Proceedings of DETC'00
ASME 2000 Design Engineering Technical Conferences
and Computers and Information in Engineering Conference
Baltimore, Maryland, September 10-13, 2000

DETC2000/DAC-14248

IMPROVED SIDE IMPACT PROTECTION: A SEARCH FOR SYSTEMS MODELING PRIORITIES

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ABSTRACT

Systems Modeling evaluates the fleetwide crashworthiness of a vehicle design across the full range of potential impact speeds, angles, collision partners, occupant seating locations, and occupant restraints. Although this approach provides a more thorough assessment of crash protection than provided by a single crash test or simulation, the development of a complete Systems Model requires exhaustive simulation of every potential crash mode – a computationally prohibitive approach. This paper presents a methodology in which real world highway accident data is used to systematically develop Systems Modeling strategies that fully expose the tradeoffs between computational expense and model fidelity as measured by Harm. Using Australian side impact accident data, the paper illustrates the methodology by developing two computationally efficient strategies for developing a Systems Model for the evaluation and optimization of Side Impact protection.

KEYWORDS: Side Impact, Systems Modeling, Crashworthiness, Crash Models, Social Cost, Harm

INTRODUCTION

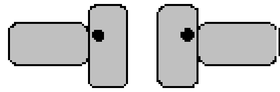
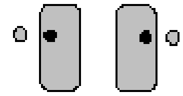
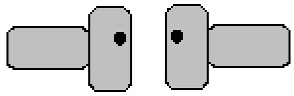
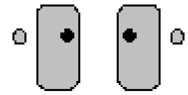
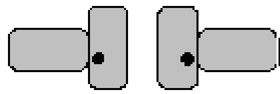
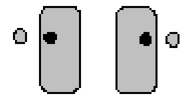
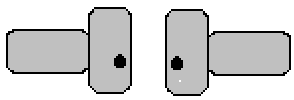
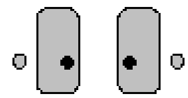
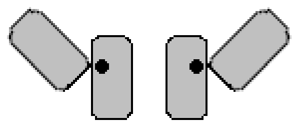
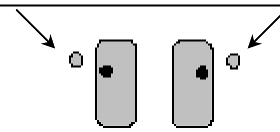
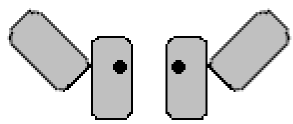
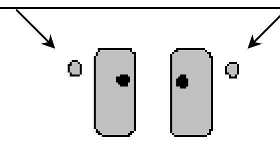
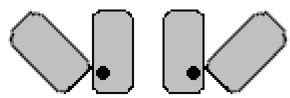
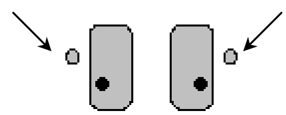
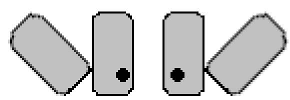
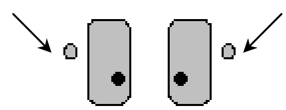
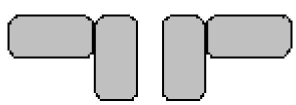
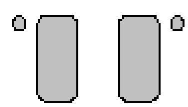
In the Improved Side Impact Protection project, underway at the Monash University Accident Research Centre (MUARC), Systems Modeling of side impacts will be used to optimize vehicle design for enhanced side impact protection. Systems Modeling is a significant enhancement over conventional methods for assessing crash safety performance (Ford, 1975, 1978; Zimmerman, 1984; White et al, 1985; Gabler et al, 1994, 2000; Sparke, 1998). Traditionally, the crash performance of a particular vehicle design has been evaluated based upon the results of a single crash test, e.g. the New Car Assessment Program (NCAP) (Hackney, et al, 1996), or a single computer simulation using a code such as MADYMO (TNO, 1997). Although single crash tests or simulations provide a useful indicator of crash safety in a particular crash mode, the results of one test cannot be readily extrapolated to infer the fleet wide safety performance of a car.

When on the highway, cars are subjected to not one, but a myriad of different types of accidents. Systems Modeling attempts to capture this fleetwide crash safety performance by evaluating car design across the full range of potential impact speeds, angles, collision partners, occupant seating locations, and occupant restraints. The outcome of each of these collision modes is computed in units of fatalities, injuries, or social cost, weighted by its probability of occurrence, and summed. The result is a system-wide measure of safety performance of the car design in terms such as the annual number of fatalities or harm incurred by accident-involved occupants of this car.

