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Vehicle mismatch: injury patterns and severity

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Abstract

Light truck vehicles (LTV) are becoming more popular on US highways. This creates greater opportunity for collisions with passenger vehicles (PV). The mismatch in weight, stiffness, and height between LTV and PV has been surmised to result in increased fatalities among PV occupants when their vehicles collide with LTV. We reviewed cases of vehicle mismatch collisions in the Seattle Crash Injury Research and Engineering Network (CIREN) database to establish patterns and source of injury. Of the first 200 Seattle CIREN cases reviewed, 32 collisions with 41 occupant cases were found to involve LTV versus PV. The cases were reviewed by type of collision and vehicle of injured occupant: side impact of PV with LTV, front impact of PV with LTV, and front impact of LTV with PV.

For each type of crash, injury patterns and mechanisms were identified. For side impact to PV, head and upper thorax injuries were frequently encountered due to LTV bumper frame contact above the PV side door reinforcement. For frontal impact to PV, severe multiple extremity fractures along with some head and chest injuries were caused by intrusion of the instrument panel and steering column due to bumper frame override of the LTV. Underriding of the PV when colliding with the LTV resulted in severe lower extremity fractures of the LTV occupant due to intrusion of the toe pan into the vehicle compartment of the LTV.

The injuries and the sources identified in this case series support the need for re-designing both LTV and PV to improve vehicle compatibility. Revising Federal Motor Vehicle Safety Standard 214 to reinforce the entire door, consider adding side airbags, and re-engineering LTV bumpers and/or frame heights and PV front ends are possible ways to reduce these injuries and deaths by making the vehicles more compatible.

Keywords: Crash; Injury; Mismatch; Safety; Side impact

1. Introduction

From 1980 to 1998, there was a steady decrease in the number of fatalities resulting from passenger vehicle (PV) versus PV collisions (Lombardo, 2001). However, since 1980, there has also been an increase in fatalities resulting from the collision of PV and light truck vehicles (LTV). LTV include sport utility vehicles (SUV), pickup trucks, and vans which are constructed on a truck frame. This increase is surmised to be due to the mismatch between the PV and LTV and the increasing representation of LTV in the vehicle fleet.

Vehicle mismatch is defined as design differences between vehicle types which result in disproportionate damage patterns to the vehicles involved in a collision; these design differences include weight, frame height, and stiffness. This is also known as crash incompatibility (IIHS, 1999). The damage patterns can result in a violation of the structural integrity of the passenger compartment resulting in increased risk of serious injury or death to the occupants. Studies by the Insurance Institute of Highway Safety (IIHS) have shown that the relative risk of death for occupants of PV involved in frontal collisions with LTV is 3–4 times greater than those involved in similar collisions with another PV. For side impacts, the relative risk of death can be 27–48 times greater for the occupants of the PV (IIHS, 1999).

LTV are becoming more common on our highways. For the year 2000, Motor vehicle registrations show 77.8 million light trucks in the US, a 63.8% increase from 1990. During the same period, there was a 1% decrease in the number of registered PV. LTV now represent 40% of all registered motor vehicles (Office of Highway Policy Information, 2000) and the LTV market share has increased from 14.2% in 1996 to 21% in 2000 (Polk, 2001). If these trends continue, LTV

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will soon become the majority of vehicles on the road, resulting in even greater occurrences of vehicle mismatch.

The Crash Injury Research and Engineering Network (CIREN) was developed under the National Highway Traffic Safety Administration (NHTSA) to provide detailed crash site analysis and specific occupant injury data to improve the prevention, treatment, and rehabilitation of motor vehicle crash injuries. The purpose of the current study is to examine crashes with vehicle mismatch to determine the kinematic mechanisms of occupant injury and identify possible design improvements to reduce fatalities and prevent severe injury.

2. Methods

2.1. CIREN database and case selection

The Harborview Injury Prevention and Research Center (HIPRC) is one of 10 CIREN centers. Inclusion criteria for the CIREN database include: (1) the vehicle can not roll nor can the occupant have been ejected from the vehicle, (2) the case occupants must have been restrained or have an airbag deploy, have sustained at least one injury with abbreviated injury severity score (AIS) ≥ 3, and have been in a vehicle manufactured within the last 6 years. For each enrolled crash the following data were obtained: medical data on injured occupants, crash scene data, and vehicle damage information. Each crash scene and vehicle investigation used the format established by the National Automotive Sampling System (NASS) (NASS, 1996). Each case was then reviewed by a multidisciplinary team consisting of a crash investigator, a bioengineer, a research nurse, a radiologist, and physicians to establish a probable mechanism of injury. Each injury is discussed and sources of injury (contact points) are identified and classified as certain, probable, or possible.

2.2. Crash investigation

Scaled documentation of each crash site was performed including the collection of information on the roadway, traffic controls, road surface type, conditions, and road grade at pre- and post-impact locations. Physical evidence, such as tire skid marks, was used to determine the heading angle and post-impact trajectory of the colliding vehicles. A scaled drawing of the impact and final rest positions of the vehicles was used to assist in the calculation of the speed and force of the impact. Exterior vehicle inspections included detailed measurements of direct and induced damage. Using a contour gauge, a damage crush profile was obtained from the front bumper or side plane and a specific collision deformation code (CDC), which incorporates the principal direction of force (PDOF), was assigned (CIREN, 2000). These measurements were entered into a crash analysis program (Win SMASH, version 2.2.1, US Department of Transportation) which estimates the change in velocity (ΔV) of the vehicle during impact and hence the energy absorbed during the crash event.

Inspection of the interior of the vehicle was completed to determine the exact points of contact and restraint system use. Contact points were identified by locating scuffs, cracks, and even skin transfers. This also included an assessment of the integrity of the passenger compartment and the measurement of component intrusion.

