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Implications of Functional Capacity Loss and Fatality for Vehicle Safety Prioritization

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Objective: We investigate the use of the Functional Capacity Index (FCI) as a tool for establishing vehicle safety priorities by comparing the life year burden of injuries to the burden of fatality in frontal and side automotive crashes. We demonstrate FCI's utility by investigating in detail the resulting disabling injuries and their life year costs.

Methods: We selected occupants in the 2000–2013 NASS-CDS database involved in frontal and side crashes, merged their injuries with FCI, and then used the merged data to estimate each occupant's overall functional loss. Lifetime functional loss was assessed by combining this measure of impairment with the occupants' expected future life spans, estimated from the Social Security Administration's Actuarial Life Table.

Results: Frontal crashes produce a large number of disabling injuries, particularly to the lower extremities. In our population, these crashes are estimated to account for approximately 400,000 life years lost to disability in comparison with 500,000 life years lost to fatality. Victims of side crashes experienced a higher rate of fatality but a significantly lower rate of disabling injury (0.3 vs. 1.0%), resulting in approximately 370,000 life years lost to fatality versus 50,000 life years lost to disability.

Conclusions: The burden of disabling injuries to car crash survivors should be considered when setting vehicle safety design priorities. In frontal crashes this burden in life years is similar to the burden attributable to fatality.

Keywords: NASS-CDS, disability, impairment, societal cost, injury burden

Introduction

Crash survivability has been the traditional quantitative focus for vehicle safety design, largely because motor vehicle crashes were the fourth leading cause of death (Luchter 1994) and continue to be a leading cause of death in the United States (Centers for Disease Control and Prevention 2015) and globally (World Health Organization 2013). As a result, occupants in modern vehicles are much more likely to survive a serious crash than occupants in older vehicles. Nonetheless, the focus on survivability only indirectly addresses long-term impairment and disability. These long-term effects of injury need to be quantified in order for governments and vehicle manufacturers to effectively prioritize vehicle safety decisions.

Long-term quality of life measures are already being used in other automotive safety decisions. For instance, the U.S. Department of Transportation mandates the use of quality adjusted life year (QALY) costs for cost-benefit analyses of road safety decisions, and the NHTSA uses QALY estimates for comparing the cost and utility of regulatory alternatives (Spicer et al. 2011).

Life quality costs of injury have been investigated by several research groups, and Polinder et al. (2012) provide a good review of the current state of injury burden measurement. In addition, several health status scales have been developed with the purpose of equating specific injuries with their long-term impairment.

The Injury Impairment Index (III; Hirsch and Eppinger 1984) measures functional capacity losses attributable to specific injuries at the level described by the Abbreviate Injury Scale (AIS) codebook. Experienced physicians rated the resulting level of impairment for the majority of moderate (AIS 2) to critical (AIS 5) injuries across 6 impairment categories: mobility, cognitive/psychological, cosmetic, sensory, pain, and daily living. The III has been recently updated, but it has not been subjected to a detailed evaluation (Spicer and Miller 2010; Spicer et al. 2011).

The Injury Impairment Scale (IIS) is another scale designed to assess injury impairment. It was developed by medical specialists and researchers in North America and Europe (Association for the Advancement of Automotive Medicine [AAAM] 1994) and is based on the conceptual framework of States and Viano (1990). The IIS classifies impairment on a scale ranging from 0 (normal function, no impairment) to 6 (impairment level precludes any useful function) for each injury in the 1990 revision of AIS across 6 functional dimensions (mobility, cognitive, cosmetic interfering with function, sensory, sexual/reproductive, and pain). Following the publication of the IIS, 4 studies applying (Bradford et al. 1994) or attempting to validate (Campbell et al. 1994; van Koch et al. 1994; Yates et al. 1994) the measure were presented at the AAAM conference. Though correlations were observed between select injury types and IIS in a restricted age population, it was concluded that the IIS offered insufficient resolution for minor and moderate level impairments and did not represent actual impairment levels reported in patient populations a year post-injury.