The Tradeoff between Model Accuracy and Model Development Costs

The drawback of Systems Modeling is cost. Systems Modeling requires the execution of large numbers of computational models in order to develop a system-wide measure of safety performance. There are two primary components of Systems Modeling cost. The first component is the large engineering man-hour investment to develop models for crash simulation codes such as MADYMO. The second cost component is the enormous computational time required to execute these MADYMO models over all permutations and combinations of possible crash configurations.

Table 1. A Subset of the Universe of Side Impact Configurations

	Vehicle Impacts	Pole Impacts
Front Seat, Near Side, Perpendicular Impact		
Front Seat, Far Side, Perpendicular Impact		
Rear Seat, Near Side, Perpendicular Impact		
Rear Seat, Far Side, Perpendicular Impact		
Front Seat, Near Side, Angled Impact		
Front Seat, Far Side, Angled Impact		
Rear Seat, Near Side, Angled Impact		
Rear Seat, Far Side, Angled Impact		
L-Type (Non Compartment Strike)		

A subset of the universe of potential side crash configurations is shown in Table 1. Each crash configuration, which is simulated in the Systems Model, requires its own MADYMO model. For example, the car-to-car crash mode requires a different MADYMO model than the pole-to-car crash mode. Although developing more MADYMO models improves the accuracy of the estimates of total harm, this strategy also escalates the engineering and computational costs. To make the Systems Modeling approach feasible, it is typically not practical to model all crash modes. Those crash modes which are rare or of little social consequence can be safely neglected in order to minimize analysis costs while having little outcome on the final result. The challenge then is to determine the minimum number of crash configurations which must be modeled in order to capture the systems wide essence of side impact societal cost.

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OBJECTIVE

The objective of this study is to identify those crash modes that should be modeled as part of a Systems approach to Improved Side Impact Protection.

TECHNICAL APPROACH

In this study, Harm (Fildes et al, 1994) will be used as a measure of social cost and the metric for setting modeling priorities. The approach will be to rank order all side impact crash modes by both Harm and relative frequency of occurrence. This rank ordering can then be used as a means of assigning priorities for model development based upon the "importance" of each crash mode.

The MUARC Crashed Vehicle File

This study is based upon the analysis of the MUARC Crashed Vehicle File (CVF). The CVF is a detailed record of real world crashes which occurred in Victoria, Australia from 1989 to 1992. To be included in the CVF, the crash had to involve at least one occupant who was either hospitalized or killed. The CVF is comprised of 501 crashes involving 606 injured occupants. Of these cases, the CVF contains 198 side impacts involving 234 occupants. The CVF contains only injured occupants. Uninjured occupants are not included in the file.

The record of each accident includes crash type, principal direction of force, crash profile, vehicle deformations, occupant description, a description of the injuries sustained, and the source of these injuries. Change of velocity during impact was calculated using the CRASH3 accident reconstruction program. Occupant injuries were scored using the Abbreviated Injury Scale (AIS85) procedure and vehicle damage was evaluated using the procedure specified in the U.S. National Automotive Sampling System (NASS).

In interpreting the study which follows, it should be emphasized that CVF is a sample of car crashes which occurred in Victoria in 1989-1992. The CVF is several years old, and reflects the fleet composition and accident environment of the period 1989-92. Likewise, the sample of crashes in the CVF reflects the traffic accident environment of Victoria, Australia. The CVF is not a national database of crash records, and in particular, is biased toward the ratio of urban-to-rural crashes which is unique to the State of Victoria.

Measuring Social Cost with Harm

Harm is one of several methods of measuring the social cost of traffic accidents. Two other more common measures are number of fatalities and number of injuries. Both fatality and injury counts however provide unrealistic snapshots of social cost. Fatal accidents are extremely rare, and unrepresentative of the majority of traffic accidents. Determining research priorities based upon fatal accidents can bias a study to consider only the most catastrophic accident modes – at the expense of potentially more prevalent accident modes which are disabling but non-fatal. On the other hand, basing research priorities upon total number of injuries ignores the fact that most injuries are minor abrasions and bruises, and present no significant threat to life.