2.3. Injury data

Injury data were derived by the multidisciplinary team following review of individual hospital reports, radiographs, and autopsy reports. Injuries were coded using the 1990 AIS and an overall injury severity score (ISS) was calculated (AIS, 1990; Copes et al., 1990). Patient interviews were also performed to supplement crash and injury data. The study was approved by the University of Washington Institutional Review Board.

2.4. Case selection criteria

The first 200 Seattle CIREN cases (HIPRC) were reviewed for vehicle mismatch collisions. For the purpose of this review, mismatch collisions were defined as collisions between PV defined as vehicles on car frames (passenger vehicles, minivans) and LTV defined as vehicles on truck frames (SUVs, pickup trucks, vans). Forty-eight crashes with 63 occupants were identified as vehicle mismatch collisions for initial review. Of these, 32 crashes (34 enrolled vehicles) were between light truck vehicles (LTV) and passenger vehicles (PV) with 41 occupants and were reviewed. The remaining 16 collisions involved extreme mismatches of passenger vehicles with semi-trucks or buses and were not reviewed. Of the 34 LTV versus PV enrolled crash vehicles, 14 were PV with side impact (16 occupants), 15 were PV with front impact (19 occupants), and five were LTV with front impact (6 occupants). For each crash, case occupants were reviewed if they were seated near the site of impact (near side for side, front seat for front).

2.5. Data review

For each case, both crash and injury data were reviewed. Crash data included restraint use, air bag deployment, seat location in vehicle, target vehicle (case vehicle), impacting vehicle, vehicle weights, ΔV, and maximum intrusions experienced by the case occupant. Injury data included the age and sex of the case occupant, a listing of injuries reported, maximum AIS, ISS, whether the case was a fatality, and the sources of injuries as determined by the multidisciplinary team. Injury data from the impacting vehicle (non case vehicle) were obtained from the initial police reports as estimated by the officer on the scene.

3. Results

3.1. Side impact collisions

Table 1 displays the crash data for PV involved in side impact collisions with LTV. Fourteen collisions with 16 near sided occupants were identified. The intrusions listed are those closest to the occupant in question. Table 2 displays the injury data for each target vehicle occupant, as well as the on-scene estimation of injury in the impacting vehicle as reported by the police. Two case reports followed by a summary of the findings for the cases reviewed are presented.

3.1.1. Side impact case reports

3.1.1.1. Side impact Case 4. The case occupant is a 36-year-old female who was the restrained driver of the case vehicle (1993 full size four-door sedan) involved in a left side impact with a large van with a PDOF of 280° degrees and a ΔV of 26 mph. The majority of the direct damage was into the case vehicle's driver door, extending forward to above the left front tire. The base of the van's bumper frame was measured at 43 cm above the ground with the front hood transition point at almost 1.2 m above the ground. The direct damage on the case vehicle began at the middle of the driver's door and extended almost to the roof side rail. The direct damage on the van's front hood edge showed the outline of the left side roof A-pillar of the case vehicle and next to this was a slight rounded dent. This dent was possibly an occupant contact and matched the seated height and location of the case occupant's head (Fig. 1). Lateral intrusion was measured at 28 cm at both the middle and upper driver door panel and was due to the frame height of the van. Deformation and scuffing were found on the interior door panel and armrest, matching the occupant's left pelvis and chest.

Injuries identified were a subarachnoid hemorrhage, an atlanto-occiptial subluxation, torn thoracic aorta with extravasation, multiple rib fractures, and an unstable right pelvic fracture. The subject required emergent thoracotomy for repair of the aortic tear and angiographic embolization for bleeding from the pelvic fracture. In addition, she required halo placement, intracranial pressure monitor placement, and open reduction and internal fixation (ORIF) of the pelvic fracture.

The subject's hospital course was complicated by prolonged ventilator dependence due to traumatic brain injury and pneumonia, persistent left hemiparesis, and impaired swallowing requiring tube feeding. After a 4 week hospital stay and 8 weeks in a skilled nursing facility, the halo was removed, the subject's mental status and hemiparesis had improved, she was tolerating oral intake, and was transferred to a rehabilitation facility.

3.1.1.2. Side impact Case 11. This case occupant was a 32-year-old unrestrained female front seat passenger in a 2000 intermediate sedan that was involved in a right side collision with a 2000 large SUV, striking both right side passenger doors. A side air bag deployed from the door panel in this case occupant's position. The maximum exterior crush occurred on the upper door side panels due the greater bumper frame height of the SUV (Fig. 2). The PDOF was 80° and ΔV was calculated at 18 mph, however, this is likely low due to damage from the extrication interfering with the measurements. The major component intrusions were from the upper door panel with 21 cm and the B-pillar with 25 cm. The case occupant had the seat track in the most rearward position allowing the pelvic region to make contact with this

Table 1
PV side impact crash data

Case #	Target vehicle	Weight (kg)	Impacting vehicle	Weight (kg)	ΔV (m/s)	Maximum intrusion (cm)
1	1996 Toyota Corolla	1050	1994 Ford F250	1930	20	B-pillar 37, window frame 40, Door 38
2	1993 Ford Tempo	1180	1995 Dodge Dakota	1800	20	Door panel 46, window frame 37
3	1990 Ford Taurus	1341	1992 Wrangler jeep	1553	17	Door 26, B-pillar 23
4	1993 Acura Vigor	1425	1986 Ford Econoline van	2002	26	A-pillar 25, door 20, side panel 26, B-pillar 20
5	1998 Nissan Sentra	1050	1991 Olds Bravada	1764	29	B-pillar 46, door 34
6	1993 Saturn SL1	1076	1998 Dodge Ram pickup truck	2083	18	Door 29
7	1998 Subaru Impreza	1267	1986 GMC Suburban	1945	19	Pass door 40
8	1997 Saturn SC1	1043	1997 Isuzu trooper	1939	25	Door 42, B-pillar 40
9	1997 Buick LeSabre	1560	1995 Ford Econoline van	2400	16	Side 29
10	2000 Honda Civic	1070	1991 Chevy S-10 blazer	1445	29	B-pillar 45, door 45, rear seat 39
11	2000 Mercedes-Benz C230	1474	2000 Ford Expedition	2516	18	B-pillar 25, door 21
12	1999 Olds Intrigue	1543	1984 Cherokee jeep	1834	22	Door 28, B-pillar 24
13	1995 Buick LeSabre	1552	1985 Ford van	1897	12	Window 30, door 23
14a	1997 Honda CRV	1435	Dodge Ram truck	*	*	B-pillar 27, window 28
14b	1997 Honda CRV	1435	Dodge Ram truck	*	*	None
14c	1997 Honda CRV	1435	Dodge Ram truck	*	*	Door 26