Blincoe et al. (2014) have developed economic cost models that have been used to estimate societal dollar costs of specific crash configurations (Zaloshnja et al. 2006). Blincoe et. al.'s models are derived from sampled real-world crash data with victims stratified by AIS severity and body region, and they use III together with the estimated value of a statistical life as the basis for quality of life costs (Miller et al. 1995). Though these models provide estimates for both short- and long-term costs, they are best able to describe the short-term costs directly attributable to the crash rather than the costs of long-term impairment. Blincoe et al. (2014) note that "there is currently no incidence database organized by injury outcome. The development and use of such a database could improve the accuracy of economic cost estimates, and might result in a significant shift in the relative number of injuries regarded as serious" (p. 8). Furthermore, the economic costs associated with long-term impairment are heavily dependent on the estimated value of a statistical life, feasible values of which range from $5.2 to $12.9 million dollars, and therefore there is "far more uncertainty regarding the accuracy of estimates of lost quality-of-life than there is regarding economic costs" (Blincoe et al. 2014, p. 10).

The Functional Capacity Index (FCI; MacKenzie et al. 1994, 1996) was developed to quantify the long-term effects of injuries in survivors of serious motor vehicle crashes. FCI measures functional ability one year after injury on a scale from 0 (death) to 100 (no impairment) across each of 10 dimensions of everyday living: eating, excretory function, sexual function, ambulation, hand and arm function, bending and lifting, visual function, auditory function, speech, and cognitive function. The most recent version of FCI measures disability using the standard gamble technique, which asks subjects whether they would prefer to live with long-term impairment or undergo a procedure that would either result in death or complete cure with a specified probability. As an example, consider an injured subject who is willing to accept at most a 10% a chance of death in order to be completely cured of impairment. Such a subject views the utility of their current (impaired) state as equivalent to the utility of a 90% chance of full recovery balanced with a 10% chance of death. Because death has 0 utility, this implies that the subject values his or her current state as equivalent to 90% of a fully functional life. Therefore, the probability of death that a subject is willing to accept can be interpreted as the proportion of life lost to disability.

FCI scores are linked to AIS injury codes under four assumptions (MacKenzie et al. 1994): the individual survives the injury; the individual is 18 to 34 years old and has no pre-injury morbidities; the acute care and rehabilitation received is appropriate and timely; and the injury described is the only injury sustained by the individual. The quintiles of the resulting FCI scores are included in the current AIS coding manual (Gennarelli and Wodzin 2008), with an FCI score of 1 corresponding to the most disabling injuries and a score of 5 corresponding to the least.

Long-term impairment is an important component of the societal burden of motor vehicle crashes, and these costs should be considered when setting vehicle safety design priorities. The objective of the present work is to investigate FCI's feasibility for assessing the injury impairment burden resulting from frontal and side crashes and FCI's usefulness in establishing safety priorities. Though none of the previously discussed metrics have been validated, FCI was chosen because it has been updated recently, is available for the current AIS coding manual, and uses a technique (standard gamble) that has a direct life year interpretation.

Methods

A natural measure for the societal cost of a fatal injury is the number of years the victim would have been expected to live had he or she not been killed; we refer to this quantity as life years lost to fatality. At a societal level, estimates of expected future life span are provided by the Social Security Administration (SSA 2010) Actuarial Life Table. For example, a 45-year-old female will, on average, live an additional 37.63 years, so if she were fatally injured, the societal cost would be 37.63 life years lost.

The costs of nonfatal disabling injury are more difficult to quantify, but a commonly used metric is the QALY, which accounts for both life span and quality of life. Luchter (1995) first used FCI to estimate a version of the QALY, termed life years lost to injury (LLI), which combines the percentage incapacitation measured by FCI with expected life span. For example, if the same 45-year-old female instead receives a disabling injury with an FCI score of 90, then this is interpreted as a 10% loss of life spread over 37.63 years, with a total societal cost of 3.763 years.

Following the just described methods, we assess the disability burden due to automobile crashes by combining injuries documented in the 2000–2013 NASS-CDS database with the long-term disability estimates provided by FCI and occupants' expected future life spans, as estimated from the SSA Actuarial Life Table.

To provide a basis for comparison, occupants' injuries were also merged with the Blincoe et al. (2014) dollar cost esti-

mates, accounting for body region, injury severity, fracture or dislocation, and hospitalization. Blincoe et al. (2014) further separated costs into 10 categories measuring aspects such as direct medical cost, lost wages, and quality of life. For each occupant we looked across all injuries and selected the greatest cost in each category.

