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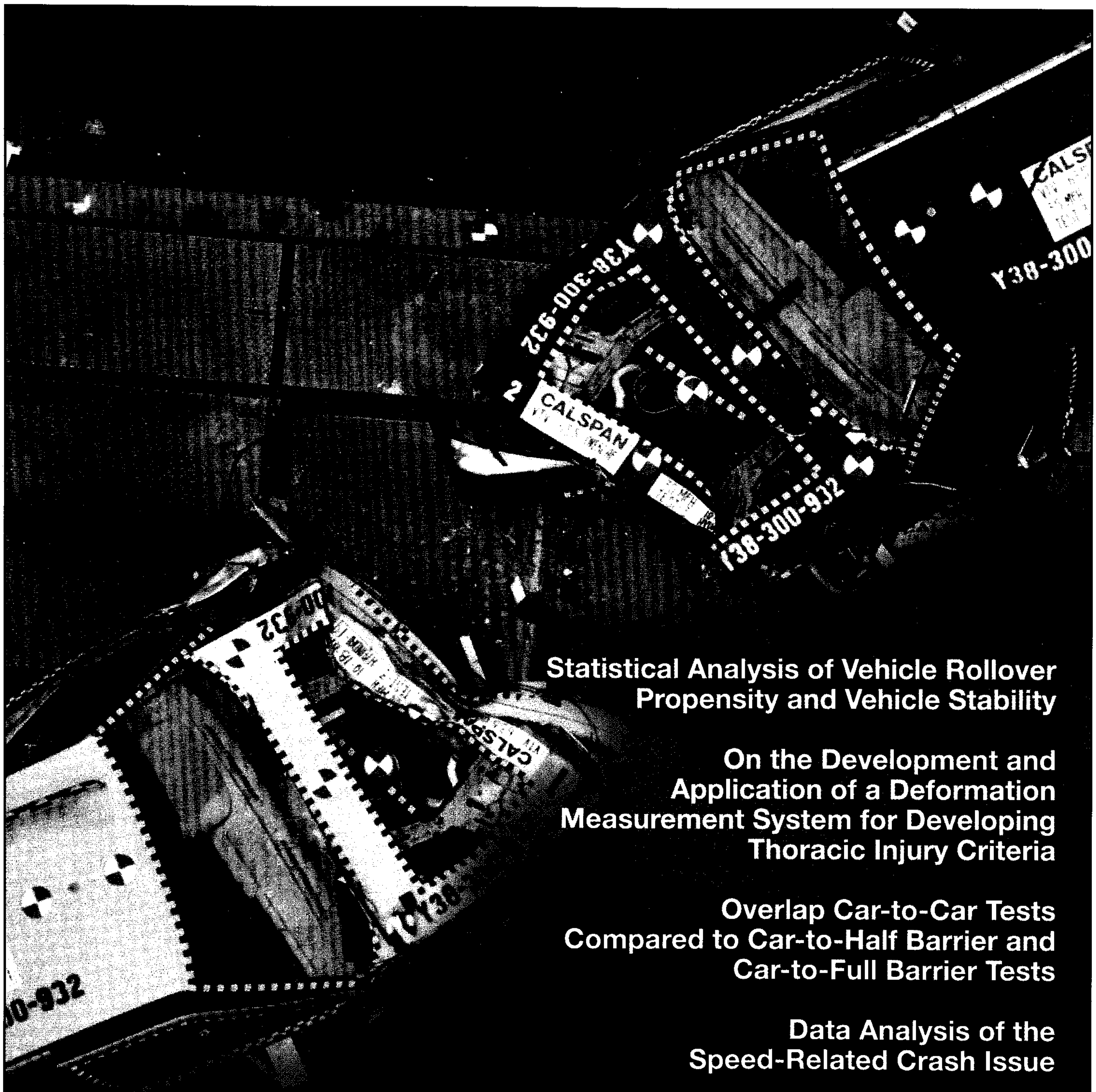
# Auto & Traffic Safety




Statistical Analysis of Vehicle Rollover Propensity and Vehicle Stability

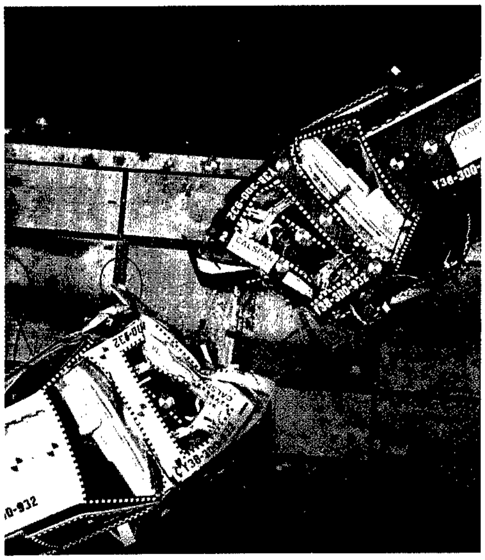
On the Development and Application of a Deformation Measurement System for Developing Thoracic Injury Criteria

Overlap Car-to-Car Tests Compared to Car-to-Half Barrier and Car-to-Full Barrier Tests

Data Analysis of the Speed-Related Crash Issue

# Technical Articles





**ON THE COVER:**

*These two cars were part of series of tests conducted to develop a crash test that will produce the intrusion-related injuries seen in actual highway accidents. Both cars were 1987 Hyundai Excel GLS models. Just before impact, each car was traveling at 56.8 kilometers per hour (35.3 miles per hour). The centerlines of the vehicles were offset such that approximately two-thirds of the bumper width was engaged.*
***Photo: Shirley Mandel, Arvin/Calspan Corp.***

# Departments

# MESSAGE FROM THE ADMINISTRATOR



*Auto & Traffic Safety* is published periodically by the Superintendent of Documents, U.S. Government Printing Office (GPO), Washington, DC 20402.

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## About This Issue . . .

Welcome to this, the second issue of *Auto & Traffic Safety*. Like the first, it includes results from a wide range of NHTSA's safety research activities.

In his paper, Terry Klein investigates the rollover propensity of light-duty vehicles. Rollovers, as measured by either fatalities or incapacitating injuries per involved occupant, are the most dangerous type of collision for all classes of light vehicles. As discussed in this paper, regression analyses were used to examine the ability of a number of stability measures to predict rollover propensity.

In the second paper, Rolf Eppinger, Richard Morgan, and Nopporn Khaewpong discuss the EPIDM system designed and patented by NHTSA—a new tool for measuring chest deflection. The authors focus on the operational theory underlying the EPIDM, its physical characteristics, some experimental results, and various processes that are being used to develop advanced thoracic injury criteria.

Improving frontal crash protection is part of NHTSA's priority plan. The third article, by Carl Ragland and Gayle Dalrymple, sheds light on this very subject. It discusses a series of baseline car-to-car tests conducted to provide comparisons of crash responses between full frontal barrier, car-to-barrier overlap, and car-to-car overlap impacts.

In the fourth and final article, by Noble N. Bowie and Marie Walz, the authors use the most recent data available to examine the size of the "speeding problem" in the United States. Speeding has been recognized for decades as a significant, and highly complex, safety issue. In this paper, the authors examine information pertaining to crash avoidance and severity as well as related crash characteristics—alcohol, vehicle type, roadway condition, etc. Of particular interest is the use of an innovative methodology to estimate the economic impact of speed-related crashes.

Our intent is to publish *Auto & Traffic Safety* twice a year. For the third issue, we plan to emphasize research results concerning the air bag restraint system. Papers are being prepared.

As we gain more experience with publishing this journal, we will be working to make it more informative and useful to you, its readers. If you have comments or suggestions, please send them along.

**George L. Parker**
*Associate Administrator*
*for Research and Development*

# Statistical Analysis of Vehicle Rollover Propensity and Vehicle Stability

*by* **Terry M. Klein**

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***Abstract***

This report summarizes the accident-data collection, processing, and analysis methodology used by the National Highway Traffic Safety Administration (NHTSA) in a major Agency investigation of the rollover propensity of light-duty vehicles. Specifically, these efforts were initiated in response to two petitions for rulemaking requesting the development of a standard for rollover stability. Logistic regression models were used to investigate the ability of a number of stability measures to predict vehicle rollover propensity, while accounting for a number of driver and environmental factors. It is not the intent of this paper to document formal Agency policy in the area of any possible rulemaking efforts, and as such, references to rulemaking activities are not discussed. A more complete discussion of the events leading to this research activity and descriptions of the specific vehicles and vehicle metrics used in the analysis and how they were measured can be found in reference (1).

## *Introduction*

Rollover accidents occur for many reasons. As with any accident, all three components of the driver/vehicle/environment system play a part in the development of the situation that results in a crash. However, there are extremes wherein a factor or factors related to one part of the system predominates in the causation of the accident. Take the case of a driver falling asleep at the wheel; or consider an unexpected patch of ice on an otherwise clear roadway resulting in a skid; or consider a vehicle which has such a low level of rollover stability that a simple, but severe, steering input by the driver, as part of an accident-avoidance maneuver, results in the vehicle's rolling over. The vast majority of crashes are caused by the interaction of factors from all three parts of the driver/vehicle/environment system.

Rollovers are of particular interest since these accidents are the most dangerous type of collision for all classes of light vehicles, measured by either fatalities or incapacitating injuries per involved occupant. In terms of fatalities per registered vehicle, rollovers are second only to frontal crashes in their level of severity. These results are presented in a 1986 report documenting analyses conducted by NHTSA's National Center for Statistics and Analysis (NCSA) (2). These high injury/fatality rates are even more alarming given that rollovers are by far the least frequently occurring crash mode, as measured by accident involvements per registered vehicle. The National Accident Sampling System's (NASS's) General Estimates System (GES) data file for 1989 (3) estimates 137,600 rollover accidents involving passenger cars. Of these, 124,800 were single-vehicle rollovers, and the vast majority of these, 114,800, occurred off the roadway. For light trucks and vans there were 75,600 rollovers, of which 65,800 were single-vehicle rollovers and 57,200 occurred off road. Based on NASS data, nearly 90 percent of rollovers occurred in single-vehicle accidents. Various studies of accident data indicate that, in from 50 percent to 80 percent of all rollovers, the vehicle was out of control (skidding sideways or spinning) prior to overturning.

[Note: These estimates are based on a probability sample of police accident reports. Since

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*Author's Note:* Subsequent to the original July 1992 publication of this work, it was discovered that the values of the variable *Critical Sliding Velocity (CSV)* used as predictors in models examined in the analyses had been computed incorrectly. New values of *CSV* were submitted to the Rulemaking Docket in April 1993, and the analysis has been repeated. All references to *CSV* have been removed from this report (except in Table 3; see note to that table). The revised values will be documented in a NHTSA Technical Report soon to be released.

the estimates are based on a sample, they are subject to both sampling and nonsampling errors. The Technical Note for the 1988, 1989, and 1990 NASS's GES (4) explains the GES sample design and the precision of the estimates. A 95-percent confidence interval is formed based on the estimates ± 1.96 standard errors. For the estimates presented in this report, using the generalized variance formulas results in 95 percent confidence intervals (rounded to the nearest hundred) of:

137,600 ± 25,500
124,800 ± 23,500
114,800 ± 21,600
75,600 ± 15,700
65,800 ± 13,700
57,200 ± 13,700. ]

This paper describes the accident data and the methods employed to collect and analyze them. The data were generated from five state accident data files of those maintained by NHTSA's NCSA. A companion paper (5) presents an overview of NHTSA's rollover rulemaking program.