Recognizing the need for a social cost metric that balanced the number of injuries with the severity of the injuries, Malliaris et al (1982) developed the Harm metric. The Harm metric determines social cost based upon injury severity. Severity is measured using the Abbreviated Injury Scale (AIS) developed by the AAAM to describe the relative threat to life of an injury. AIS levels range from 0 for no injury to 6 for unsurvivable, or fatal, injuries. The social cost includes both medical costs and indirect costs such as loss of wages.

When a person suffered multiple injuries, the previous Harm metric based the social cost upon the body region with the maximum AIS level. This method can underestimate the overall AIS level as multiple injuries aggravate the total threat to a crash victim's life. Fildes et al (1994) developed an enhanced Harm metric, presented below and used in this study, which more correctly computed the social cost of persons with multiple injuries.

$$Harm = \sum_{i=1}^{NumInjuries} Cost_i(bodyregion, AIS)$$

This method assigns a social cost to each injury, and sums these costs to estimate a total social cost of injury. *Cost*, the social cost of an injury *i,* is a function of the injury severity as measured by the AIS scale, and the body region which has been injured. In this study, $Cost_i$, the cost of injury, as defined at MUARC (Fildes et al, 1994) was used as a measure of social cost. The cost components included not only treatment and rehabilitation costs but also all other costs to society such as loss or wages and productivity, medical and emergency service infrastructure costs, legal and insurance costs, legal and insurance charges, family and associated losses and allowances for pain and suffering.

Model Selection

The objective of this study is to select those side impact modes from the broad range of possible crash modes which should be modeled as part of a Systems Model for Side Impact. Note that the emphasis is on ranking crash modes which would require the development of new computational models. Examination of the rich literature on side impact modeling and crash testing reveals a number of observations upon which to set broad model selection guidelines (Hackney et al, 1984; Trella et al, 1991, 1996). In general, a single side impact model is not sufficient to describe the full universe of potential side impact modes. New model generation is required for each unique impact geometry or loading configuration. Specific guidelines are presented below:

- Pole impacts subject the struck car to a concentrated load and must be modeled separately from vehicle impacts which subject the struck car to a distributed load.
- Angled vehicle impacts produce much larger deformations than perpendicular impacts, engage different structural components than perpendicular impacts, and must be modeled separately.

- Far side impacts fling the occupant across the compartment and must be modeled separately from near side impacts.
- Rear seat impacts engage different structure and seat geometry than do front seat impacts and must be modeled separately.
- Impact location is an important factor in determining impact severity. Compartment strikes engage less structure and are significantly more injurious than off-compartment strikes. In general, different impact locations require separate computational models.

Equally important to understand are those variations on a single MADYMO model which do not require new model development. Left and right side symmetry will be assumed in this study. Although the left and right sides of cars share many of the same structural design components, this asymmetry introduced by the steering mechanism on the driver side must nevertheless be considered when interpreting the results of a simulation. Changing occupant height is not considered to be a new model as changing from a 50th percentile occupant to a 5th percentile occupant is a relatively minor MADYMO modeling change. Likewise, changing the impact speed does not require development of a new model, as changing the initial velocity in a MADYMO simulation is a straightforward modification.

RESULTS

The discussion below presents the ranking of crash modes by striking vehicle and object, occupant seating location, impact angle, and near side vs. far side impacts.

Side Impacts by Striking Vehicle / Object

Figure 1 illustrates the distribution of harm by bullet vehicle or object. As might be expected, passenger vehicles (cars, four wheel drive vehicles, and passenger vans) were the most frequent striking object (63%) and accounted for the greatest amount of harm to drivers (57%). Heavy vehicles, e.g., delivery trucks, articulated trucks, and trams, accounted for less than 10% of the harm. Note that pole and tree impacts resulted in a disproportionate amount of harm. In the CVF, pole and tree impacts accounted for 23% of the crashes, but over 28% of the driver harm.

Figure 2 examines the distribution of harm for side impacts in cases where a passenger vehicle (car, four wheel drive, or van) was the bullet vehicle. As a class, striking cars accounted for the largest contribution of harm (45%) while passenger vans accounted for the least harm (2%). Note that a disproportionate amount of the harm can be attributed to four wheel drive-to-car collisions. Although striking four-wheel drive vehicles accounted for only 6% of the side impacts, these crashes led to 10% of the harm – suggesting an incompatibility between cars and four-wheel drive vehicles in side impact. This confirms similar findings observed in the United States (Gabler and Hollowell, 1998).