Lettered cases indicate multiple case occupants of the same vehicle and the intrusions listed are those nearest to each occupant.

* Not available due to hit and run driver.

Table 2
PV side impact injury data

Case #	Age	ISS	AIS maximum	Injuries	Source	Fatality	Impacting vehicle injury?
1	74	22	3	Pneumothorax Subdural hematoma/contusion, frontal contusion Perinephric hematoma	Door panel, certain B-pillar, possible Door panel, certain	No	No injury
2	8	25	5	Subdural hematoma, intraparechymal hemorrhage	R window sill, probable	No	No injury
3	19	9	3	Multiple pelvic/sacral fractures	Door, certain	No	Non-disabling injury
4	36	41	4	Subarachnoid hematoma, atlanto-occipital subluxation Multiple pelvic/sacral fractures with arterial bleed Multiple rib fractures hemothorax, thoracic aortic tear	Direct contact to van hood, certain Door, certain Door, probable	No	Non-disabling injury
5	23	66	5	Rib fractures, pulmonary laceration, hemothorax Spleen/renal laceration Pelvic fracture, ruptured retroperitoneal hematoma	Door, probable Door, probable Door, probable	Yes	Minor injury
6	27	4	2	Zygoma/maxillary complex fracture, facial laceration	Exterior of other vehicle, possible	No	No injury
7	20	11	3	Rib fracture Superior/inferior pubic rami fracture, sacral fracture	Door, probable Door, probable	No	No injury
8	50	50	5	Shear injury to brain Rib fractures, hemo/pneumothorax Pelvic fracture	Noncontact, probable B-pillar, probable Transmission console, probable	Yes	Non-disabling injury
9	72	75	6	Multiple rib fractures Aortic transection	Impact with door, probable Indirect, probable	Yes	No injury
10	16	75	6	Brain laceration, subdural hemorrhage, skull fractures Multiple rib fractures, hemothorax, lung contusions Pelvic fracture Splenic and liver lacerations	Contact with other vehicle, possible Intruding door, probable Door, probable Undetermined	Yes	Disabling injury
11	32	22	3	Rib fractures, pneumothorax Multiple pelvic/sacral fractures Concussion Omental vessel bleeding	Door, but air bag protect, probable B-pillar seat too far back, probable Noncontact deceleration, probable Armrest, possible	No	No injury
12	82	35	5	Flail chest, heart laceration, diaphragm injury Pelvic fracture Vertebral fracture/cord injury	Door panel intrusion, certain Door panel intrusion, certain Noncontact, probable	Yes	Possible injury
13	70	21	4	Laryngeal fracture, pneumothorax Ankle fracture, closed	Shoulder belt/door/B-pillar, possible Kick panel, probable	No	Possible injury
14a	29	24	4	Rib fractures, pneumothorax Renal hematoma Vertebral fracture	Door, probable Door, possible Door, probable	No	No injury
14b	15m	5	2	Concussion, facial contusions	Undetermined	No	No injury
14c	5	9	2	Clavicle fracture, hand wound Concussion	Door, probable Window sill, probable	No	No injury

Each line under injuries corresponds to a specific body region (e.g. head, chest) and is matched with its source.

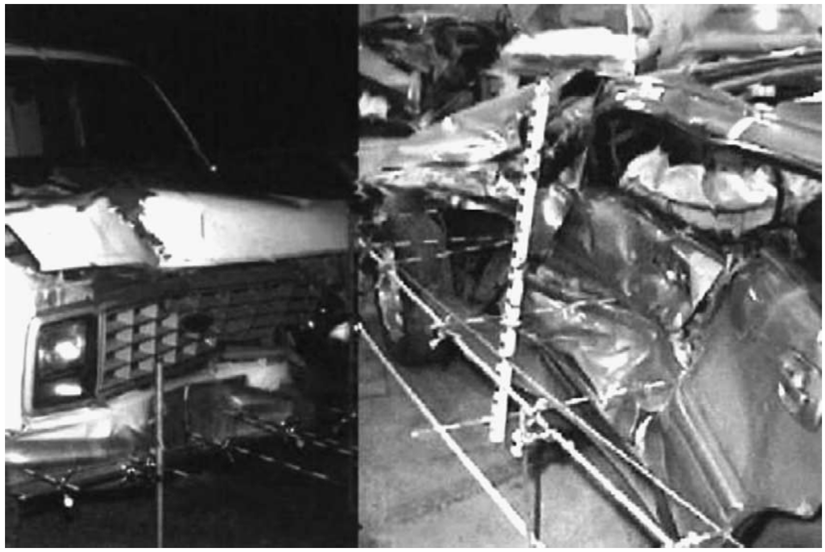

Fig. 1. External damage photographs from side impact Case 4 showing impacting vehicle (left) and target vehicle (right). Note the imprint of the car's A-pillar on the hood of the van. A dent can be seen from contact of the subjects head with the hood of the van, just to the right of the A-pillar mark.