### *Data Collection and Processing*

NHTSA maintains a collection of accident data files for 26 states. A subset of these data tapes, which the states provide annually, formed the basis of the analyses reported herein, supplemented by data obtained through measurement and simulation. These last data are static and dynamic vehicle metrics hypothesized to be related to vehicle rollover propensity.

Five states were selected for use in this analysis: Georgia (1987-1988), Maryland (1986-1988), Michigan (1986-1988), New Mexico (1986-1988), and Utah (1986-1988). These five states consistently and accurately report a high proportion of Vehicle Identification Numbers (VIN's) for those vehicles involved in accidents. In addition, individual VIN's were also subjected to an intensive correction process described in detail in (1).

### *Accident Definitions*

A single-vehicle accident was defined as all overturns, collisions with parked vehicles or other fixed objects, and noncollision accidents. Single-vehicle accidents do not include collisions with pedestrians, other vehicles on the roadway, bicycles, trains, or animals.

Two of the states, Maryland and Utah, whose automated accident report data files were used in this analysis, use multiple-accident event coding schemes in preparing the accident reports upon which these automated files are based. Because of these differences in the accident event coding schemes, it was necessary to define different criteria for determining whether the kind of rollover of interest occurred in accidents in those states.

The criteria were developed in an attempt to have an accident that was coded as a "first-event rollover" in Michigan, but which would be coded differently in one of the states that uses a multiple-accident-event code, still be classified as a rollover for inclusion in the database used in this analysis. To prevent confusion, this accident type was referred to as a "primary-event rollover" and was defined as all incidents in which the first significant harmful event in the single-vehicle accident was a rollover, and did not include incidents in which a rollover followed a collision with a substantial object other than one which would trip the vehicle. For Utah, this category included reports in which the first event was described as "run off the road" and the second event was a rollover. For Maryland, this category also included those reports in which the first event was a "collision with a ditch, berm, or culvert" followed by a vehicle rollover.

### *Methodology*

The dependent variable was defined as a dichotomous (0,1) outcome indicating whether or not the specific vehicle experienced a primary-event rollover in the accident. The initial non-vehicle-related independent variables used were as follows:

- Driver alcohol or drug use: ALC_DRUG = (0,1);
- Driver error noted by police: DRV_ERR = (0,1);
- Driver age: AGE = actual age;
- Driver age less than 25: UNDER25 = (0,1);
- Driver sex: MALE = (0,1);
- Slippery road surface condition: BAD_SURF = (0,1);
- Curved section of road: CURVED = (0,1);
- Rural area: RURAL = (0,1);
- Accident occurred off road: OFF_ROAD = (0,1); and
- Road grade: RD_GRADE = (0,1).

In addition, the following vehicle metrics were initially used in the modeling effort:

- Wheelbase: L;
- Static stability factor: SSF;
- Tilt table ratio: TTR;
- Side pull ratio: SPR;
- Rollover prevention metric: RPM;
- Braking stability: BRAKSTAB; and
- Percentage of vehicle weight on rear axle (the distance between the front axle and the center of gravity, divided by the wheelbase (L)): A_DIV_L.

Since the dependent variable was dichotomous, the analytical method chosen was logistic regression. This methodology was selected because it presents the (conditional) probability of an outcome (in the current instance, whether or not the vehicle rolled over) in terms of several independent variables, allowing the analyst to construct a model that adjusts for covariate factors (such as the driver- and accident-level variables), while measuring the effect of the vehicle metrics hypothesized to contribute to rollover propensity. This analytical approach has been successfully applied in a previous analysis of rollover propensity (6) at the recommendation of this author after he reviewed an enlightening analysis conducted using linear regression methods (7).

A summary of the sample sizes for each state is displayed in Table 1. As can be seen, Georgia, Michigan, and Utah have similar rates of primary-event rollover—in the 17-20 percent range. Maryland's rate is 50 percent less and New Mexico's rate is 50 percent greater than the other three states'. Possible explanations for some of these differences could be state-to-state accident reporting criteria/thresholds or differences in the geographic distribution of accident location (rural vs. urban roads).

In all of the initial state model estimation runs, the stepwise option of the LOGIST program was utilized. This option permits the introduction of variables into the model one at a time, in a *stepwise* manner. This was necessitated by the fact that many of the vehicle metrics are highly correlated, or collinear. Estimates and standard errors for highly collinear variables are not reliable, and in many cases, are not available in the printed output. Table 2 presents the correlation matrix of the vehicle metrics, shown in upper-triangular form (since the matrix is symmetric).

The variables *Static Stability Factor*, *Tilt Table Ratio*, *Side Pull Ratio*, and *Rollover Prevention Metric* are all highly correlated—in the range of

**Table 1. Sample Sizes for States Analyzed**

| | GEORGIA | MARYLAND | MICHIGAN | NEW MEXICO | UTAH |
|---|---|---|---|---|---|
| Single-Vehicle Accidents | 16,221 | 11,278 | 42,412 | 3,273 | 2,976 |
| Rollovers | 2,756 | 1,143 | 8,146 | 1,031 | 585 |
| Rate | 17% | 10% | 19% | 32% | 20% |

**Table 2. Correlation Matrix of Vehicle Metrics**

| VEHICLE METRIC | STATIC STABILITY FACTOR | TILT TABLE RATIO | SIDE PULL RATIO | ROLLOVER PREVENTION METRIC | WHEEL-BASE | PERCENTAGE OF VEHICLE WEIGHT ON REAR AXLE | BRAKING STABILITY |
|---|---|---|---|---|---|---|---|
| Static Stability Factor | 1.00 | 0.85 | 0.88 | 0.88 | -0.16 | -0.43 | 0.46 |
| Tilt Table Ratio | | 1.00 | 0.80 | 0.78 | 0.02 | -0.35 | 0.43 |
| Side Pull Ratio | | | 1.00 | 0.84 | -0.11 | -0.35 | 0.41 |
| Rollover Prevention Metric | | | | 1.00 | -0.17 | -0.39 | 0.35 |
| Wheelbase | | | | | 1.00 | -0.14 | 0.36 |
| Percentage of Vehicle Weight on Rear Axle (A_DIV_L) | | | | | | 1.00 | 0.20 |
| Braking Stability (BRAKSTAB) | | | | | | | 1.00 |

0.78 to 0.88. The remaining variables exhibit much lower levels of correlation, with *Wheelbase* apparently not correlated to any high degree with any other vehicle metric.

### *Results of Logistic Regression Analysis*

The initial model estimates showed fairly consistent results among the five states. Some differences in whether variables were significant or not can likely be attributed to the large differences in sample sizes (between Michigan and New Mexico/Utah, for example). The variable *Rural* was always one of the most significant variables in each of the states, entering first or second into the stepwise regressions. This was followed by the variable *Tilt Table Ratio*, which entered first (in Georgia) or second into the regressions in every state but Maryland, where *Static Stability Factor* entered second.

Table 3 shows the results of the initial model estimations for each of the five states. The number under each column is indicative of the order in which each variable entered the initial models, with a *1* meaning the first variable to enter, etc.

At this point in the process, it was decided to focus on the following four vehicle metrics: *Tilt Table Ratio, Static Stability Factor, Side Pull,* and *Rollover Prevention Metric.* This decision was based on the outcome of the initial model runs where stepwise analysis indicated that two general groups of vehicle metrics were found to be significant. These are the rollover metrics, both tripped and untripped, and the directional control metrics, consisting of *Wheelbase, Braking Stability,* and *A_DIV_L.* Of all the vehicle metrics, those associated with measures of roll propensity, as demonstrated by *Tilt*

**Table 3. Results of Initial Stepwise Model Estimation**

| VEHICLE METRIC | GEORGIA | MARYLAND | MICHIGAN | NEW MEXICO | UTAH |
|---|---|---|---|---|---|
| Driver Alcohol or Drug Use (ALC_DRUG) | 3 | | 7 | 11 | 5 |
| Driver Error Noted by Police (DRV_ERR) | | 6 | | 4 | 4 |
| Driver Age (AGE) | 4 | | 6 | 7 | |
| Driver Age Less Than 25 (UNDER25) | | 5 | 11 | | |
| Driver Sex (MALE) | NO | | | | |
| Slippery Road Surface Condition (BAD_SURF) | 5 | | 12 | 10 | |
| Curved Section of Road (CURVED) | NA | 3 | 5 | 8 | |
| Rural Area (RURAL) | 2 | 1 | 1 | 1 | 1 |
| Accident Occurred Off-Road (OFF_ROAD) | 7 | | 10 | 3 | 3 |
| Road Grade (RD_GRADE) | NA | | NA | 5 | |
| Wheelbase | | 4 | 3 | | |
| Static Stability Factor | 8 | 2 | 4 | | |
| Tilt Table Ratio | 1 | | 2 | 2 | 2 |
| Side Pull Ratio | | | 13* | | |
| Critical Sliding Velocity** | 6 | | 9 | 6 | |
| Rollover Prevention Metric | | | 8* | | |
| Braking Stability (BRAKSTAB) | | | 15 | 9 | |
| Percentage of Vehicle Weight on Rear Axle (A_DIV_L) | | | 14 | | 6 |

*Variable deleted from model in later step.
**Due to errors in the values of *Critical Sliding Velocity (CSV)* used in these analyses, results related to that variable are in error, and all other references to *CSV* have been removed from this report. However, the results related to *CSV* are included here to show the complete sequence of variables entering the models.
NA = Variable not available from state data file.
NO = Variable available from state data file but not obtained for this analysis.

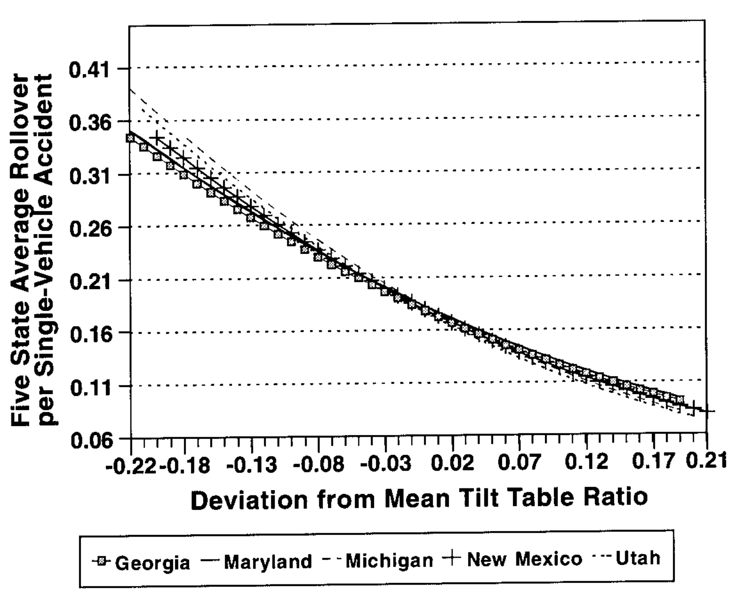
*Table Ratio* and *Static Stability Factor*, tended to enter the model earlier than the directional control variables. In an effort to limit the number of vehicle metrics for possible regulatory purposes, metrics with the higher rankings in the model were selected as the most promising metrics to relate to rollover accidents.

