Initial impact on driver's side. Driver ejected through right front window (3 cases).*
c) *Driver, unrestrained. Right front passenger (with/without restraint). Counterclockwise rotation. Driver either ejected completely through left front window early in roll-over or partially during initial impact on driver's side (2 cases).*
d) *Driver, restrained. Counterclockwise rotation. Partial ejection on impacted (driver's) side of vehicle (2 cases). (See Fig. 5).*

however, in one case of a partially ejected restrained driver, the fracture was more localized (Fig. 5). In another similar rollover, the head of the restrained driver, who was partially ejected, contacted the ground. The postmortem examination revealed severe crushing of the skull. No diagram was available.

Pedestrians

Sixteen individuals (two children) died after being struck by cars. Ten were dead at the scene. Known head contacts included: hood edge (two-year-old and four-year-old hit by vehicles travelling at estimated speeds of 30 km/h (19 mph) and 50 km/h (31 mph) respectively); hood surface (four deaths, speeds estimated at 35 km/h (22 mph) and 60 km/h (37 mph) in two cases) and windshield area including A-pillar and roof rail (six deaths; in four cases, speeds estimated at 40, 55, 80, 100 km/h or 25, 34, 50, 62 mph, respectively). Of the 14 autopsies performed, five were illustrated by a skull diagram. Fracture patterns were noted (Fig. 6). Two cases had radiology reports available.

Discussion

Skull fractures occur in one-half of road traffic deaths and three-quarters of fatalities with major head injuries [*9*]. Vault and basal fracture patterns and mechanisms have been described [*10–13*]. A cranial fracture can indicate the severity, nature and usually but not always the site of head impact [*14,15*]. Most of our studied cases had basal skull fractures and were dead at the scene either from cranio-cerebral trauma or multiple injuries. In our series, cranial fractures were seen at autopsy in about two-thirds of the cases; the remainder were observed by external examination.

The decelerative force experienced by a motor vehicle occupant during a collision is dependent directly on the velocity change of that vehicle and inversely on the duration of the velocity change. Determination of BEV approximates the velocity change of not only a crushed vehicle but also its restrained occupants. In frontal crashes, the time duration of the velocity change experienced by the passenger depends largely on restraint use. Restrained individuals experience similar deceleration as the impacted vehicle over a relatively long stopping distance. Generally, the crushing phase of a vehicle is usually about 0.12 s [*16*]. For example, a velocity change of 40 km/h (25 mph) over this time would mean a vehicle deceleration of 9.4 g. In contrast, an unrestrained occupant who contacts an unyielding surface will stop more abruptly (in the order of .01 s) over a shorter head excursion distance relative to his/her vehicle thereby experiencing a higher deceleration force. Similarly, a restrained individual could stop more abruptly if intruded upon by either the car interior or incoming vehicle. In this study, of the frontal impact cases in which BEV was calculated, fatalities with skull fractures occurred in vehicles which had documented crush profiles reflecting velocities above 50 km/h (about 30 mph). All victims of the various frontal impacts were intruded upon and, with the exception of fatalities due to collisions with heavy trucks, these individuals tended to be unrestrained. In impacts with other cars and light trucks, the car interior, particularly a pillar support, was the major head contact. In many heavy truck collisions, the truck bumper tore off the car roof.