We restricted our analysis to NASS-CDS occupants greater than 16 years of age, traveling in vehicles less than 10 years old and weighing less than than 4,536 kg, who were belted, nonejected, and not involved in a vehicle fire or rollover. In addition, we excluded pregnant women after the first trimester. For frontal crash victims, we further selected for front left or right seat occupants in vehicles whose most severe impact had a primary direction of force from 330° to 30° with general area of damage indicated to be frontal. For the side crash query, we additionally selected occupants in outboard seating positions in vehicles whose most severe impact had a primary direction of force from 60° to 120° or from 240° to 300°, with the general area of damage indicated to be either left or right.

We then merged the AIS injury codes for each included occupant with the FCI measures of impairment. Before 2010, NASS-CDS included only AIS 90 or 98 codes, where as FCI is linked to the more detailed AIS 2005 (2008 update). In these instances, a single older AIS code could potentially correspond to multiple AIS 2005 codes, each with different estimates of long-term impairment. When this happened, we conservatively assumed that the occupant had sustained the least disabling injury.

The overall FCI score for an individual injury is calculated by the formula

$$\text{FCI} = 40 \times \prod_{d=1}^{10} \left(\frac{\text{FCI}_d - 60}{40} \right) + 60, \qquad (1)$$

where FCI_d is the FCI score for the injury in the dth dimension (e.g., bending and lifting). Equation (1) is slightly modified from the version published in MacKenzie et al. (1996) in order to accommodate 3 subsequent revisions to FCI. First, the FCI scale was reversed to make higher scores correspond to less disability. Second, in the standard gamble approach no level of impairment caused subjects on average to be willing to accept more than a 40% chance of death, so FCI scores for survivors were adjusted to range from 60 to 100; similar results have been found in the health economics literature (e.g., Brazier et al. 2004). Third, the dimension weights are incorporated into the individual FCI_d.

For each occupant, we used 2 approaches to combining FCI across injuries. The first, which we call $\text{FCI}_{\min}$, is simply to use the overall most incapacitating injury while ignoring all other injuries. The second, which we call whole-body FCI, or FCI_{WB}, takes the most disabling injury in each dimension and combines them according to Eq. (1).

Finally, we compared the survey weighted costs of injuries, measured in both FCI life years and dollars across NASS-CDS frontal and side crashes. All data management and analyses were performed in SAS version 9.4 (SAS Institute, Cary, NC), and SAS procedures for analyzing complex sample surveys were used throughout.

Table 1. Total societal costs of frontal and side impacts by fatality status in FCI_{WB} life years lost and in millions of 2010 dollars.

	Frontal		Side	
	Fatal	NonFatal	Fatal	NonFatal
Number of cases	350	21,235	240	5,751
Total survey weight	15,694	9,308,159	11,667	2,659,136
Life years lost	497,939	401,018	371,547	47,231
Medical	$178	$27,199	$132	$8,240
Emergency medical service	$14	$397	$11	$112
Wage	$14,647	$48,478	$10,889	$13,272
Household productive	$4,550	$15,592	$3,382	$4,325
Insurance administration	$444	$24,128	$330	$6,269
Legal	$1,671	$12,520	$1,242	$3,368
Property damage	$176	$19,851	$131	$5,375
Workplace	$185	$2,730	$137	$769
Congestion	$90	$3,979	$67	$1,055
Total	$21,865	$154,309	$16,255	$42,592
Quality of life	$121,584	$278,518	$90,386	$91,638

Tables were generate in R (R Core Team 2014) using the xtable package (Dahl 2014).

Results

The frontal crash query yielded 21,585 cases representing a survey weighted 9,323,853 occupants. The side crash query yielded 5,991 cases representing a survey weighted 2,670,803 occupants.

For the first analysis, we compared the societal costs of fatality to the long-term societal costs of non fatal injury. Table 1 shows these costs in life years lost measured by FCI_{WB} and in dollar costs. The row labeled "Total" represents the sum of the non-quality of life dollar costs aggregated across occupants; it differs slightly from the sum of the other dollar costs in the table in that it represents the single worst total cost injury for each occupant, rather than the occupant's worst cost in each category taken across injuries.

These results show that on a societal level, the life year burden of long-term injury for frontal crash victims is approximately 80% of the burden due to fatality. Dollar costs for nonfatal crashes are much higher than for fatal crashes, which is unsurprising because a very small proportion of crashes result in fatality, whereas a large proportion of crashes have economic costs. It is worth noting that life year and dollar costs are not directly comparable. Many of the dollar costs can be attributable to short-term costs from the crash and events immediately following from the crash. Long-term dollar costs are incorporated through an average across all accident victims, so survivors with permanent disability are grouped with those who fully recover. Quality of life costs due to fatality are taken to be the value of a statistical life. In contrast, life years lost neglects all short-term costs and injuries to focus only on resulting long-term disability, with loss assessed at the individual level.