As discussed in more detail in reference (1), the vehicle metrics are further divided into two major categories. The first category *(Tilt Table Ratio, Static Stability Factor, Side Pull Ratio)* is characterized as measures of untripped or "steady-state lateral acceleration" rollover stability. Since these three metrics are highly collinear, only one of them was used in any subsequent analysis. Based on the initial step-wise regression runs, the *Tilt Table Ratio* was selected.

The second category *(Rollover Prevention Metric)* is characterized as a measure of a more dynamic, tripped, rollover situation. This metric was studied in the subsequent analysis.

For these five models, the individual states' estimates for the coefficient of *Tilt Table Ratio* all fell in the range (–4.81, –4.03), suggesting a reasonably consistent relationship between *Tilt Table Ratio* and *Rollover Propensity* among the different states.

**Figure 1. Predicted Rollover Rates per Single-Vehicle Accident as Means of Deviation from Mean Tilt Table Ratio**




The five predicted curves of rollover rate per single vehicle accident as a function of *Tilt Table Ratio* are shown in Figure 1. Note that these curves have been normalized so as to make the comparison between *Rollover Rate* and *Tilt Table Ratio* easier to see. This normalization was accomplished by adding a constant based on the difference between each state's accident experience and the weighted average rollover rate of all five states. A different constant was used to normalize each state's curve.

### *Additional Models Based on Michigan Data*

As can be see in Figure 1, the relationship between *Predicted Rollover Rate* and *Tilt Table Ratio* is fairly consistent among the five states used in this analysis. In an effort to parsimoniously represent rollover propensity as a function of a single-vehicle metric, a number of models were estimated, using a consistent set of non-vehicle covariates, for Michigan. This state was chosen for these exploratory analyses because it had the largest sample size, and the explanatory power of the model (as evidenced by the C-statistic) was near the midpoint of the previously estimated models. While the Michigan data were not subjected to the in-depth VIN correction procedure, reference (1) documents an analysis which indicates that this should have little effect on the modeling results.

Three models were run using *Tilt Table Ratio, Stability Factor,* and *Side Pull Ratio* sequentially, maintaining the same set of nonvehicle covariates in each replication of the model. *Rollover Prevention Metric* was not used in this part of the analysis since the results for previous models showed that it was sometimes nonsignificant.

This analysis indicated that the models using *Tilt Table Ratio* were superior to those using the remaining metrics. The ordering of the results from best to worst is as follows: *Tilt Table Ratio, Static Stability Factor,* and *Side Pull Ratio.* The variable *Rural* was always the most important variable in each of the three estimated models, followed consistently by the vehicle metric, which was more significant than the remaining nonvehicle covariates.

### *Additional Detailed Models Based on Michigan Data*

Additional models were investigated in an attempt to improve model fit. These included the addition of a number of variables sequentially, in order to assess the contribution of their addition to the model. The baseline model against which the additional models were compared consisted of the following variables (for Michigan data): *Alcohol/Drug, Curved, Rural, Off-Road, Driver Age, Under 25, Albrakes,* and *Tilt Table Ratio.* The following variables were investigated: *Tilt Table Ratio Squared, Vehicle Class/Drive Configuration, and Single-Vehicle Accidents Per Registered Vehicle (Single-Vehicle Rate).*

A parallel exploratory effort using linear regression models at the make/model or vehicle level suggested that the addition of the *Tilt Table Ratio Squared* might account for an apparent nonlinearity in the relationship between rollover rate and *Tilt Table Ratio.*

The addition of *Vehicle Class/Drive Configuration* was expected to improve model fit. These variables served to crossclassify the various make/models into logical categories as follows. *Vehicle Class* consisted of four dichotomous variables representing *Passenger Cars, Pickup Trucks, Vans,* and *Sport* (utility) vehicles. The last three variables were used in the analysis, leaving passenger cars as the reference group, with the coefficients of the remaining class variables describing the log odds of rolling over relative to passenger cars. Any of the four variables may be omitted arbitrarily without loss of generality. *Drive Configuration* consisted of three dichotomous variables representing *Rear-wheel, Front-wheel,* and *Four-wheel* drive availability. *Rear-wheel* drive was chosen to be the reference group and was omitted from the modeling, again without loss of generality. The reason for expecting improvement in model fit stems from the differences in rollover rates between the vehicle classes.

At a minimum, inclusion of *Vehicle Class* variables would be expected to contribute to improving model fit by accounting for the differences in mean rollover rate for each vehicle category. *Drive Configuration* was intended to provide a further breakdown of the vehicle classes.

The use of *Single-Vehicle Rate* was exploratory, and was based on a parallel effort using linear regression models at the vehicle level after accumulating vehicle registration data provided by R. L. Polk, Inc. The *Single-Vehicle Rate* can be viewed as a surrogate for a number of unobservable factors such as aggressive driving behavior (differences in driver age are likely to be insufficient to capture subtle differences even among drivers of the same ages; that is, all 25-year-old drivers are not the same), trip purpose (work-related, commuting, recreational, etc.), as well as other vehicle-level differences among the various make/models which are not included explicitly in the model.

Little improvement was found from adding the *Tilt Table Ratio Squared.*

Individually, the addition of *Vehicle Class/Drive Configuration* and *Single-Vehicle Accident Rate* represented relatively large improvements in model fit. However, the greatest improvement resulted from the use of the combination of *Vehicle Class, Drive Configuration,* and *Single-Vehicle Rate.*

*Vehicle Class/Drive Configuration and Single-Vehicle Rate:* This model was estimated using the baseline model (with *Tilt Table Ratio*), *Vehicle Class/Drive Configuration*, and *Single-Vehicle Rate.* This model provided the best model fit and improvement over the baseline model. The C-statistic was 0.753 and the vehicle-level $R^2$ was 0.80, the highest values yet encountered in these analyses.

In this model, the coefficients of *Sport, Pickup,* and *Van* were statistically significant, as were the coefficients of *Front-wheel* and *Four-wheel* drive. In contrast with the model with *Vehicle Class/Drive Configuration* and without *Single-Vehicle Rate*, the coefficients for *Van* in this model was statistically significant and positive, indicating a greater propensity to rollover compared with passenger cars when accounting for the rate of single-vehicle accidents per registered vehicle. The specific results indicated that sport utility vehicles were significantly more likely than passenger cars to roll over, followed by vans (significantly greater), pickup trucks (significantly greater), and passenger cars (the reference group). In addition, front-wheel drive vehicles were significantly more likely to roll over than were rear-wheel drive vehicles; and four-wheel drive vehicles were significantly more likely to roll over than were rear-wheel drive vehicles (the reference group).

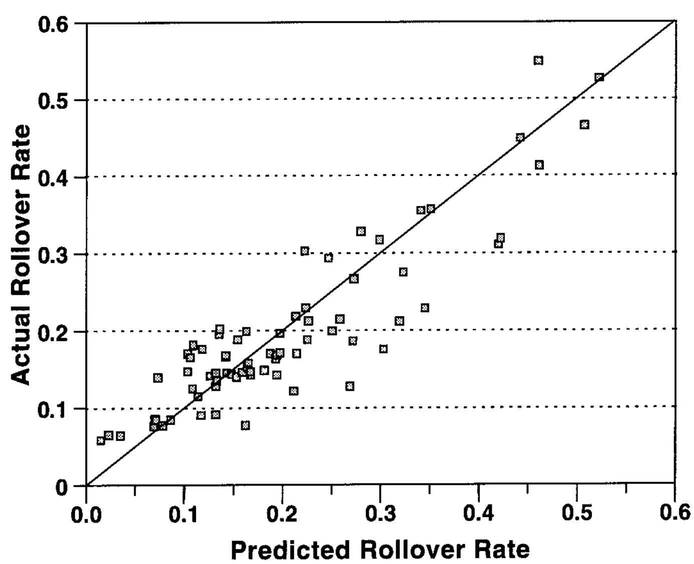
Figure 2 shows a graph of actual vs. predicted rollover rates for this model. Accompanying the large improvement in $R^2$, compared with the model using only *Tilt Table Ratio*, is a tightly fitting cluster of observations below a rollover rate of 0.30 and a centering of actual vs. predicted rollover rates for vehicles with higher actual rates. Even vehicles with rollover rates greater than 0.35 appear to be scattered on both sides of the diagonal whose slope equals one, where actual equals predicted rollover rate. This finding is encouraging since the model appears to fit well over the entire range of actual rollover rates. Table 4 presents the final estimated coefficients and statistics for this model.

### *Further Analyses*

A number of additional analyses are fully documented in (1). These analyses included an exploratory investigation into how well models fit the individual vehicle classes (*Passenger Cars, Pickup Trucks, Vans,* and *Sport Utility Vehicles*. Each of the vehicle class models incorporated the *Tilt Table Ratio*, *Single-Vehicle Rate*, and *Drive Configuration*, as appropriate. Many of these analyses were hampered by the small sample sizes resulting from analyzing the individual vehicle classes, with little ability to make meaningful inferences within vehicle class due to the limited number of different vehicles within the van, pickup, and sport utility classes.

A second set of investigations focused on earlier analyses conducted by Malliaris (9), which demonstrated the relationship of rollover propensity with a categorical classification of driver age, sex, and alcohol involvement. The current effort used explicit representations of these variables as follows: driver age is represented by the continuous variable *Driver Age*, as well as the additional dichotomous variable *Under 25*; alcohol (and/or drug) involvement is represented by the dichotomous variable *Alc_drug*. All three of these variables were statistically significant in the aggregate models discussed earlier. *Driver Sex* was found not to be significant as a predictor of rollover propensity in earlier models.

**Figure 2. Results Using Tilt Table Ratio, Vehicle Class/Drive Configuration, and Single-Vehicle Rate (State of Michigan, Make/Models with at Least 25 SVA's)**




Three age categories were defined for use in the logistic regression model: 16 to 25 years, 26 to 35 years, and 36 years and older. The model incorporated all of the accident location variables (*Rural, Curved*, and *Off_road*) used in the earlier aggregate analyses, as well as *Anti-Lock Brakes, Tilt Table Ratio, Vehicle Class/ Drive Configuration*, and *Single-Vehicle Rate*.

The results of this model estimation were in general agreement with the results from the models using driver age, sex, and alcohol/drug involvement. That is, alcohol/drug involvement increases the risk of rollover given a single-vehicle accident; and rollover propensity increases with decreasing driver age. The lack of a consistent pattern for driver sex also agreed with the lack of statistical significance for *MALE* in the earlier models.

From this analysis, the author concluded that the use of the 12 cells does not provide any additional information beyond the use of the individual variables for driver age and alcohol/ drug involvement, and thus was not pursued further.

A last analysis attempted to investigate the effect of not having subjected the Michigan accident data to all of the stages of the rigorous VIN-correction procedure as was applied to the other states. The method used to determine the adequacy of the Michigan file was based on an analysis of the data from Georgia, using both the final computerized/manual corrected file and the original uncorrected data directly from the state data file. This presented both the best and worst cases, respectively, since the Michigan data were subjected at a minimum to automated corrections.