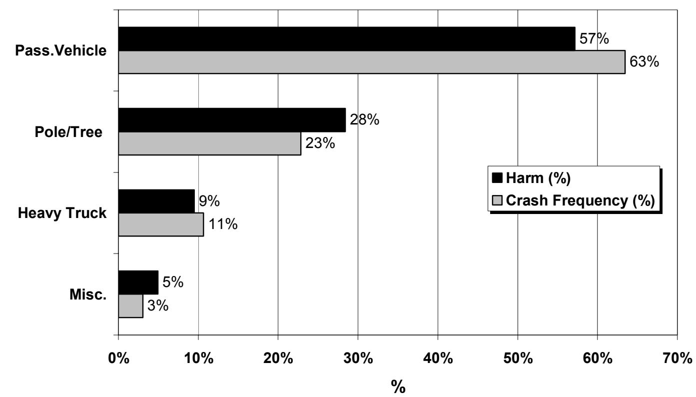

Figure 1. Distribution of Side Impacts by Striking Vehicle/Object (CVF 1989-92)

As these data are approximately ten years old, we would expect current data to show a change in the relative proportion of harm from striking cars and 4 wheel drives. Currently, four-wheel drive vehicles account for approximately 20% of passenger vehicle sales in Australia. We can expect that four-wheel drive vehicles would lead to at least this fraction of passenger vehicle harm, and possibly higher due to the crash incompatibility of cars and four-wheel drives.

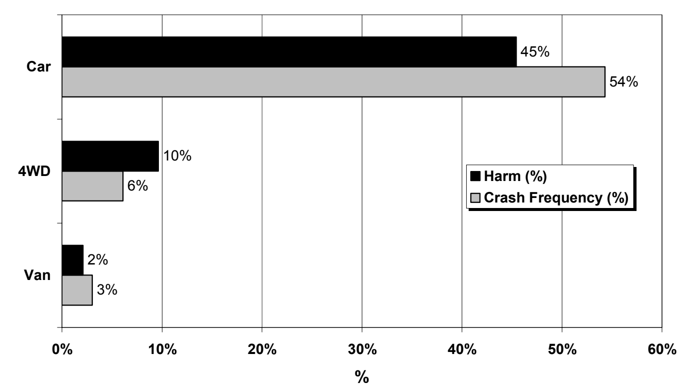

Figure 2. Distribution of Side Impacts by Striking Vehicle/Object (CVF 1989-92)

This rank ordering suggests that the Systems Model should contain cars, four-wheel drive vehicles, and poles as bullet vehicles. The ranking further suggests that modeling of heavy trucks and passenger vans would be of only limited value. Collisions with passenger vans are relatively rare (only 2% of all collisions). Collisions with heavy vehicles are not common (under 10% of harm), and, in any case, it is unclear what injury countermeasures, if any, are available to alleviate the harm from these frequently catastrophic encounters.

Distribution of Side Struck Occupants by Seating Location

Figure 3 shows the distribution of side impact harm by occupant seating location for all side impacts in the CVF. Because every car carries a driver but does not necessarily carry any passengers, we would expect drivers to incur the majority of injuries in side impact. As confirmed in Figure 3, drivers were the most frequently injured occupant (61%) in side impact and accounted for the greatest amount of harm (62%). Left front seat passengers were the next most frequently involved occupant (27%) and accounted for 23% of the harm. Rear seat passengers were the least frequently involved occupant (12%) and incurred only 15% of the harm.

As the Systems Model can capture 85% of the harm by modeling only the front seat occupants, there appears to be little computational benefit from modeling the rear seat occupants. Note that this recommendation addresses which occupants should be modeled – not which occupants should be protected. As rear seat occupants are frequently children, it is imperative that occupant protection be made available to rear seat occupants as well as front seat occupants. It is expected that design features developed under this research program, e.g. improved padding, which improve side impact protection for front seat occupants will provide guidance for designing occupant protection for rear seat occupants as well.