In comparison with frontal crashes, side crashes show a much lower societal burden due to disabling injury, with the majority of the life year costs due to fatality. The lower injury burden is due to both a higher rate of fatalities in side crashes,

Table 2. AIS Body regions for each occupant's most disabling injury by FCI

Region	Frontal			Side		
	Life years lost	Count	Survey weight	Life years lost	Count	Survey weight
Head	35,676	55	4,093	26,064	50	2,124
Face	4,199	10	641	900	4	268
Abdomen	151	4	35	286	1	40
Spine	8,283	12	767	649	2	58
Upper extremity	11,492	19	3,035	1,118	5	259
Lower extremity	338,113	773	86,055	18,022	67	5,583

as well as a lower rate of long-term impairment in survivors. In frontal crashes 0.17% (95% confidence interval [CI] 0.11%, 0.22%) of occupants were fatally injured and 1.01% (0.72%, 1.31%) of survivors sustained disabling injuries, whereas in side crashes 0.44% (0.31%, 0.56%) of occupants were fatally injured, and only 0.31% (0.17%, 0.46%) of survivors sustained disabling injuries. The dollar costs for side crashes show a similar pattern, with fatal crashes accounting for a much higher proportion of the overall side dollar costs than they do in frontal crashes.

We next looked at the AIS body regions that contribute to long-term impairment by looking at the most disabling injury for each surviving occupant; these results are shown in Table 2. In frontal crashes, lower extremity injuries account for the overwhelming majority of occupants' most disabling injuries and their life year costs. In side crashes, lower extremity injuries are still the most common disabling injuries, but head injuries represent a larger portion of the overall societal cost due to their increased severity. The AIS body regions not shown in Table 2 (external, neck, and thorax) never appeared in injuries causing the most long term impairment.

Table 3 shows the most impaired functional dimension across survivors. These results are broadly consistent with the most injured body regions. In both frontal and side crashes, ambulation was the worst affected dimension, which makes sense when compared with the high frequency of lower extremity injury. Interestingly, despite the relative rarity of upper extremity injuries in frontal crash victims, hand and arm function is the second worst affected functional domain; review of these cases found that the non–upper extremity injuries were either spinal or brain injuries which would affect hand and arm function. For side crash victims, cognitive function is the second most commonly affected dimension, which is consistent with the frequency of head injury.

Table 4 shows the 10 most disabling injuries in survivors of frontal and side crashes, ranked by life years lost attributable to that specific injury. Had we instead ranked frontal crash injuries by survey weight, the order would have changed slightly, and the bottom 2 injuries (i.e., cranial VII nerve laceration, bilateral subcortical hemorrhage) in the table would have been replaced by 2 additional lower extremity injuries: tibia shaft fracture, complex, open (survey weight 3,405); and ankle dislocation, no articular cartilage involvement, open (2,259). Had we ranked the side crash injuries by survey weight, the injuries cerebrum hematoma subcortical hemorrhage bilateral; cerebrum brain edema, severe; and cerebrum hematoma, subdural, large, bilateral

would have been replaced by tibia shaft fracture, complex, open (418); cerebrum hematoma, subdural, small, bilateral (362); and fibula fracture, through joint, bimalleolar (334). These potential differences in rankings reflect the severely incapacitating nature of the more rare head injuries in comparison with the less disabling, but more frequent, lower extremity injuries.

Discussion

This study seeks to establish the feasibility of using FCI to quantify the long-term societal costs of traumatic injury. FCI has several advantages in its favor for this purpose. First, it was directly designed to address these societal costs using knowledge gained from previous attempts to quantify long-term consequences, such as III and IIS. Second, it is based on the globally used AIS manual at the individual injury level, which allows for a more nuanced understanding of the causes and mechanisms of disabling injury. FCI's link to AIS also allows analyses of long-term disability to be performed on existing databases, such as NASS-CDS, without the need for additional data collection. Finally, FCI's units are in percentages of a life, so it is easy and conceptually reasonable to aggregate societal costs and compare them with the overall burden of fatality measured in life years.