Only small differences were found between the coefficient values for the uncorrected vs. corrected files, and in each case the same variables were statistically significant. More importantly for the analysis of rollover propensity, the coefficients of *Tilt Table Ratio* were very similar between the two models, indicating that the estimated relationship

**Table 4. Results of Model Estimation Using Tilt Table Ratio, Single-Vehicle Rate, and Vehicle Class/Drive Configuration**

| PARAMETER | ESTIMATED COEFFICIENT | STANDARD ERROR | CHI-SQUARE | P |
|---|---|---|---|---|
| Rural Area (RURAL) | 1.6721 | 0.0376 | 1,980.98 | 0.0000 |
| Single-Vehicle Rate | 0.0459 | 0.0038 | 160.87 | 0.0000 |
| Tilt Table Ratio | -3.0930 | 0.2487 | 154.64 | 0.0000 |
| Front-Wheel Drive | 0.5570 | 0.0500 | 124.01 | 0.0000 |
| Curved Section of Road (CURVED) | 0.3271 | 0.0334 | 95.79 | 0.0000 |
| Sport (Utility) Vehicle | 0.7571 | 0.0850 | 79.30 | 0.0000 |
| Driver Alcohol or Drug Use (ALC_DRUG) | 0.2428 | 0.0321 | 57.01 | 0.0000 |
| Anti-Lock Brakes | -0.6766 | 0.1009 | 44.95 | 0.0000 |
| Pickup Trucks | 0.3375 | 0.0575 | 34.46 | 0.0000 |
| Vans | 0.3815 | 0.0797 | 22.94 | 0.0000 |
| Accident Occurred Off-Road (OFF_ROAD) | -0.1850 | 0.0478 | 14.96 | 0.0001 |
| Driver Age Less Than 25 (UNDER25) | 0.1404 | 0.0384 | 13.19 | 0.0003 |
| Four-Wheel Drive | 0.1801 | 0.0561 | 10.29 | 0.0013 |
| Driver Age (AGE) | -0.0045 | 0.0016 | 8.24 | 0.0041 |

appeared to be reliable whether one used the uncorrected or corrected file.

The implication for the Michigan data was that they appear to provide a reliable source for estimating the contribution of *Tilt Table Ratio* to *Rollover Propensity*, even though the data were not exposed to the entire correction procedure. The absence of manual corrections to the Michigan data file should have little if any discernible effect on the conclusions drawn from the analysis.

### *Concluding Remarks*

The results of these analyses appear to demonstrate the existence of a relationship between measures of roll stability and a vehicle's propensity to roll over in real-world, single-vehicle accidents. Of the three basic roll stability metrics evaluated *(Tilt Table Ratio, Static Stability Factor,* and *Side Pull Ratio*) the *Tilt Table Ratio* appears to provide the greatest explanatory power, but only by a slight margin over the *Static Stability Factor.* This situation is not unreasonable since these three measures represent an approximation of the rollover stability of a vehicle exposed to a constant lateral acceleration, with each metric being based on a different set of assumptions. Thus, one would expect that there would be high correlations among the three metrics; investigations showed that this was so, with correlations in the range of 0.80 to 0.88.

Another interesting finding was the strength of the rural/urban accident location as a predictor of rollover. In the stepwise logistic regressions for the individual states, *Rural* was the first variable to enter models for four states, and the second variable to enter in the fifth. In the final model estimation for the Michigan data, the chi-square value for *Rural* was an order of magnitude greater than for the next variable, *Tilt Table Ratio.* This appears to corroborate the work of Mengert et al. (6), who also noted the importance of *Rural* as a predictor of rollover at the individual accident level.

Metrics other than *Tilt Table Ratio, Static Stability Factor,* and *Side Pull Ratio* were also investigated, and sometimes provided significant explanatory power. These included *Wheelbase* and *Braking Stability.*

However, in the interest of time, model parsimony, and the fact that these measures provided less explanatory power than the three measures of *Steady-State Lateral Acceleration Rollover Stability*, these metrics were dropped from the focus of this immediate work.

The use of the rate of single-vehicle accidents per registered vehicle resulted in a relatively large improvement in model fit, purportedly representing factors such as aggressiveness of driving behavior, trip purpose, and other vehicle-to-vehicle differences not directly accounted for in the estimated models. In addition, the incorporation of variables representing the various combinations of vehicle class and drive configuration also predictably contributed to improving model fit.


### *Acknowledgment*

This paper reports on the statistical aspect of a much larger research program. I would like to acknowledge several others who made significant contributions to this effort. Scott Shadle and John Hinch of NHTSA's Office of Vehicle Safety Standards provided a great deal of insight into the physical interpretation of the vehicle metrics which made it simpler for this statistician to understand their potential effects. In addition, their guidance in deciding what variables should be evaluated in the statistical analyses and the refinement of the final models, in consideration of the rulemaking objectives, was invaluable. Judith A. Hilton (National Center for Statistics and Analysis, NHTSA) conducted all of the data processing, including the very intensive VIN correction effort, the creation of the analytical data files and the documentation of it all. The combined efforts of all involved should be recognized.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## About the Author

**Terry M. Klein** is Chief of NHTSA's Mathematical Analysis Division. Mr. Klein has spent his entire professional career working in the area of traffic safety. After graduating from college in 1974, he worked for 10 years as a mathematical statistician in NHTSA's Office of Alcohol Countermeasures. He pioneered the application of modern time-series analysis techniques in traffic safety, evaluating a number of large-scale programs such as NHTSA's $88-million Alcohol Safety Action Projects, the effects of the 55-mph speed limit, and 21-year-old minimum-drinking-age laws. In 1984, Mr. Klein left government to become a private consultant. In this capacity, he developed the currently used methodology to impute unknown blood alcohol concentration (BAC) test results in the Fatal Accident Reporting System. In 1989, he returned to government to become the Chief of the Accident Analysis and Trends Branch. He was recently promoted to Division Chief. Recent analytical projects include light vehicle rollover, evaluation of FMVSS 208, and work in the area of alcohol fatality trends.

# On the Development and Application of a Deformation Measurement System for Developing Thoracic Injury Criteria

*by* **Rolf H. Eppinger**
**Richard M. Morgan**
*and*
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### *Abstract*

The External Peripheral Instrument for Deformation Measurement (EPIDM) system is composed of a sensing device and an analysis process. The sensing device is a band attached to the surface of the deformable body along the external peripheral path of the desired geometric cross-section. The analysis process, which determines the complete geometric description of the periphery of a cross-section of a body as it deforms in time, uses the output from strategically located sensors along the length of the band to calculate and develop the contour of the body to which it is attached. The details of the operational theory and construction of the EPIDM system are discussed, as are the procedures for developing explicit relationships between the output of the EPIDM system and classical material state variables defining structural failures that occur either at or below the surface of the body under observation. Examples of experimentally obtained thoracic deformations procured under various restraint conditions are presented, and the results are compared and discussed.

### *Introduction and Overview*

Current biomechanical research practice for developing "injury indices" consists of conducting a series of impact tests on biological specimens, obtaining characterizations of the structure's response by analyzing the signals from electronic instruments located in and on the specimen and/or observing the structure's motion at a number of locations, and determining the extent, severity, and location of the resulting injuries by post-test physical examination. Statistical procedures are then used to develop indices or relationships between parameters of the observed engineering responses and characterizations of the severity of the observed injuries.

Since both accurate injury characterizations and impact responses are desired from each test conducted, the majority of current measurement schemes obtain data from instrumentation attached to the external surface of the intact structure. These measurement schemes, because of the limited technology available, have used either miniature accelerometers to characterize the impact by a series of acceleration-time histories or high-speed photogrammetric techniques to obtain relative displacements between various structural points on the body as functions of time. Invasive instrumentation, while having the prospect of providing a more precise and detailed characterization of local structural responses, invariably introduces artifactual trauma—either during installation or during the dynamic event itself. Because this artifactual trauma is difficult or impossible to differentiate from the true impact-induced trauma, internal instrumentation has not seen wide application.

An advantage of accelerometric techniques is that they can be utilized in most automotive impact situations in which the occupants are restrained by belts and enveloping compliant structures such as air bags and padding: an advantage that the photogrammetric techniques do not have since visual contact cannot be maintained throughout many of these impact situations. A disadvantage of accelerometric techniques is that each sensor is attached locally to the structure and will experience the structure's local rotations. This causes the sensitive axis to experience a varying orientation during the impact event and possibly to add confounding factors to the output because these rotations are not monitored.

**Figure 1. Coordinate System Along Closed Curve of Length *L***

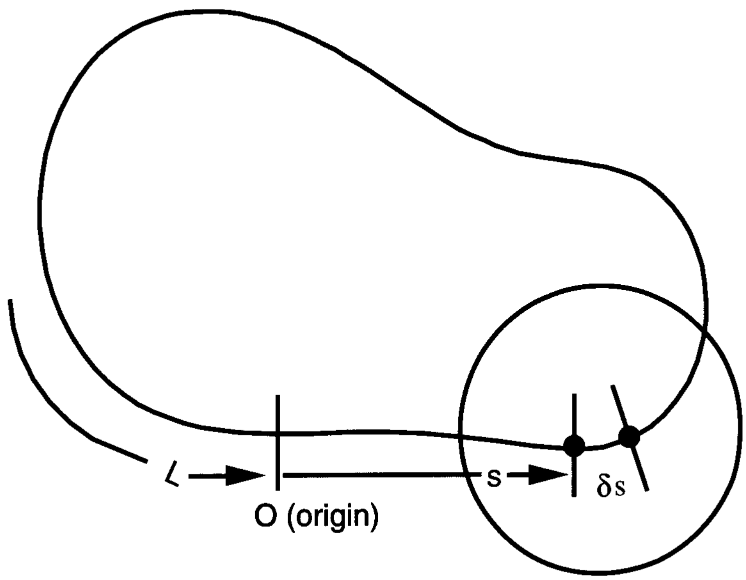



**Figure 2. Determination of Curvature at Location *s***

$$k(s) = \frac{\delta\theta}{\delta s}$$

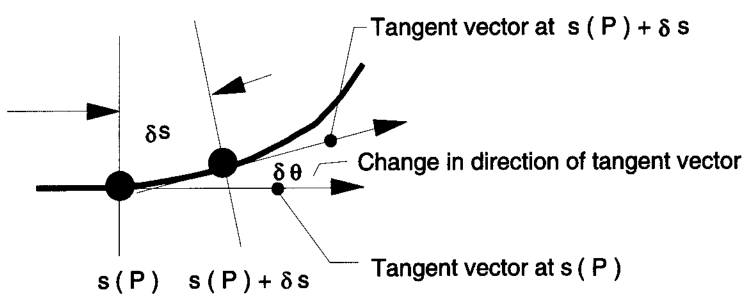
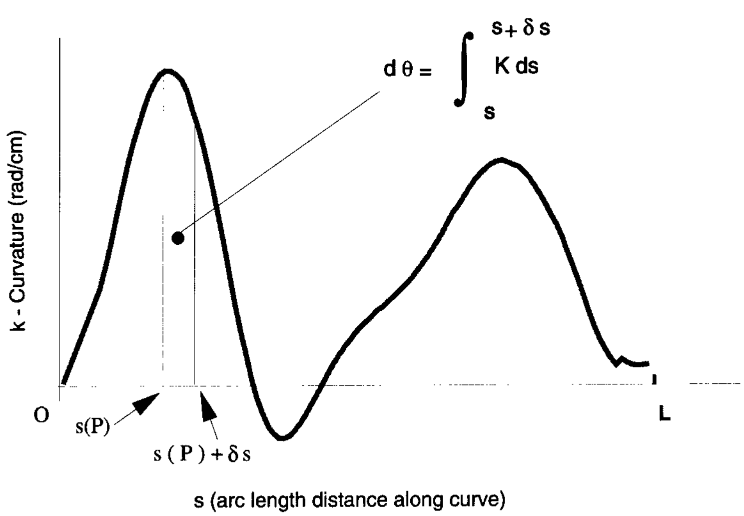



**Figure 3. Closed Curve Characterized by *k-s* Method**




The concept of monitoring and using structural surface responses to determine internal responses and failure has strong theoretical basis in mechanics; i.e., Green's Theorem. According to Green's Theorem, if one could obtain the three-dimensional acceleration-time history of two independent points on a structure and simultaneously capture its complete geometric shape as a function of time, the entire stress-strain history of a deterministic body within the closed curve could be calculated. It appears, then, that what current experimental approaches lack are not strong theoretical and rational bases, but, rather, a measurement technology that can accurately and completely measure the dynamic motions of a structure's surface under impact conditions of interest.