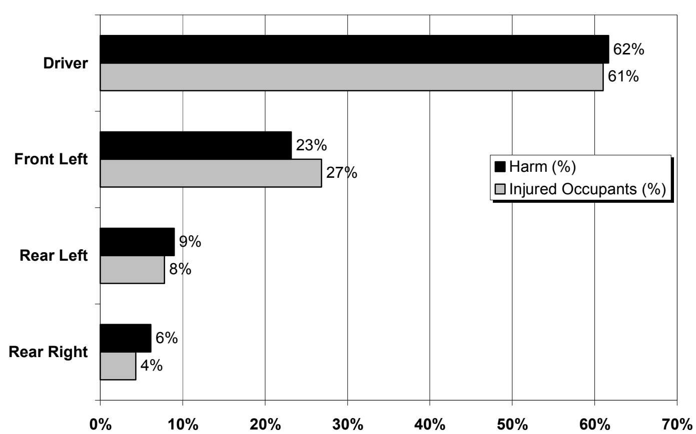

Figure 3. Distribution of Side Struck Occupants - All Crashes (CVF 1989-92)

Side Crashes by Impact Angle

Figures 4 and 5 show the distribution of side crashes by impact angle. In the CVF, each side impact is coded not only by impact angle, but also by impact region. Figure 6 shows the definition of impact region and angle used in this analysis. The analysis which follows aggregates all side impacts into two categories: impacts with passenger compartment involvement and impacts without passenger compartment involvement. The first grouping would include all impacts having NASS coding P, Y, Z, and D. The second grouping, referred to as L-type collisions here, would include NASS coding F and B. Zero degrees is the front of the struck car, 180° is the rear of the struck car and 90° is normal to the side of the struck car.

Figure 4 shows the distribution of side impacts by impact angle when the striking object was a passenger vehicle. For side impacts in which a passenger vehicle was the bullet, the most frequent angle of impact was 61-90° -- or relatively perpendicular. 50% of all harm resulted from perpendicular impacts from passenger vehicles while angled impacts from passenger cars accounted for 38% of harm for oblique impacts (91-150°), and 12% of the harm for acute angle impacts (0-60°) – roughly equal in importance. Note that perpendicular impacts and the sum of angled impacts accounted for approximately equal shares of harm. Each mode contributed approximately one half of the harm.

Figure 5 presents the distribution of side crashes by impact angle when the striking object was a pole or tree. Unlike passenger vehicle impacts, in pole/tree impacts, all angles appear to be contribute roughly the same harm. Perpendicular pole impacts account for 28% of harm. Acute angled impacts (0-60°) account for 27% of harm. Oblique angled impacts (91-150°) accounted for another 28% of harm. As the number of pole impact cases is quite small (38 cases), drawing any conclusion beyond equal likelihood of occurrence appears unjustified.

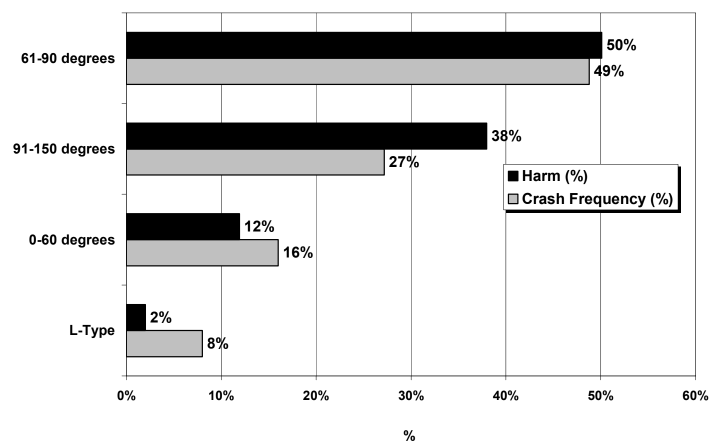

Figure 4. Distribution of Passenger Vehicle-to-Car Side Impacts by Impact Angle (CVF 1989-92)

L-type collisions, side impacts in which there was no passenger compartment involvement, resulted in only a very small fraction of the harm. L-type collisions in which a vehicle was the bullet accounted for only 1% of driver harm. L-type collisions in which a pole or tree was the bullet accounted for only 5% of driver harm. Because L-type collisions have no passenger compartment involvement, these collisions do not subject the occupants to the massive door intrusion which is characteristic of many side crashes that produce injury.