The most serious limitation to our analysis is that, as with other injury impairment metrics, the disability burdens estimated by FCI have not been validated. Validation is crucial to our having confidence in these outcomes and measures, and without validation it is impossible to know whether FCI either systematically underestimates or overestimates injury burden.

Table 3. Worst FCI dimension

Dimension	Frontal		Side	
	Count	Survey weight	Count	Survey weight
Eating	7	1,803	4	309
Excretory	11	685	0	0
Sexual	0	0	1	40
Ambulation	739	84,150	64	5,582
Hand and arm	26	3,370	12	438
Bending and lifting	29	1,692	4	106
Visual	3	289	1	8
Auditory	2	223	1	23
Speech	5	128	1	131
Cognitive	51	2,284	41	1,693

Table 4. Injuries causing the most societal loss in FCI$_{min}$ life years lost

Crash type	AIS 2005 description	Life years lost	Count	Survey weight
Frontal	Proximal tibia fracture, complete articular	63,400	60	10,673
	Talus fracture, extra articular	62,689	67	17,028
	Calcaneus fracture ≥ 2 joint surfaces, open	55,628	125	10,919
	Proximal tibia fracture, open complete articular	42,702	73	7,067
	Fibula fracture, through joint, bimalleolar	17,001	23	7,047
	Fibula fracture, above joint, open	15,861	82	5,523
	Tibia shaft fracture, complex, open	11,460	45	3,405
	Fibula fracture, through joint, bimalleolar, open	11,240	48	3,424
	Cranial VII facial nerve laceration	10,865	2	1,723
	Cerebrum hematoma subcortical hemorrhage bilateral	9,581	16	857
Side	Cerebrum, DAI confined to white matter or basal ganglia	5,992	11	339
	Cerebrum, pneumocephalus directly related to head trauma	5,195	9	340
	Proximal tibia fracture, complete articular	4,802	5	955
	Cerebrum hematoma subcortical hemorrhage bilateral	3,780	4	204
	Fibula fracture, above joint, open	3,463	8	1,050
	Proximal tibia fracture, complete articular, open	2,824	6	369
	Cranial VII facial nerve laceration	2,628	3	290
	Proximal femur fracture, trochanteric, open	2,590	5	1,330
	Cerebrum brain edema, severe	2,028	2	84
	Cerebrum hematoma, subdural, large, bilateral	1,615	2	258

There are several other limitations to FCI that likely lessen our estimate for the societal burden of injury. First, when multiple AIS 2005 codes correspond to a single AIS 90 or 98 code, we conservatively assumed that the victim had sustained the least disabling of the injuries. Second, FCI scores assume the subject is young, healthy, and given appropriate medical care. However, NASS-CDS crash victims represent the entire vehicle crash occupant population, many of whom are older than the 18–34 range assumed by FCI; on average, we expect these older victims to have worse outcomes than predicted by FCI. NASS-CDS also likely includes some victims who did not receive either timely or appropriate care, which would also increase the burden of injury. We further assumed that survivors' injuries do not lessen their expected life span. However, it is easy to imagine, for example, that a victim with reduced ambulatory ability might lead a more sedentary life, leaving him or her more prone to chronic disease. Additionally, when we aggregated FCI across injuries, we used the worst injury in each dimension, but multiple injures to the same dimension combined are potentially worse than the worst single injury.

There are also limitations to FCI that tend to lead us to overestimate the burden of injury. Most prominently, we assumed that injuries that are disabling after one year do not further improve and that the victims do not further adapt to disability, thus improving their quality of life. Should either of these occur, our estimated costs may be too high.

Conclusions

We propose using FCI to measure the long-term societal costs of injury due to motor vehicle crashes, and we demonstrate its potential utility by looking at functional capacity loss in frontal and side crashes. Our analyses demonstrates that for fontal crashes, the societal burden of disabling injuries (400,000 life years), particularly to the lower extremity (340,000 life years), are of the same order of magnitude as the burden of fatality (500,000 life years). The life year costs of incapacitating side crash injuries (50,000 life years) remain small compared to those of fatality (370,000 life years).

The costs of disabling injury are an important component of the societal costs of car crashes and should be considered when setting vehicle safety design priorities. Nonetheless, work needs to be done to validate FCI, or another measure of long-term disability, in order to ensure the usefulness of these estimated costs.

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