Obtaining the acceleration-time history of two points in space is well within the current technological capabilities of available instrumentation. Additionally, with the advent of a NHTSA-designed and -patented External Peripheral Instrument for Deformation Measurement (EPIDM) system (1), the capability of obtaining the peripheral shape is now a reality. The following discussion will focus on the operational theory of the EPIDM, the physical configuration of the transducer, some experimental results, and various processes that are being used to develop advanced thoracic injury criteria.

### *Operational Theory*

Since the desired output of the instrumentation process is the geometric description of the periphery of the cross-section of the body of interest, the authors reviewed various analytical methods for describing closed curves. The technique we found most appropriate for this application is one that describes a curve in terms of its local curvature, *k(s)*, at each position, *s*, along the length of the curve. The curvature, *k(s)*, is defined as the differential change in direction of the tangent vector divided by the differential distance along the curve; that is, ($d\Theta/ds$); and *s* is the distance along the curve in a specified direction from an arbitrary reference point. This descriptive method allows for the complete and unique description of any closed curve when the curvature is expressed as a function of *s* between 0 and *L*. Figures 1, 2, and 3 illustrate these concepts.

The process can be likened to someone driving a car around a race course following exactly the line in the middle of the road. The curvature at any point is proportional to the steering wheel angle necessary to keep the car on the line. To obtain the *k-s* curve that uniquely describes the track, one would drive around the course while recording the distance traveled and the angle of the steering wheel. To duplicate the course at another location, one would merely drive the same distance while duplicating the corresponding steering wheel angle at each point along the length of the course.

Therefore, if one is in the possession of a *k-s* characterization of a closed curve, it is a simple matter to construct its geometric shape in the more familiar cartesian coordinate system. This is done by starting at an arbitrary point *O* on the x-y plane and proceeding in an arbitrary but constant direction for a short distance, *ds* (*ds* should be at least smaller than 1/100 of the total peripheral distance of the closed curve). At this point, change direction by an amount, $d\Theta$, where $d\Theta$ is equal to the area under the *k-s* curve between the starting and ending positions, $s_1$ and $s_2$, of the incremental step just taken. By repeating this process—that is, taking an incremental step in the current direction and then establishing the new transit direction by the calculated incremental change in direction, until the sum of the incremental steps equals the length of the curve—the complete closed curve is developed in its true form.

To define a closed curve accurately and fully by the *k-s* method, *k* must be a continuous function of *s*; that is, *k* must be defined for every possible value of *s*. Since most measurement techniques allow only a finite number of physical measurements, we developed a process which constructs a continuous approximation of the true *k-s* curve given only *n* true values of the curvature along the length of the closed curve. Figure 4 illustrates a set of ten hypothetical curvature values associated with ten positions along the length of the band. Using a computer algorithm called an interpolatory cubic spline, ten separate equations are developed. Each equation defines and describes a curve connecting two adjacent known curvature values. These equations are also interrelated in such a way that they connect at the known curvature points and the connection is smooth (i.e., without a bump or kink where they connect).

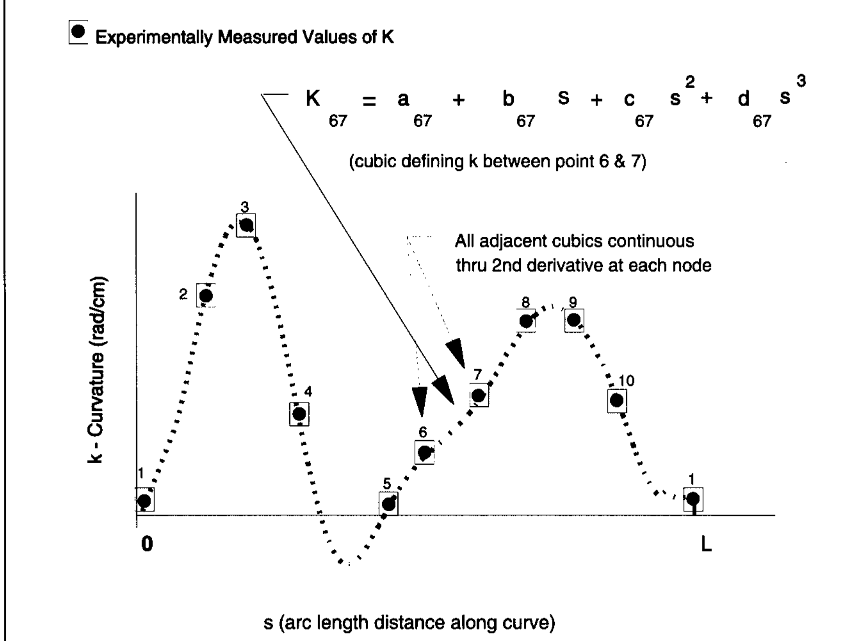
Since the splined *k-s* representation of the closed curve is only an approximation, possibilities for the introduction of error are always present. These errors present themselves in the reconstruction of the true curve as either an inability to create a closed curve or—if the curve is closed—to not have a smooth transition at the point where the beginning of the curve joins the end. We developed compensation algorithms that minutely adjust the splined *k-s* curve to eliminate these errors. Their form and rationale are discussed in (1) and (2).

The accurate duplication of a specific curve by this technique is dependent on both the spatial frequency of the curvature, *k*, along the length of the curve and the number of curvature measurements made along the length of the curve. That is, the more the curvature changes along the length of the curve, the more observations that must be made in order to see and duplicate these changes. The choice of the appropriate number of curvature measurements and their placement becomes the responsibility of the user of this process and is dependent on the complexity of the problem being studied.

***Physical Configuration of Transducer***

To determine the curvature at *n* points around the periphery of an object such as the human thorax, a steel band measuring 0.0254 cm thick, 1.27 cm wide, and 1.4 meters long is employed. This band is then directly attached around the periphery of the structure of interest and is compelled to conform to all the geometric shapes the structure experiences during an entire dynamic event. At each of *n* locations along the length of the band, strain gauges forming a four-active-arm Wheatstone bridge are attached. Each bridge is configured to be sensitive to longitudinal bending across the 0.0254-cm dimension and to produce an output voltage directly proportional to the local curva-

**Figure 4. Construction of Approximate *k-s* Curve**



ture. Figure 5 illustrates the overall layout of the complete band and the positioning of single bridges on the band.

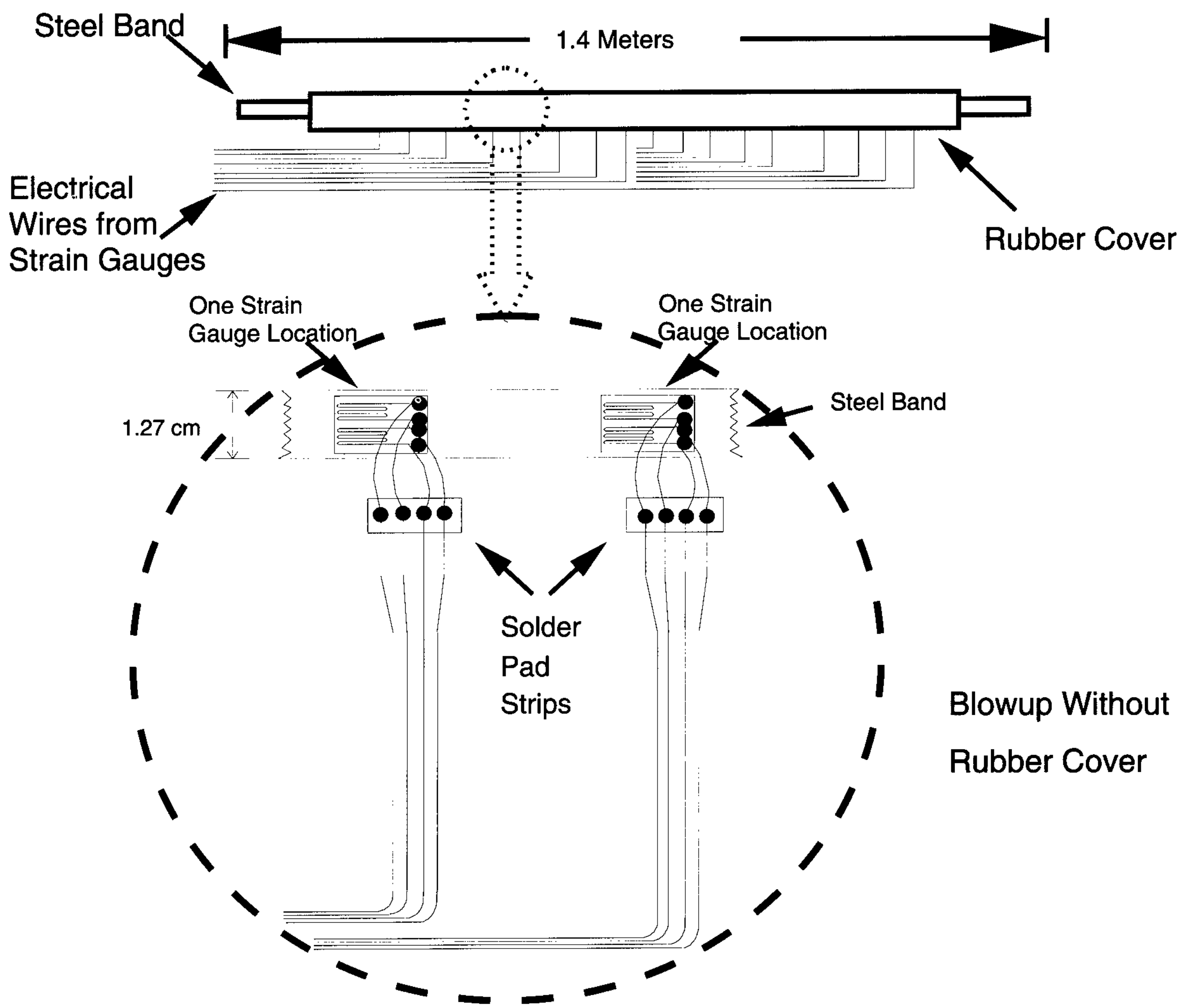
The four-active-arm configuration allows the bridge circuit to negate the effects of longitudinal tension in the band as well as temperature effects but to maintain its sensitivity to changes in curvature. Each bridge is individually calibrated by placing the band over a series of circular mandrels of different radii, noting simultaneously the bridge output voltage and the imposed curvature.