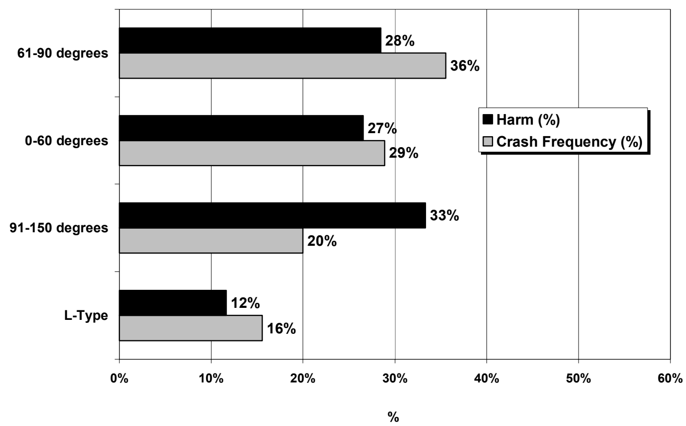

Figure 5. Distribution of Pole-to-Car Side Impacts by Impact Angle (CVF 1989-92)

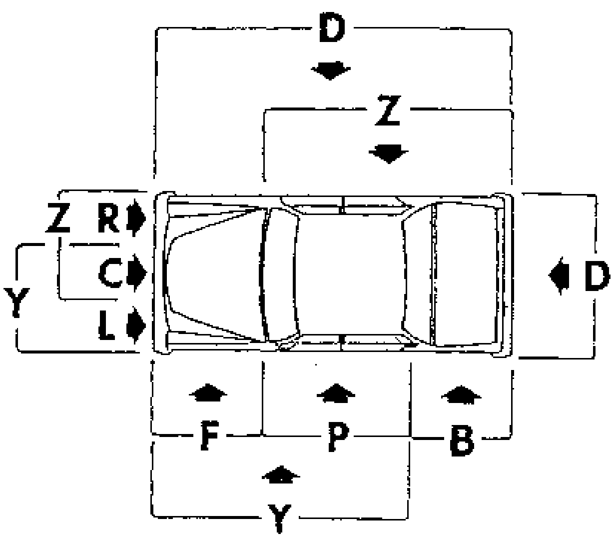

Figure 6. Side Crash Impact Locations

When the bullet object is a passenger vehicle or pole/tree, these rankings suggest that the Systems Model should include a perpendicular impact model and an angled side impact mode. However, there appears to be only limited benefit to modeling L-type collisions. When the bullet vehicle is a passenger vehicle, the angled model should simulate a 120^o impact. For pole and tree impacts, these analyses suggest that there is equal priority for developing either an acute angled impact (0-60^o) or an oblique angled impact (91-150^o). However, the injury patterns from each type of angled impact should be examined prior to selecting which angle of impact is simulated. If sufficient computational resources are available, it would be beneficial to model both acute and oblique impact angles for both passenger vehicle and pole/tree impacts.

Side Impacts: Near Side vs. Far Side Impacts

Of the 231 occupants subjected to side impact in the CVF, 165 occupants were seated on the struck, or near side, of car while 66 occupants were seated on the far side of the car. Figure 7 shows that 71% of all occupants were on the near side of the impact resulting in 67% of the harm. This proportion of near side to far side injured occupants was relatively constant regardless of whether the bullet object was a passenger vehicle or a pole/tree.

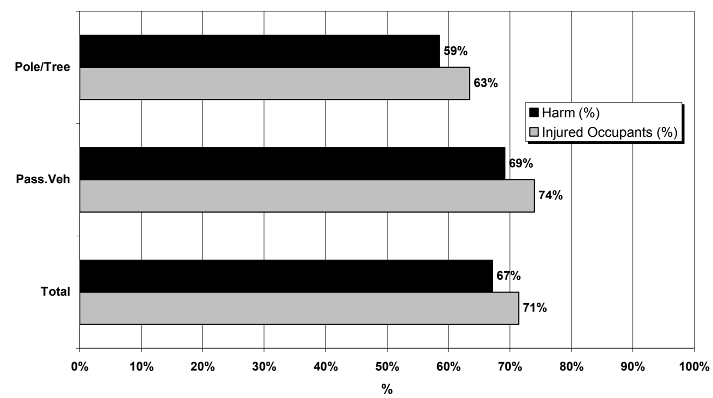

Figure 7. Near versus Far Side Impacts (CVF 1989-92)

Although near side impacted occupants account for the majority of injuried persons and harm, far side impacted occupants account for nearly 1/3 of all harm and injured persons. Other research has shown that the two types of collisions are characterized by substantially different injury patterns. These two types of collisions may require different types of countermeasures for occupant protection. As the Systems Model can be tailored for either developing combined near and far side impact countermeasures, or near side impact countermeasures only, this study will present both scenarios as modeling options.