Compared to a frontal collision, a motor vehicle occupant is more vulnerable to injury in a side collision. In near-side impacts, a restraint system may not provide as much protection as in frontal collisions particularly if there is significant intrusion into the passenger compartment. Also, the reduced head excursion distance, because of the greater proximity of the occupant to a hard surface, for example, B-pillar, is a factor. In this series, most of the fatalities in near-side collisions with another car/light truck, heavy truck and fixed object were in intruded passenger compartments. Many of the victims wore seat belts. The major head contacts in impacts with other vehicles were either the car interior or the incoming automobile. Those individuals intruded upon by a fixed object frequently hit their heads on that structure. Occupants, mostly unrestrained, were also fully or partly ejected following near-side collisions with cars/light trucks and fixed objects. Head contact occurred either with the incoming vehicle, fixed object or the ground. In far-side impacts, restraints will often prevent the occupant from striking their heads on an opposite surface; however, in this study, occasional cases of skull fractures in restrained individuals involved in far-side impacts of relatively low velocity (BEV about 40 km/h or 25 mph) and with moderate vehicle deformation were noted. At least one victim slipped out of the restraint. MacKay et al. noted the risk of head injury in belted occupants who slipped out of their restraints during far-side impacts of slight to moderate severity [*17*]. The most significant factor responsible for a skull fracture in our study of far-side impacts was intrusion into the passenger compartment. Most of these victims were unrestrained. MacKay et al. also observed that the most severe head injuries were associated with passenger compartment intrusion almost up to or beyond the center line of the car (VDE $\geq$ 4, velocity change based on crush measurements >40 km/h or 25 mph). The adequacy of the seatbelt in protecting far-side occupants was considered

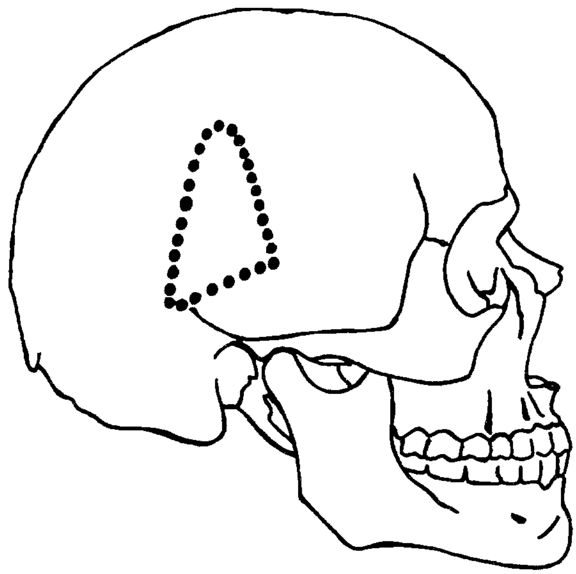


FIG. 5—a) *Skull fracture seen in restrained driver whose head contacted car roof following partial ejection on initial impact (driver's side). Fracture extended into base of skull.*
b) *Deformed roof (driver's side) from initial impact. Blood was noted on roof.*
c) *Driver found in her seat. Blood spatter on car roof interior from right scalp laceration.*

irrelevant under these circumstances [*17*]. In our review of side impacts (near-side and far-side), about one-half of the occupant skull fractures occurred in cars with measured crush profiles reflecting a BEV range of about 20 to 40 km/h (12 to 25 mph). Many of these individuals were restrained and suffered intrusion into the passenger compartment.

Passenger compartment intrusion was a factor in 78% (43/55) of skull fractures in frontal, side and rear collision fatalities. This included 18/21 (86%) of restrained occupants. Of these 18, 11 of the belted victims were in side collisions. Green et al. have observed the vulnerability of restrained occupants fatally injured by passenger compartment intrusion during side collisions. Head and neck injuries predominated as a major or sole cause of death [*18*].

A rollover collision is a complex sequence of events occurring usually at high speed (>65 km/h or 40 mph) [*19*]. In this series, roof intrusion from rollover into fixed objects was a factor in some cases in which skull fractures were observed; however, most victims were ejected. Depending on the direction of vehicle rotation, side of initial roof impact with the ground (that is, side opposite to the direction of the rollover) and occupant number, location, motion and restraint use, skull fractures could be due to contacts with either the vehicle interior (for example, roof pillars, roof), vehicle exterior (including roof) or the ground. The resulting skull fractures were severe, reflecting the sudden decelerative forces involved. On occasion, the fracture pattern correlated specifically with the surface impacted during the rollover.