Since much of the expected use of this device is envisioned to be on cadaveric specimens exposed to automotive impacts, one would want the entire transducer to be durable. Currently, this is accomplished by molding a rubber jacket around the band. This encapsulation process provides sufficient abrasion resistance so that the contact forces generated during an impact will not compromise the gauges. It also provides a barrier against moisture.

### *Experimental Results*

Both static and dynamic tests were conducted to examine the accuracy and robustness of the measurements methodology (2). In static tests, the instrumented band was joined end to end, its peripheral length noted; it was then held statically in a deformed shape. The deformed shape was then recorded and used as the reference for comparing the accuracy of the EPIDM process. For dynamic testing, the instrumented band was wrapped around an ellipsoidal slab of foam and dynamically deformed. The band's geometric shape was recorded throughout the

**Figure 5. Side View of Chest Band**



event using high-speed cinematography, while the outputs of the strain gauge bridges were sampled at 4,000 samples per second. Again, the film shapes and the EPIDM-generated shapes were compared. Using actual test dummies, additional efforts (3) investigated the gauge spacing required to capture the various deformation patterns produced by belt and air bag restraint systems.

As a result of these efforts, the band is currently configured to have 40 bridge sites spaced 2.54 cm apart along its length. Laboratories with an abundant number of available data-capture channels record the curvature signal at all 40 bridge sites. In practice, many laboratories do not have an adequate number of channels available for recording all 40 signals and must use the smallest number of gauges necessary for an accurate reconstruction of the contours. The current recommended practice is to use 24 of the 40 gauges along the length of the band. Eleven of the 24 are along a 25.4-cm span using a 2.54-cm spacing, with the remaining 13 using a 5-cm spacing. The 2.54-cm spacing is used in areas where the major restraint forces are to be applied, such as the frontal portion of the chest, where the curvature changes are expected to be the greatest and most frequent. The 5-cm spacing is used in less active areas such as along the back side of the chest.

Using this configuration, a number of experiments have been completed using various restraint systems, including the 3-point belt, the 2-point belt with knee bolster, and air bag with lap belt. The impact conditions represent a 48-kilometer-per-hour frontal impact into a rigid wall. Figure 6 illustrates the typical location of the two instrumented bands on the chest of the subject, and Figure 7 illustrates the output of the EPIDM process for a 3-point belt test and a deploying-air-bag-with-lap-belt test. In Figure 7, the EPIDM was placed at the position of the fourth rib for both human subjects. The EPIDM contours for the 3-point belt are shown on the left of Figure 7; the EPIDM contours for the air bag are on the right. With the belt-restraint condition, local deformation of the chest wall is more pronounced than with the air bag restraint system.

### *Application of Methodology to Injury Index Development*

Since the primary purpose for the development of the EPIDM process was to provide a greater understanding of the responses of and injuries to the human thorax interacting with various restraint systems, examination of the relationship of the variables derived by this measurement methodology to the material state variables commonly associated with structural failure has been pursued by the authors. Two generic types of failures are of interest: failures of the surface of the structure, that is damage to the bony cage; and failures or injuries to the structures within the rib cage. Different approaches have been developed to study each case.

Both field and laboratory studies have shown that thoracic skeletal injuries occur not only at sites where the crash forces are applied but also at sites remote from the application of force. This evidence, together with the observations that the thorax undergoes significant deformation during an impact, suggests that rib failure may be primarily a result of bending. One of the by-products of the EPIDM process is that for any time—beginning prior to and through-

**Figure 6. Chest Band Wrapped Human Subject Showing Location Relative to Skeleton**

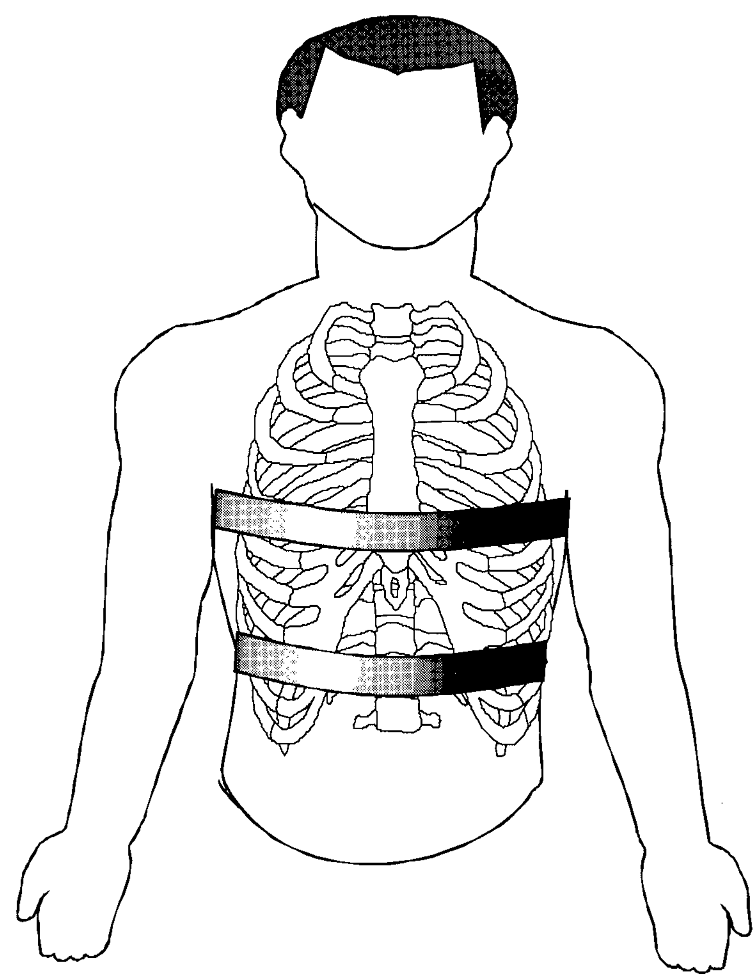
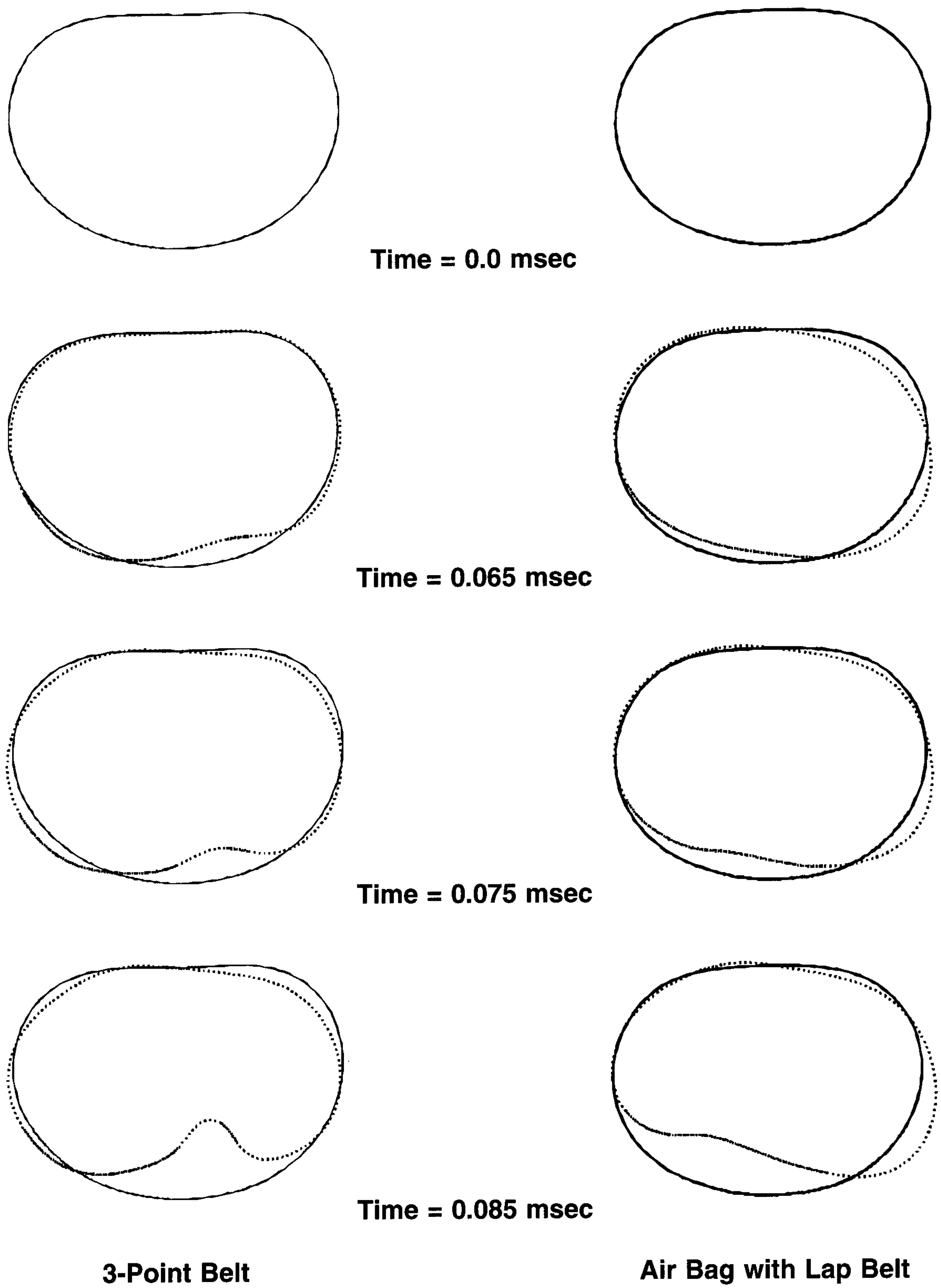


Figure 7. Chest Band Shapes in 3-Point Belt and Air Bag with Lap Belt



out the impact event—it generates an accurate estimation of the local curvature completely around the periphery of the chest. (In making this statement, we are assuming that the curvature changes measured at the exterior surfaces of the chest flesh also mirror similar changes in the underlying thoracic skeletal structure.) If one assumes that the geometric shape of the thorax prior to impact is in an unstrained state, then the strain at any location at some later time during the impact, using simple beam-bending theory, is directly proportional to the difference between the current curvature and the initial curvature. Figure 8 illustrates two *k-s* curves, one defining the original shape of the thorax and one defining the shape of the thorax during the impact. In Figure 9, the difference between these two curvatures, *dk*, is plotted as a function of the distance along the band together with a hypothesized fracture onset level.