B-pillar intrusion. The door panel intrusion appeared to contact the lower right chest, but the side airbag protected the upper chest by covering the upper door panel (Fig. 3). This side airbag, which extended vertically 27 cm above the armrest, covering the lower side window area, also prevented the head from contacting with the side interior and possibly even from striking the front of the SUV.

After a prolonged extrication, the following injuries were identified: right rib fractures 7–9 with right pneumothorax, a bleeding omental vessel, a transverse colon hematoma, and multiple pelvic fractures. The subject had a right chest tube placed and underwent laparotomy. The pelvic fractures were deemed non-operative by the consulting orthopedic team.

Post-operatively, the subject progressed well. On hospital day 8, the tube was removed, and she was discharged to a skilled nursing facility for an additional 6 weeks of rehabilitation. At 3 months post-injury, she was full weight bearing, and at 1 year, she had returned to most usual activities and her pain had resolved.

3.1.2. *Side impact findings*

In side impact collisions with vehicle mismatch, we examined injury outcomes for each vehicle. Whereas a majority (11/14) of the LTV occupants sustained no injury or a non-disabling injury, 11 of the PV occupants sustained major injuries and 5 died (15/16). The injury distribution of PV occupants can be seen in Fig. 4. The most common areas for injury include the chest (73%) and the head (53%). These injuries were attributed to intrusion of the door panels, B-pillar, and in some cases direct contact with the impacting vehicle. In almost all collisions, intrusion

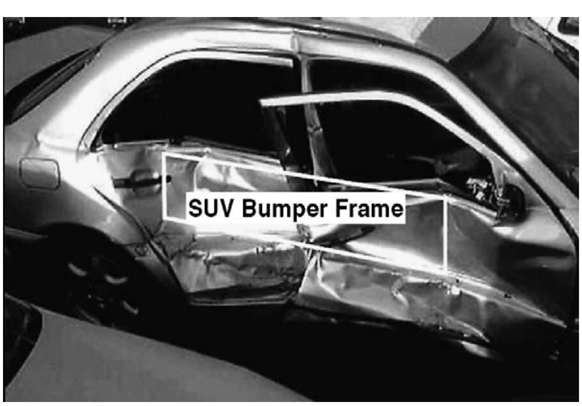

Fig. 2. Side impact Case 11 external damage demonstrating upper door intrusion. The box indicates the contact area of the SUV bumper frame.

Fig. 3. Side impact Case 11 internal damage demonstrating rearward position of the seat with airbag deployment protecting the head and upper chest.

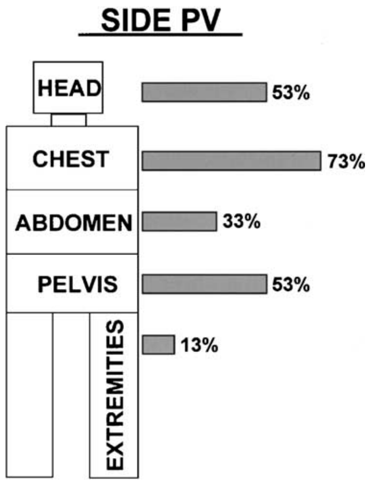

Fig. 4. Injury distribution for passenger vehicle occupants in side impact collisions (percent of patients with injury AIS $\geq$ 2 to designated body regions).

into the passenger compartment was seen ranging from 20 to 47 cm.

The greater LTV bumper frame height resulted in intrusion above the mid to lower door reinforcement designed to satisfy federal motor vehicle safety standard (FMVSS) 214. The LTV frames contacted the PV frames in weaker, non-reinforced areas, leading to maximal intrusions into the head and upper thorax of the occupants (Fig. 5). In three cases, the occupants head actually contacted with the hood of the LTV. In the second case discussed, the observed pattern of head and upper thoracic injury may have been prevented by the side airbag, demonstrating how airbags may help ameliorate this problem. However, this subject still sustained serious injuries to her abdomen and pelvis, which were not protected by the airbag due to the positioning of the seat with respect to the B-pillar.

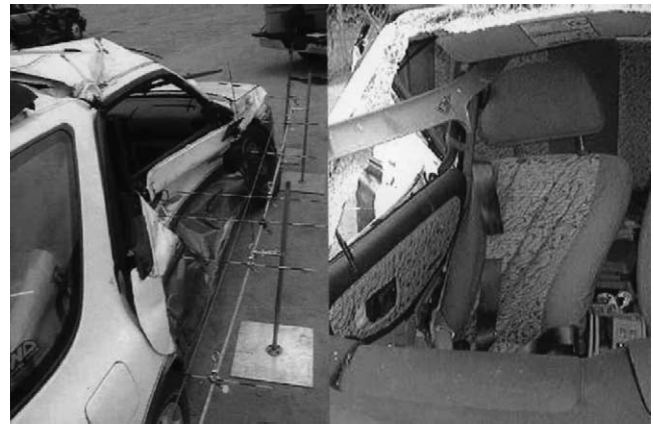

Fig. 5. Side impact collision above reinforcement with exterior and interior views demonstrating contact with upper chest and head.

3.2. Front impact collisions

3.2.1. Passenger vehicles

Table 3 displays the crash data for PV involved in front end collisions with LTV. Fifteen collisions with 19 front seat case occupants were identified. Table 4 contains the injury data for each occupant. A case report followed by summary findings is presented.