Ravani et al. studied injury patterns in frontal motor vehicle pedestrian collisions as related to five kinematic trajectories: wrap, somersault, forward projection, fender vault and roof vault [*20*] (Fig. 7). Wrap is the most common. A decelerating vehicle (average velocity 30 km/h or 19 mph) causes the upper body of the struck pedestrian to bend

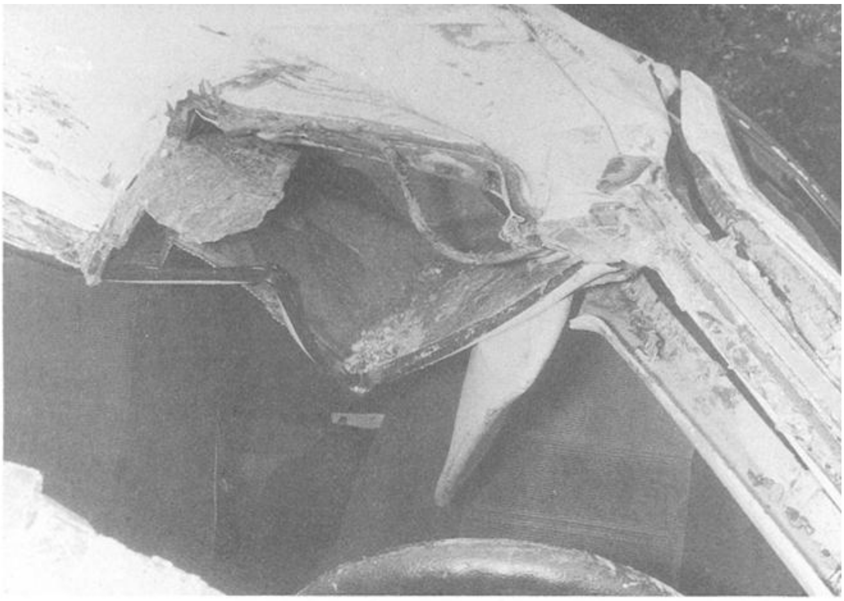
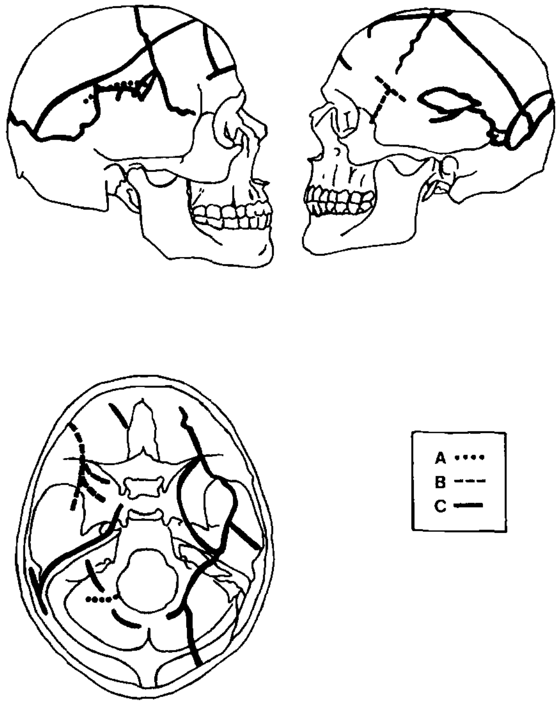