Since, both theoretically and practically, local stresses and strains in the ribs are a function of the chest's deviation from its original geometry and failure is a function of the local stresses and strains, it is highly likely that a statistical analysis of data obtained from tests exposing a series of specimens to a variety of restraint and crash conditions would yield a failure relationship, such as the one in Figure 9. Because both the geometric and material properties of the rib structure vary around the chest, one would anticipate that the critical dk will vary in different regions of the chest as shown. The high critical value in the sternal area is reasoned to exist because the area's cartilaginous nature makes it very flexible and, therefore, would require large changes in curvature to induce failure. However, because of the greater section modulus in the spinal area, a low critical value is anticipated in the spinal area because small changes in curvature would produce high tensile stresses.

An alternative approach, one that promises to possibly yield both a methodology that detects rib fractures as well as one that detects internal injuries, combines the output of the EPIDM process and the structural modeling capabilities of finite element analysis (FEA) in a unique manner. Since the EPIDM process provides the geometric description of the chest both prior to and continuously throughout the impact, a model of the chest is constructed possessing the same shape as the undeformed chest. Then, by using the information from the EPIDM process, this model is made to deform, in time, exactly the same way as did the real chest. By having the model possess both appropriate material and geometric properties of the structures of the chest, the FEA process calculates the stresses and strains throughout the entire structure. We anticipate that associations between critical levels of stress and the probability of injury can be developed by merging the experimentally obtained injury data detailing sites and severity of either rib fractures or internal injuries with the calculated stress levels at both sites of failure and non-failure. A more extensive discussion on these proposed procedures is presented in another paper (4).

Examples of the boundary stimulation approach are illustrated in Figures 10 and 11. Figure 10 shows the results of stimulating an artificial rib and spine structure with the experimentally derived shapes of test specimens undergoing impact in both the belt and air bag restraints previously shown in Figure 7. The various

**Figure 8. *k-s* Curves at 0 and 38 Milliseconds: Data from a "Typical" 48-kph 3-Point Belt Test**

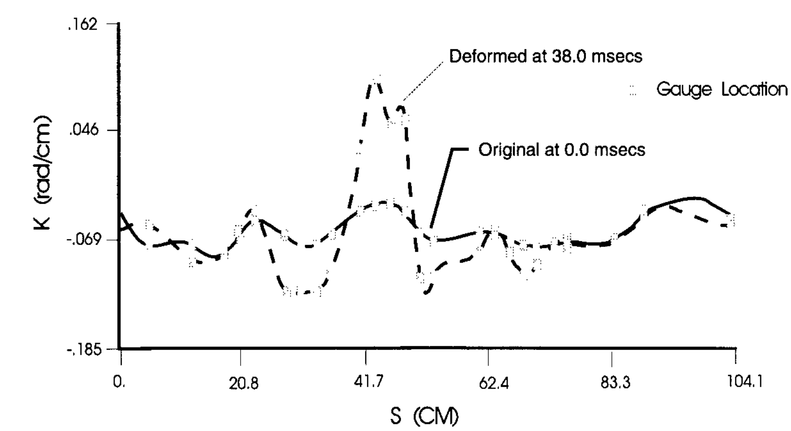



**Figure 9. Hypothesized Fracture Tolerance Diagram at the Level of the 4th, 5th, and 6th Ribs**

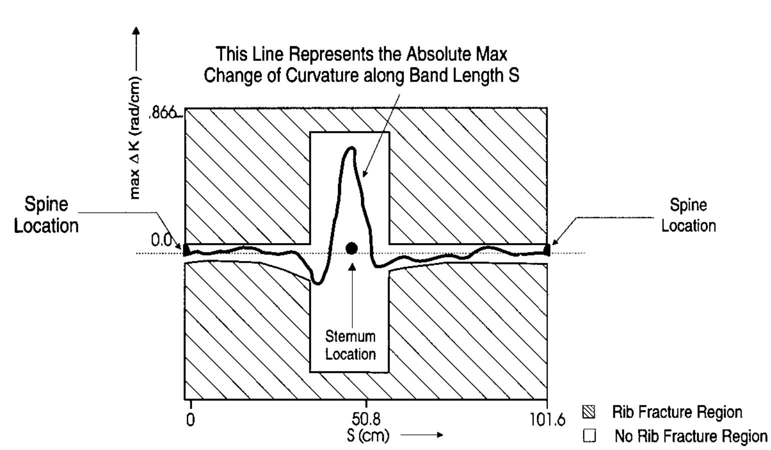


**Figure 10. Principal Stress Patterns in 3-Point Belt and Air Bag with Lap Belt**

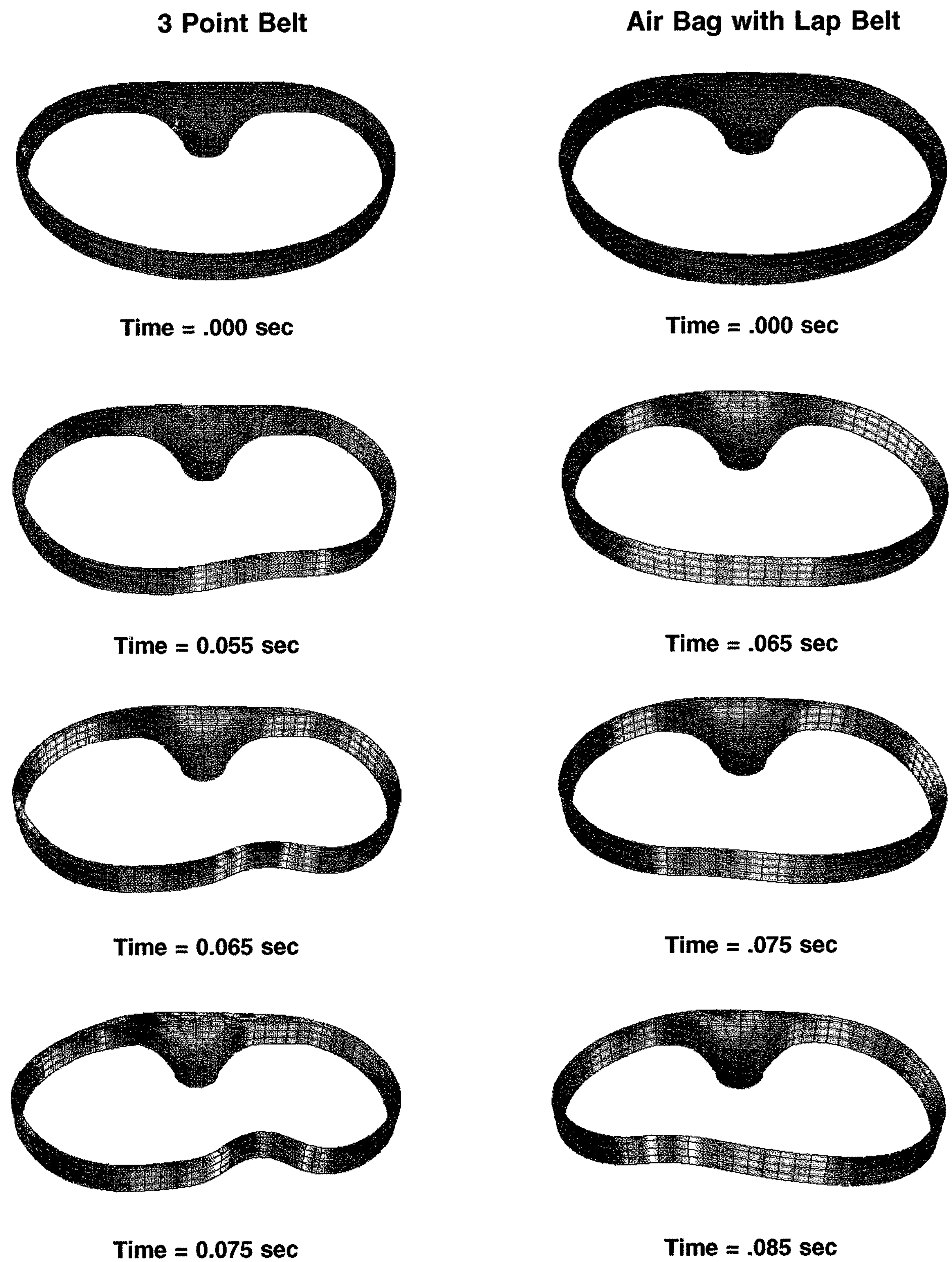
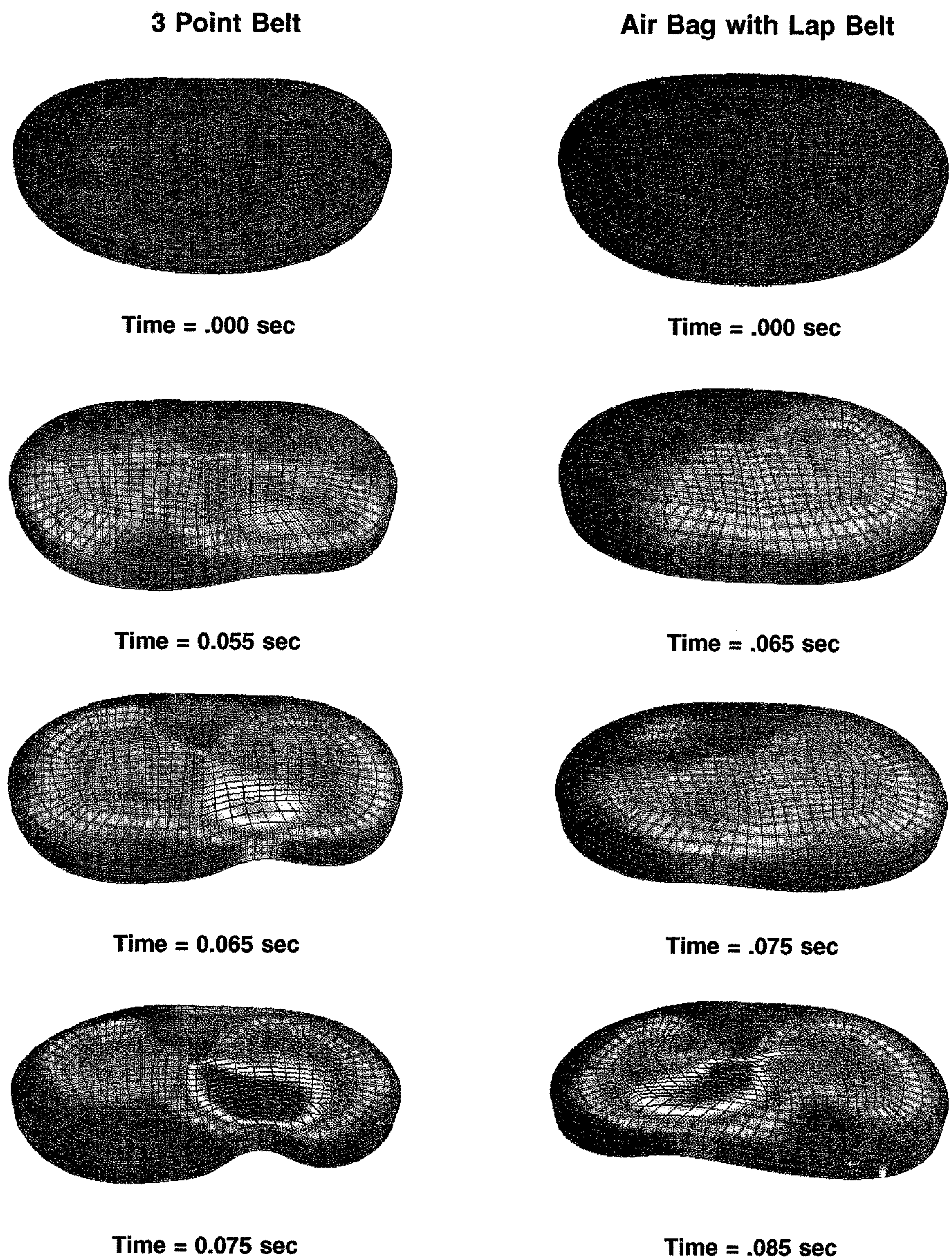


Figure 11. Internal Strain Patterns in 3-Point Belt and Air Bag with Lap Belt



regions of colors represent the gradation of stress levels produced in the analytical bone models when undergoing their respective deformations. They indicate that the concentrated forces applied locally to the chest by a belt system do cause greater local stresses than does the air bag restraint which applies force over a much greater area. Likewise, Figure 11 illustrates the internal stress distributions and how they vary through time for the same two test conditions. Again, because the analytical configurations are experiencing different deformation time-histories, the magnitude and location of the induced strains produced by the belt and bag systems can be seen to be different.