3.2.1.1. Front impact passenger vehicle case report—Case 12. This frontal crash involved a 36 year-old female restrained driver of the case vehicle (1996 minivan) which was impacted head on by a large SUV. The PDOF was about 12

Table 3
PV front impact crash data

Case #	Case vehicle	Weight (kg)	Impacting vehicle	Weight (kg)	ΔV (m/s)	Maximum intrusion (cm)
1	1992 Toyta Corolla wagon	1040	1993 Ford Explorer	1810	37	Hood 44, windshield 44, instrument 35
2	1993 Mercedes 190E	1360	1992 Ford Explorer	1840	25	Windsheild 20, instrument 21, knee bolster 21
3	1994 Honda Civic four door	1051	1997 Toyota 4-Runner	1884	35	Windsheild 17, hood 17
4	1991 Toyota Corolla four door	1022	1994 GMC safari van	1843	35	None
5	1990 Toyta Celica	1223	1994 Chevy Astro van	1626	24	None
6	1998 Suzuki Esteem Wagon	1010	1992 Dodge Dakota	1969	25	Toe pan 7, A-pillar 5, instrument 4
7ab	1992 Toyota Corolla	1020	1995 Honda Passport	1830	22	Toe pan 2, windsheild 1
8	1996 Toyota Corolla	1050	1989 Chevy Blazer	1377	32	Instrument 47, A-pillar 40, toe pan 35, Bumper 88
9	1993 Geo Tracker	1105	1997 Toyota Tacoma	1245	40	A-pillar 32, instrument 31, ext 91
10	1998 Chevy Cavalier	1172	1976 Ford F-150 pickup	1826	19	Toe pan 8
11a–c	1994 Dodge Grand Caravan	1604	1994 Ford Explorer	1884	12	A: instrument 24, sidepanel 28, windshield 20; B: B-pillar 20; C: C-pillar 5
12	1996 Plymouth Voyager	1714	1983 Wagoner jeep	1919	27	Toe pan 45, instrument 42
13	1995 Mazda Protégé	1082	1989 Ford ranger	1524	17	None
14	1995 Toyota Avalon	1490	1999 Chevy Suburban	2448	55	Instrument 16, toe pan 18, steering 12
15ab	1999 Buick Centry	1521	1997 Ford Explorer	1935	Unknown	A: windshield 8, steering 8; B: toe pan 16

Lettered cases indicate multiple case occupants of the same vehicle and the intrusions listed are those nearest to each occupant.

Table 4
PV front impact injury data

Case #	Age	ISS	AIS maximum	Injuries	Source	Fatality	Impacting vehicle injury
1	60	41	4	Zygomatic arch fracture Rib fractures, pneumothorax Femur, pelvis, radius/ulna fracture Extraperitoneal bladder rupture, mesenteric contusion	External hood intrusion, certain Steering column, probable Instrument panel, certain Shoulder belt only, possible	Yes	Disabling injury
2	63	14	3	Rib and clavicle fractures Tibia/fibula and lateral maleolus fracture, degloving	Age/seatbelt, certain Knee bolster/floor, certain	No	Non-disabling injury
3	21	14	3	Femoral shaft fracture Ankle fracture Spleen contusion	Knee bolster, certain Toe pan, probable Steering wheel, probable	No	Non-disabling injury
4	47	75	6	Rib and sternum fractures, hemothorax, heart lacerations Kidney laceration, retroperitoneal hematoma	Shoulder with no lap belt, probable Shoulder with no lap belt, probable	Yes	Non-disabling injury
5	26	9	3	Femur fracture	Knee bolster/center dash, certain	No	No injuries
6	39	10	3	Acetabular fracture Radius/ulna fractures	Knee bolster, certain A-pillar, certain Unbelted obese	No	Disabling injury
7a	58	10	3	Femur fracture Severe scalp laceration	Braking/no lap belt/instrument panel, certain B-pillar/belt attachment, certain	No	No injuries
7b	24	9	3	Femur fracture	Glove box, certain	No	No injuries
8	30	75	6	Flail chest, pulmonary contusions, thoracic aortic transection Open femur fracture Pelvic fracture, extensive hemorrhage	Door/steering, possible Instrument/bolster, certain Door, probable	Yes	No injuries
9	17	10	3	Pelvic fracture, hip dislocation, sciatic nerve injury	Instrument panel, certain	No	Non-disabling injury
10	63	14	3	Complex ankle fracture Concussion Chest wall contusions	Loading while braking, toe pan intrusion, certain Undetermined Undetermined	No	No injuries
11a	41	5	2	Severe scalp/galeal laceration, concussion	Airbag, probable	No	Non-disabling injury
11b	8	12	2	Multiple facial fractures, severe scalp wound Tibia fracture Wrist fracture	Windshield, probable Seat back support, possible Undetermined	No	Non-disabling injury
11c	11	5	2	Facial nerve injury, scalp and facial degloving	C-pillar, possible	No	Non-disabling injury
12	36	24	3	Hip and femur fractures Tibial plateau fractures	Axial loading, dash/knee bolster, certain Knee bolster, certain	No	Non-disabling injury
13	31	6	1	Concussion Contusions and abrasions: chest wall, extremities Abdominal contusion	Noncontact, probable Airbag, probable Belt, certain	No	Possible injury
14	74	75	6	Atlanto-occiptial disassociation, brain laceration	Airbag, probable	Yes	Disabling injury

Table 4 (*Continued*)

Case #	Age	ISS	AIS maximum	Injuries	Source	Fatality	Impacting vehicle injury
				Flail chest, sternal fracture, pericardial/atrial/aortic lacerations	Belt, possible		
				Femur fracture	Knee bolster, probable		
				Tibial plateau fractures	Floor pan/bolster, certain		
				Liver laceration	Belt, possible		
15a	60	34	4	Rib fractures, hemothorax, pulmonary contusions	Intrusion of steering column, certain	No	No injuries
				Splenic laceration	Intrusion of steering column, certain		
				Lumbar fracture	Unknown		
				Patella fracture	Knee bolster intrusion, certain		
				Humerus/radius/ulna/scapula fracture	Undetermined		
15b	61	27	3	C1-2 subluxation, concussion	Noncontact, probable	No	No injuries
				Pneumothorax	Seatbelt, certain		
				Humerus/radius fractures	Instrument panel intrusion, probable		