FIG. 5—*Continued.*



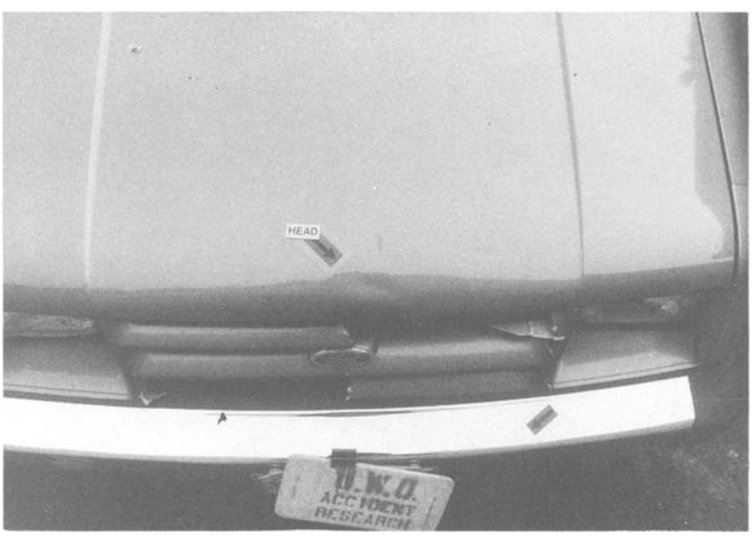


FIG. 6—*Skull fractures observed in certain pedestrian-car collisions.*
a) *2 yr. old F. Head contact with hood edge (arrow) of car traveling about 50 km/h (30 mph).*
b) *20 yr. old M hit by car going about 35 km/h (22 mph). Contacted hood of vehicle* (arrow).
c) *29 yr. old M hit by car travelling 80 km/h (50 mph). Contacted hood, windshield and roof of vehicle* (arrows).

FIG. 6—*Continued.*

over contacting the hood. Even an individual with a center of gravity lower than the hood edge (such as, a child) can display such a trajectory if enough energy is transferred to the victim. As the vehicle brakes, the pedestrian is separated from it and strikes the road. Somersault, a variation of the wrap trajectory, is the least common. The vehicle is usually travelling at a higher impact speed (average 60 km/h or 37 mph), causing the pedestrian to flip in mid-air. Forward projection is most common among children. Because of a lower center of gravity relative to the hood edge, the child is accelerated in the direction of the travelling vehicle (average velocity 20 km/h or 12 mph). Adult pedestrians can experience a similar situation when hit by a vehicle with a broad front (for example, a van) (Fig. 7*b*). Also, forward projection can occur in adults hit by a car travelling at a low speed (average <15 km/h or 9 mph) (Fig. 7*a*). Fender vault describes