DISCUSSION

This study has rank ordered each side impact configuration by harm and frequency. Based upon these rankings, the discussion that follows presents two strategies for developing a Systems Model. Noting that near side impacts contribute approximately 70% of the harm, the first option presented is a Systems Modeling strategy in which only near side impact crashes are simulated. The second option presented is a Systems Modeling strategy in which the combined effects of near and far side impacts are simulated. Note that both strategies focus only on side impacts with passenger vehicles and pole/trees. Collisions with heavy trucks and miscellaneous vehicles, e.g. horse trailers, are not considered.

The findings of this study are summarized in Figures 8 and 9. Each crash mode is listed in descending order by its relative contribution to total harm. From a harm perspective, the most important models to develop are for the crash modes at the top of the chart. Likewise, the least important models to develop are for the crash modes at the bottom of the chart. Each crash mode is labeled with the percentage of cumulative harm which would be captured if this crash mode and all preceding modes on the list were included in the final Systems Model.

Each crash mode in Figures 8 and 9 includes all impact angles. Recalling that angled impacts contribute approximately the same amount of harm as perpendicular impacts, both impact angles should be included in a Systems Model. Therefore, each crash mode selected in Figures 8 and 9 will require the development of at least two separate models: one for perpendicular impact and one for angled impact. For example for the crash mode of a vehicle striking a car, both a perpendicular vehicle impact and an angled vehicle impact should be modeled.

Strategy 1: The Near Side Only Systems Model

Figure 8 shows the results of the near side only modeling strategy. For near side impacts, the crash configuration which accounts for the most harm (29%) is the driver struck by a passenger vehicle. The next most important configuration is the left front seat occupant struck by a passenger vehicle. Together these two near side modes account for 57% of the near side harm. As the driver side structure is expected to differ little from the passenger side structure, both modes can be aggregated into a single model for simulation purposes. The third and fourth most important crash modes both arise from near side pole impacts to drivers and front-seat passengers. As with near side vehicle impacts, these two modes can also be lumped together in a single crash model. Together, the first four crash types contribute 86% of the near side harm.

Table 2. Near Side Only Computational Models

Crash Model	Impact Location	Configuration	Impact Angle
1	Near Side	Vehicle-to-car	Perpendicular
2	Near Side	Vehicle-to-car	Angled
3	Near Side	Pole-to-car	Perpendicular
4	Near Side	Pole-to-car	Angled

This analysis suggests that 86% of the near side impact harm can be captured with only the four computational models shown in Table 2. The remaining eight crash modes, comprising rear seat occupants, contribute only 14% of the total near side harm.

Strategy 2: The Combined Near and Far Side Systems Model:

Figure 9 presents the results of the combined near and far side modeling scenario. The crash configuration which accounts for the most harm (37%) is the near-side, front seat occupant (driver or passenger) struck by a passenger vehicle. The next most important configuration is the near-side, front seat occupant struck by a pole or tree. Combining these two near side impact modes accounts for the majority of harm (56%). The third and fourth most important crash modes are both of the far side configuration. Far-side drivers struck by passenger vehicles, combined with the preceding two modes, account for a cumulative harm of 74%. Far-side drivers struck by a pole or tree, combined with the preceding three modes, account for a cumulative harm of 88%.

This analysis suggests that fully 88% of the side impact harm can be captured with only the eight computational models listed in Table 3. The remaining crash six crash modes, primarily rear seat occupants, contribute only 12% to the harm total.

Table 3. Combined Near and Far Side Computational Models

Crash Model	Impact Location	Configuration	Impact Angle
1	Near Side	Vehicle-to-car	Perpendicular
2	Near Side	Vehicle-to-car	Angled
3	Near Side	Pole-to-car	Perpendicular
4	Near Side	Pole-to-car	Angled
5	Far Side	Vehicle-to-car	Perpendicular
6	Far Side	Vehicle-to-car	Angled
7	Far Side	Pole-to-car	Perpendicular
8	Far Side	Pole-to-car	Angled