Each line under injuries corresponds to a specific body region and is matched with its source.

o'clock and ΔV was 27 mph. Due to the mismatch in vehicle heights the SUV's bumper frame impacted above the case vehicle's bumper frame. Thus, the direct damage on the case vehicle occurred at the weaker areas of the grill and hood extending to the base of the windshield, causing significant longitudinal intrusion into the passenger compartment (Fig. 6). The instrument panel and knee bolster system intruded longitudinally 45 cm along with the toe pan at 42 cm. Interior contact evidence showed that both of the driver's knees had pocketed into the knee bolster system during the frontal force of the crash. The severe longitudinal intrusion minimized the occupant space, increased the axial loads on the lower extremities and forced the driver rearward into the fixed seatback. The seatbelt and frontal airbag deployment protected the chest and head of the driver. The extrication required to free the driver's lower extremities took 53 min.

Injuries included: left intratrochanteric hip fracture, left severely comminuted midshaft femur fracture, right transverse midshaft femur fracture, bilateral tibial plateau fractures, and left third toe proximal interphanalgeal joint dislocation. The subject required five orthopedic operative procedures during her 17 day hospital course. Her course was complicated by a deep vein thrombosis and an infection of the right tibial wound. Her post discharge course was further complicated by right knee arthrofibrosis requiring additional procedures. She was able to return to work at 5 months post-injury, however, at 2 years post-injury was still requiring physical therapy.

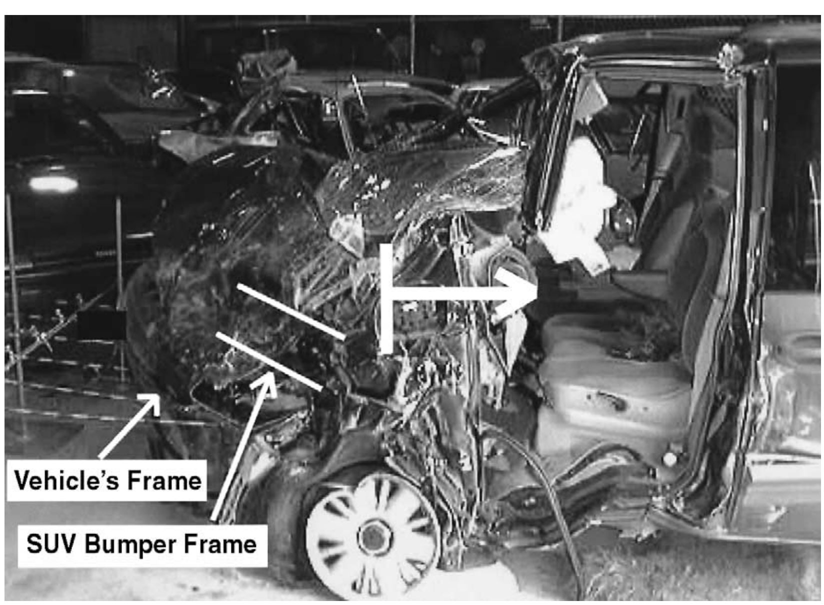

Fig. 6. Front impact Case 12 external damage. Note the extensive deformation above the bumper frame, as well as the intrusion of the A-pillar and instrument panel (original position indicated by bar with arrow) into the passenger compartment.

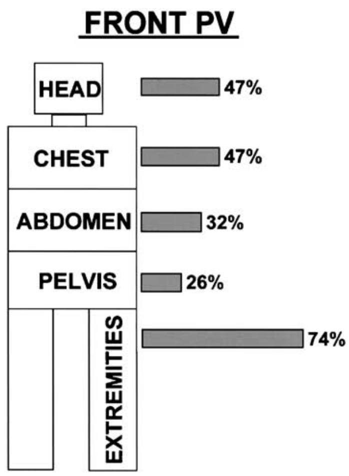

Fig. 7. Injury distribution for passenger vehicle occupants in front impact collisions (percent of patients with injury AIS ≥ 2 to designated body regions).

3.2.1.2. Front impact passenger vehicle findings. Once again, differences are seen in the outcome for the occupants of passenger vehicles compared to LTV occupants. In front end collisions, while no LTV occupant died, four passenger vehicle occupants died (4/19). Fourteen of the 15 surviving PV occupants sustained serious injuries, while only three of the 15 LTV occupants had a disabling injury. However, a slightly different pattern of injury distribution arises when compared to side impact collisions. A majority of PV occupants sustained extremity injuries (74%), followed by head and thorax (each with 47%) (Fig. 7). The sources of injury were commonly found to be intrusion of the instrument panel/knee bolster system, and the A-pillar. Intrusion for these collisions ranged from none to 47 cm. The bumper frames of the LTV contacted the PV above their bumper frames, an area with much lower stiffness. This resulted in greater crush, often extending to the base of the windshield or to the A-pillar, which led to direct intrusion of the instrument panel, knee bolster, and steering column. These elements have been designed to yield to the force transferred as the occupant impacts them, absorbing the force and decelerating the occupant. The intrusion of these items into the passenger compartment reduced the ride down space and created the opposite effect, increasing the forces experienced by the occupant, resulting in more severe lower extremity injuries.

3.2.2. Light truck vehicles

Table 5 displays the crash data for LTV involved in front end collisions with PV. Five collisions with six front seat case occupants were identified. Table 6 lists the injury data for each occupant. A case report and summary findings are presented.