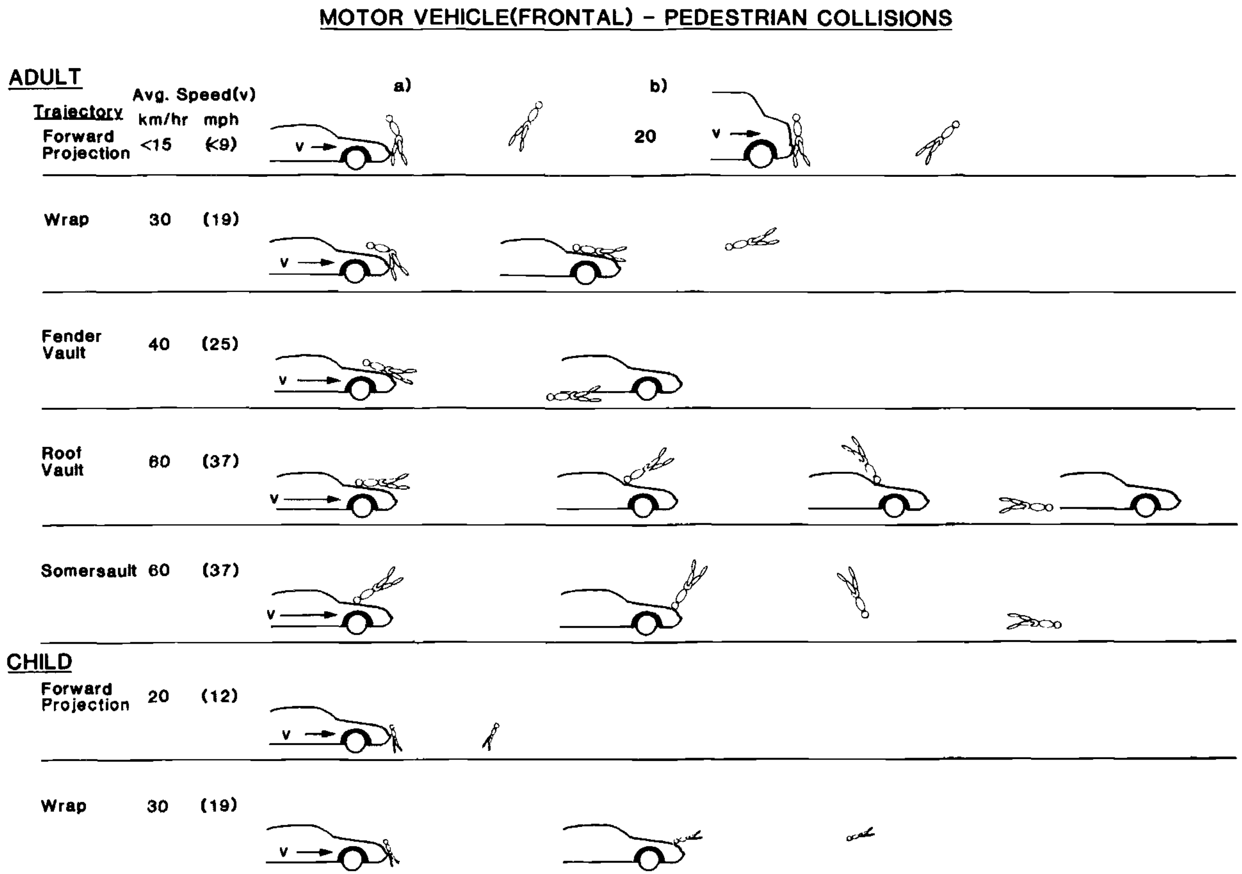


FIG. 7—*Kinematic trajectories observed in motor vehicle (frontal) —pedestrian collisions (adapted from Ravani et al.).*

a trajectory during which a pedestrian is struck by the front corner of a car (average speed 40 km/h or 25 mph). If the vehicle is braking, the victim will wrap over the fender. If the car is not braking, the individual will not only contact the right front corner but also the windshield and the A-pillar. The pedestrian will then roll off the fender when the vehicle is decelerated. Roof vault was associated with the most severe and highest percentage of injuries in Ravani's study. A motor vehicle travelling at a relatively high speed (average 60 km/h or 37 mph) lifts the pedestrian up the hood and onto (or over) the windshield, roof and even the trunk. There is usually no braking during contact with the pedestrian. Some of these trajectories were observed in our study. The pattern of the observed skull fractures reflected the trajectories of the victims (Fig. *6a*—wrap, child; Fig. *6b*—wrap, adult; Fig. *6c*—roof vault). Vehicle contacts are a major source of pedestrian head injury although ground impact may be underestimated [*21*]. Their occurrence and location depend on collision speed, relative pedestrian height and hood length and injury severity rises with higher speeds [*20,21*].

Conclusion

The postmortem recognition of a skull fracture in a victim of a motor vehicle collision certainly indicates to the observer the severity of the injury and is important in the determination of the cause of death due to craniocerebral trauma. The fractures recorded in our study were generally found to be the expected type for the reconstructed impact magnitude and direction and for the size of the impact area. In this study, documentation by diagram of cranial fractures seen at autopsy was relatively infrequent. This information accurately noted by a pathologist is not only a convenient and easily reproducible record of this injury but also permits correlation of a given skull fracture with vehicle and scene investigation findings which can increase the appreciation of the kinematics of certain impacts, allow an understanding of the factors responsible for that injury and be invaluable in accident reconstruction [*13*].

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