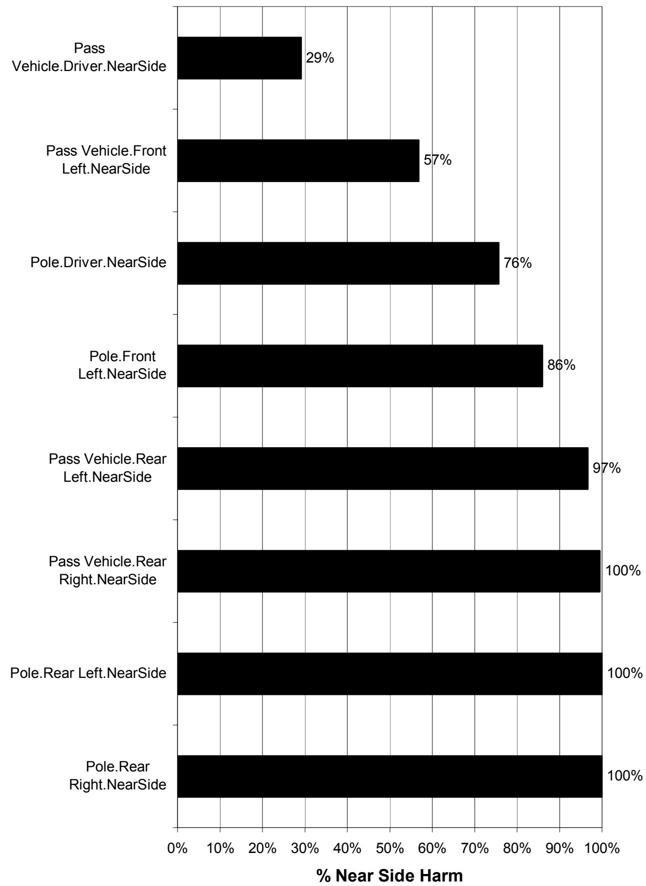

Figure 8. Systems Modeling Options: Near Side Impact Only

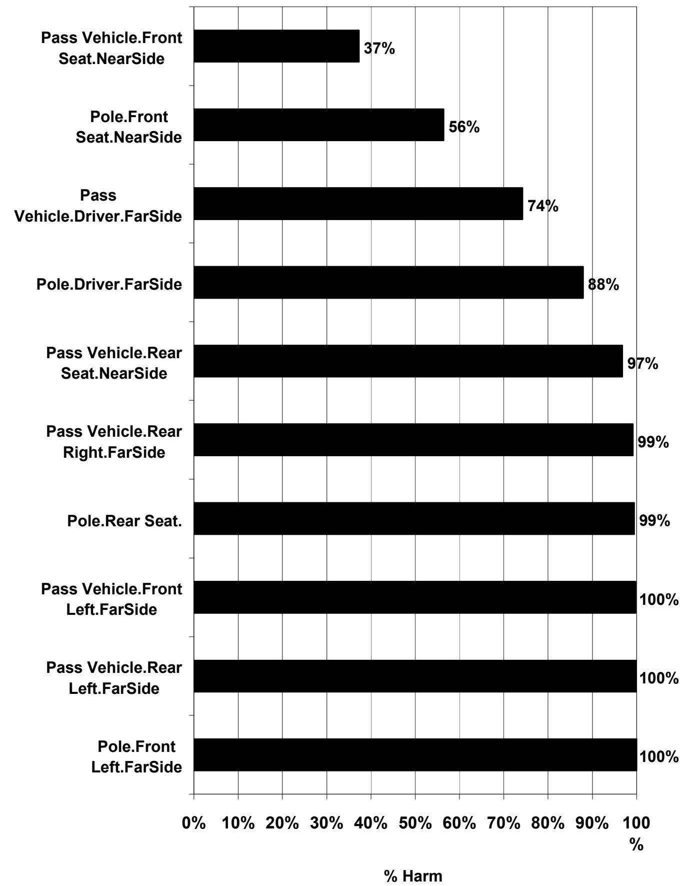

Figure 9. Systems Modeling Options: Near and Far Side Impact

CONCLUSION

This paper has presented a methodology in which highway accident data is used to systematically develop Systems Modeling strategies that fully explore the tradeoffs between computational expense and model fidelity as measured by Harm. Using Australian side impact accident data, the paper has illustrated the methodology by developing two computationally efficient strategies for developing a Systems Model for the evaluation and optimization of Side Impact protection. By modeling only front seat occupants exposed to near side impacts, the first Systems Modeling strategy captures over 55% of total Harm with only four vehicle/occupant models. By extending the first strategy to include front seat occupants exposed to both near and far side impacts, the second strategy captures over 86% of total Harm with only eight vehicle/occupant models.

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