3.2.2.1. Front impact light truck vehicle case report—Case 4. This crash involved a 50-year-old female who was the restrained driver of the case vehicle, a 2000 large SUV. A 1997 compact vehicle crossed the centerline causing a frontal offset collision with the case vehicle. The mismatch in the bumper frame heights caused the case vehicle to override the compact vehicle's bumper frame creating severe longitudinal compartment intrusion and fatally injuring the other driver. The bumper frame height of the compact vehicle impacted below the case vehicle's bumper frame striking only the front left tire and axle (Fig. 8). This forced the front left tire rearward into the floor board and toe pan exposing it at the foot controls of the case driver position (Fig. 9). The intrusion was measured at 55 cm. There was no pre-impact braking and both feet were directly impacted by this severe front tire intrusion. Extrication required 20 min.

The trauma center evaluation revealed a right closed pilon fracture with associated fibula fracture, right midfoot fracture involving metatarsals 1–5 with cuneiform and mid-tarsal dislocations, and left midfoot fractures. She had no other injuries. The subject underwent nine orthopedic surgical procedures throughout her 21 day hospital stay. At 4 months post-injury, the subject began full weight bearing ambulation with cam-walker boots. At 6 months post-injury, she was progressing well with daily rehabilitation and reporting progressively less pain.

3.2.2.2. Front impact light truck vehicle findings. In front impact collisions with PV, the majority of LTV occupants were found to have primarily lower extremity fractures (5/6), while in each striking PV at least one occupant died (6/6). Cases 2 and 3 in this group are the same collisions as cases 15 and 14 from the PV Front Impact group (the fatality from Case 15 was not enrolled in the CIREN study). See Fig. 10

Table 5
LTV front impact crash data

Case #	Target vehicle	Weight (kg)	Impacting vehicle	Weight (kg)	ΔV (m/s)	Maximum intrusion (cm)
1	1994 Ford Econoline van	2420	1989 Ford Probe	1230	34	Toe pan 30, A-pillar 20, steering 30
2a	1997 Ford Explorer	1935	1999 Buick Centry	1521	Unknown	Toe pan 60, A-pillar 28
2b	1997 Ford Explorer	1935	1999 Buick Centry	1521	Unknown	Instrument panel 14
3	1999 Chevy Suburban	2448	1995 Toyota Avalon	1490	32	Toe pan 35, front seat back 23
4	2000 Lincoln Navigator	2641	1997 Ford Escort	1114	24	Toe pan 55, floor pan 15, instrument 8
5	1997 Nissan Pathfinder	1862	1987 Toyota Celica	1145	15	Toe pan 7, floor pan 3

Lettered cases indicate multiple occupants of the same vehicle and the intrusions listed are nearest to each occupant.

Table 6
LTV front impact injury data

Case #	Age	ISS	AIS maximum	Injuries	Source	Fatality	Impacting vehicle injury
1	35	4	2	Displaced comminuted talus fracture, talus neck fracture	Toe pan intrusion, certain	No	Fatality
				Elbow laceration	Undetermined		
2a	40	13	3	IIIC open tibia/fibula fracture comminuted	Toe pan intrusion, certain	No	Fatality
				Zone I sacral fracture	Fulcrum over seatbelt, possible		
				L1/L5 compression fracture	Fulcrum over seatbelt, possible		
2b	38	6	2	T12 anterior compression fracture	Seatbelt fulcrum, possible	No	Fatality
3	28	6	2	IIIA open comminuted calcaneus/cuboid fractures with subluxation	Toe pan intrusion, certain	No	Fatality
4	50	9	3	Bilateral tibia/fibula/cuboid/cuneiform/ tarsal/metatarsal fractures	Massive toe pan intrusion, certain	No	Fatality
5	29	9	3	Tibial plateau fracture, tear of medial meniscus	Knee bolster/instrument panel, certain	No	Fatality

Each line under injuries corresponds to a specific body region and is matched with its source.

Fig. 8. Front impact LTV Case 4 external damage. Notice the underriding damage pushing the left front tire backward.

for injury patterns in LTV occupants. These lower extremity fractures consisted of severe foot and ankle fractures, each requiring multiple surgeries and prolonged rehabilitation periods. The foot and ankle fractures were caused by intrusion of the toe pan into the passenger compartment. In these cases, the toe pan intrusion ranged from 35 to 60 cm. This intrusion was found to be caused by the bumper frame of the PV underriding the bumper frame of the LTV, contacting the wheel, pushing it back and up into the toe pan. Other injuries included pelvic/sacral fractures and lower vertebral fractures which were felt to be due to a fulcrum mechanism over the seat belt.

4. Discussion

For each grouping of vehicle mismatch, definite patterns of injury and related sources are evident. Our results are similar to death risk results reported by the IIHS, who reported PV occupants were 3–4 times more likely to die than LTV occupants in frontal crashes between PV and LTV (5 deaths versus 0 in our series) (IIHS, 1999). For side impacts, they reported a 27–48-fold greater risk of death for PV occupants (5 versus 0 in our series). Of note, there were no LTV occupants who struck the side of passenger vehicles enrolled into the Seattle CIREN study. This is likely due to minimal or no injuries occurring in these occupants.

FMVSS 214 was instituted to reduce severe injuries in side impact collisions by requiring all vehicles manufactured since 1997 to pass a specific side impact crash test. The test consists of a 35 mph impact of a deformable barrier into either side of the vehicle with an anthropomorphic dummy placed in the near side position. The thoracic trauma index (TTI) and peak lateral acceleration of the pelvis are measured, as well as the initial, intermediate, and peak crush resistances. The requirements in Table 7 must be met to pass.

Fig. 9. Front Impact LTV Case 4 internal damage (right) with close up view (left). The left front tire can be seen intruding through the toe pan causing severe foot and ankle fractures.

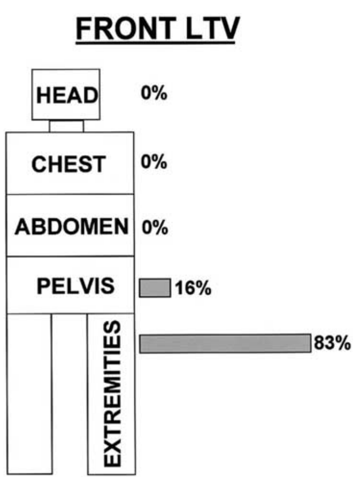

Fig. 10. Injury distribution for light truck vehicle occupants in front impact collisions (percent of patients with injury AIS ≥ 2 to designated body regions).

Table 7
FMVSS 214 requirements

Component	Requirement
Thoracic trauma index	$\leq$85 g for two-door or $\leq$90 g for four-door vehicles
Peak lateral acceleration of the pelvis	$\leq$130 g
Contact door	Shall not separate from the car
Opposite door	Shall not disengage
Initial crush resistance	$\geq$2250 lbs
Intermediate crush resistance	$\geq$3500 lbs
Peak crush resistance	$\geq$2 times the curb weight or 7000 lbs

The specifications of the deformable barrier are that it must consist of a rigid steel cylinder or semi cylinder 305 mm in diameter, the top be at least 13 mm above the bottom edge of the door window opening, but not of any length that would cause contact with any structure above the bottom edge of the door window opening during the test; the bottom begins 127 mm above the lowest point of the door (NHTSA, 1996). The resulting reinforcements are most commonly a single steel beam at the mid-door or lower door cage, leaving the upper portion of the door essentially unprotected. When LTV collide with PV, the higher bumper frame contacts the door above the reinforcement, deforming the non-reinforced part of the door, creating upper thoracic and head injuries

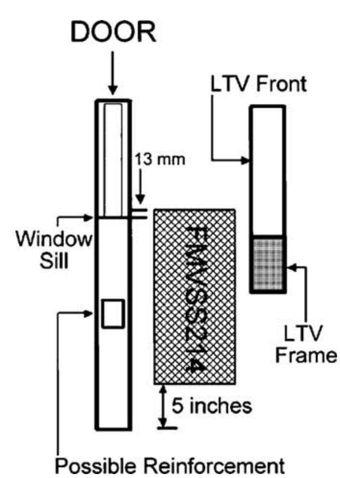

Fig. 11. FMVSS 214 crash test barrier compared to LTV front end. The FMVSS 214 barrier begins 127 mm above the bottom of the door and ends no more than 13 mm above the window sill. The LTV front end is considerably higher, striking above the reinforcement that would pass FMVSS 214.

(Fig. 11). The IIHS is currently using a barrier 30 cm higher than the NHTSA barrier to simulate LTV impacts. Revision of FMVSS 214 to require better performance when vehicles are struck by higher barriers may help minimize injuries from side impact mismatch collisions.

In addition to the height factor, weight and stiffness of the vehicles also play significant roles. The IIHS performed a series of side impact crash tests impacting a Grand Marquis with several different vehicles with varying height and weight (IIHS, 1999). The first impact was with a Lincoln Town Car, which resulted in no significant injury indicators from the BioSID dummy. The next vehicle was an F-150 4×2 pick up truck, which had increased deformation and some measures of injury, none of which were serious. This was followed by a raised F-150 4×2 pick up, which caused increased deformation to the upper door, with increased chest injury indicators and increased head injury indicators due to the head striking the F-150 hood. An F-150 4×2 with increased weight and height resulted in extensive deformation, maximal chest injury, as well as head injury from striking the truck hood. Lastly, an F-150 4×4 pickup was used; this resulted in the most extensive structural damage, severe head injury indicators, but less severe chest injury indicators. This was despite having similar height and weight characteristics to the height/weight enhanced 4×2. The 4×4 had tow hooks on the front end which contacted the reinforced portion of the door, striking the pelvis and moving the dummy to the side before the chest impact could occur. These results have led the IIHS to recommend re-design of LTV front ends to spread the impact load horizontally and vertically. Our results strongly support the need for such changes.

Re-designing the front ends of LTV can also improve outcomes from front end collisions by eliminating the override/underride problem seen in our cases. There are definite differences in bumper frame height between LTV and PV. By designing a lower, reinforced bumper in continuity with the LTV frame, the impact to the PV could be applied to its strong frame, rather than the much weaker grill. This would allow the crumple zones and other designed safety features to absorb a majority of the impact, minimizing intrusion into the occupant compartment. This would also prevent the toe pan intrusion seen in the LTV, reducing the frequency of severe lower extremity fractures. Several automobile manufacturers are voluntarily re-designing their LTV to make them more compatible with passenger vehicles (Bradshear, 2000). However, industry wide design improvements of both LTV and PV will be needed to reduce the effect of mismatch.

Another improvement recommended by the IIHS was to install side airbags with head protection (IIHS, 1999). Side impact Case 13 demonstrates a success story of door mounted side airbag. This patient's thoracic rib fractures were lower than seen in other cases and the head injury limited to a concussion. Side airbags with both head and chest protection could be used to overcome the worsened incompatibility of side impact collisions due to the PV side structures being weaker than the LTV front end structures and the limited crush space available prior to intruding into the occupant compartment.

In conclusion, vehicle mismatch is associated with death and serious injury in automotive crashes. With increasing numbers of LTV on our highways, design improvements to both PV and LTV must be considered. This case series demonstrates the injury patterns that arise from mismatch in side impact and frontal collisions to both PV and LTV occupants and the suspected mechanisms of these injuries. Our findings support the following recommendations: revision of FMVSS 214 to improve performance of vehicles when struck by a higher barrier, re-design of LTV and PV front ends to improve collision compatibility to minimize over/underride, and consider installation of side airbags to protect the head and chest.

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