### *Summary*

It was and is the intent of the EPIDM process to increase the quantitative level and detail of descriptions of the effects of crash forces on the human thorax and, from this added information, develop more definitive injury criteria to guide in the design, evaluation, and regulation of automotive safety systems. To accomplish this goal with the EPIDM process, the burden of acquiring many more channels of high speed, transient data (approximately 40 channels per band) in an already complex experimental situation must be undertaken. Justification for the assumption of this additional experimental burden can be taken from William Thomson, also known as Lord Kelvin, who once said, ". . . when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of an unsatisfactory kind." Additional comfort can be found in this extension of his thought: the more you can measure about what you are studying, and express it in numbers, the more your knowledge about it expands and is useful.

To date, efforts indicate that the EPIDM process provides significantly greater and more accurate information on the effects of the impact process on the human thorax and, as a result, several new avenues to develop processes to detect the occurrence and severity of any resulting injuries appear to be available. Also, because of these initial successes, the EPIDM process is being used in an ever-increasing sphere of experimental procedures. The authors hope that, ultimately, the additional experimental complexities demanded by the process are justified and outweighed by the deeper understanding of the impact-injury process that should result.

### *Note*

This paper represents an updated version of a paper that was originally published in the *Proceedings of the 33rd Stapp Car Crash Conference*, Paper No. 892426, vol. P-227 by the Society of Automotive Engineers, Inc., Warrendale, PA, October 1989.

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## About the Authors

***Rolf H. Eppinger*** has been with NHTSA for 21 years and the Chief of the Biomechanics Division within the Office of Crashworthiness Research of NHTSA's Research and Development for the past 15 years. His formal education consists of a Bachelors and Masters in Mechanical Engineering and a Ph.D. in Mechanical Engineering Sciences from Wayne State University in Detroit. In his current capacity as Division Chief, he formulates, develops, and executes research programs to achieve Agency requirements in the areas of human impact injury research, human injury simulation and analysis, and crash test dummy development necessary for defining, developing, and implementing Federal motor vehicle safety standards. These efforts have led to the development of the Thoracic Trauma Index and the side impact dummy (SID) which are the basis of NHTSA's new dynamic side impact protection standard. Current research interests are injury mechanisms of the brain, neck, thorax, and abdomen; analytical simulation of human

impact response and injury; development of biomechanical instrumentation techniques and anthropomorphic test devices; and investigating the effects that multiple injuries have on mortality and morbidity.

***Richard M. Morgan*** obtained a Bachelors and Masters degree in physics at North Carolina State University, and did postgraduate work at American University. He directed the early development of engineering programs that showed the feasibility of air bags and provided the major technical support for the final issuance of FMVSS No. 208, the Federal standard for frontal protection. He organized, directed, and coordinated complex projects that significantly contributed to the upgrade of FMVSS No. 214, the Federal side-impact standard. More recently, he established Agency Centers at several major universities for the study of traffic safety problems. Mr. Morgan is the author or co-author of 33 magazine articles and journal papers on different aspects of motor vehicle safety.

***Nopporn Khaewpong*** has been with the Biomechanics Division of the NHTSA Office of Crashworthiness Research since 1991. His involvement with the group, however, dates back to 1983 when he joined as an on-site contractor; first as a junior engineer and later as the contract manager and principal engineer. During this period he was involved in the planning and administration of the Biomechanics database, analysis of the data for the development of the Thoracic Trauma Index, and development of a PC-based software package to analyze the data from the chest band instrument. His current research interests include developing a new thoracic injury criterion, studies of injury mechanism of children involved in car crash accidents, and analytical simulation of human thoracic impact response and injury. He received his Bachelor of Science in Civil Engineering from Khon Kaen University of Thailand in 1972, and his Master of Science in Structural Engineering from George Washington University in 1974.

# Overlap Car-to-Car Tests Compared to Car-to-Half Barrier and Car-to-Full Barrier Tests

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*Office of Vehicle Safety Standards National Highway Traffic Safety Administration*

*Abstract*

In issuing Federal Motor Vehicle Safety Standard (FMVSS) No. 208, "Occupant Crash Protection," the National Highway Traffic Safety Administration (NHTSA) has established crash protection requirements for passenger cars at up to 30 mph in frontal impacts into a barrier. The lives and injuries that will be saved are substantial. However, NHTSA estimates that, even after full implementation of this standard, frontal impacts will account for approximately 10,900 passenger-car and light-truck fatalities per year. Because of this continued safety problem, NHTSA has added the improvement of frontal crash protection to its priority plan, initiating research to investigate concepts to mitigate the problem; such research includes the evaluation of advanced restraints, improved structural integrity, and improved energy-absorbing interiors. NHTSA has also begun a detailed study to define the safety problem for frontal impacts subsequent to the implementation of FMVSS No. 208. Based on the results of this study, NHTSA is now designing a comprehensive research program to identify mitigation concepts. The research program will use real-world crash data, laboratory crash test data, and computer simulations to arrive at countermeasures. This paper presents some preliminary analyses of the laboratory crash tests for exploring possible test procedures that can be used to further evaluate structural integrity countermeasures. A series of baseline car-to-car tests were conducted to provide comparisons of crash responses between full frontal barrier, car-to-barrier overlap and car-to-car overlap impacts. The term overlap used in this paper is the percentage of the vehicle front width that, upon impact, comes in contact with another car or object. These tests were useful in providing a better understanding of the crash kinematics by crash mode at 63.5-percent overlap and 90-percent overlap. They were conducted with each car moving at 35 mph and were compared to previously conducted full-frontal barrier and 50-percent overlap barrier tests at 25 mph and 35 mph.

### *Introduction*

A series of tests were conducted by Calspan, Inc., under contract to the National Highway Traffic Administration (NHTSA), to compare crash responses between full frontal barrier, car-to-barrier overlap, and car-to-car overlap impacts. This series of tests used two vehicle models that have been extensively crash tested in the New Car Assessment Program (NCAP) and NHTSA research programs. The tests were used to better understand the crash kinematics by crash mode for different frontal test conditions. This research supports one of NHTSA's high priority programs as contained in the Agency's 1991-1993 priority plan (1), and forms one part of the work supporting an advanced frontal crash program as discussed at the 12th Experimental Safety Vehicle Conference (2,3).

### *Background*

This paper discusses several crash test conditions that have been considered by NHTSA and others as alternatives or supplements for fixed-barrier testing. The objective of these alternatives to the fixed barrier test is to more closely match the crash behavior of typical cars in typical accidents. In theory, the design of safety systems (structures, air bags, restraints, steering assemblies, etc.) subjected to these crash test conditions will result in improved safety performance in the accident configurations replicated. NHTSA is examining these and other crash test conditions to improve the effectiveness of crash testing.

**Partial Fixed Barrier.** One test condition that has been used by Mercedes, Auto Motor and Sport, and others is a partial overlap barrier, usually with some degree of shape. The barrier is designed to contact only a portion of the front structure, is rigid (non-yielding), can be flat or angled, and typically has a rounded edge. This test condition is similar in complexity to full barrier impact crash testing. Carefully aligning the vehicle with the barrier to ensure consistent overlap at initiation of impact is the only additional requirement. Except for the initial expenditure for the test hardware, the cost of conducting this type of test is the same as for a fixed full barrier test. Overlap or fixed full rigid barrier crash testing can not incorporate all the subtleties of car-to-car crashes. These subtleties occur, for instance, when stiff areas of one car impact soft areas of another, causing excessive penetration of the other vehicle.

**Partial Fixed Barrier with Deformable Face.** This test incorporates some form of deformable element into the face of a fixed barrier. Structures of a vehicle front end are represented by deformable honeycomb material of varying depths to simulate the crush of a struck vehicle. The fixed barrier surface could be stepped, to accommodate the back surface of this geometry, while the front, crushable surface remains flat. This stepped fixed barrier configuration would serve three purposes. First, it would allow deformation into the opposing structure (up to a point) so that structural hard points would behave as though they were hitting a vehicle front end. Second, it would allow greater edge deformation, so that the bumper of the subject vehicle can deform at a progressively greater angle—similar to the deformation expected in a car-to-car collision. Finally, this test configuration would promote structural compatibility by matching the crush characteristics of the subject vehicle with the characteristics of the honeycomb for optimum crash performance.

This test type closely matches the car-to-car test damage pattern and is only slightly more involved than the full barrier test because of the need for careful alignment. It accomplishes the match by allowing for progressively increasing angular crush of the front structure by deformation of the barrier (more on the edge than in the center). Front-to-front compatibility could also be achieved with a standardized crushable element, allowing frontal structures to be designed for optimum performance.

Adding a crushable element to the face of a conventional fixed barrier tends to create an unrealistic crash response in terms of energy absorbed at a given speed, because energy-absorbing capability is added to the barrier, while the kinetic energy of the impact remains unchanged from a fixed barrier test. The additional energy absorption needs to be minimized, so that it is a small percentage of the total energy dissipated in the crash. The added energy-absorption capacity must, at the same time, be large enough to be effective for the previously stated advantages. The crash tests may need to be conducted at a higher speed than conventional barrier tests to compensate for the addition of energy-absorbing material to the barrier face. There is also increased time and cost resulting from the need to replace the crushable element after every test.

**Deformable Moving Barrier.** This is probably the most complicated test. The basic test would use a deformable moving barrier impacting the front of a car moving at an equivalent speed in an overlap configuration. If the deformable element of the moving barrier is properly selected, this type of crash test may closely simulate a car-to-car crash. A non-crushable or stiff element may be required to represent the engine.

Theoretically, this type of test could simulate any particular car-to-car crash by varying the properties of the honeycomb in the crushable element. The crushable element would be designed to stimulate the optimal vehicle frontal stiffness needed for stiffness compatibility in the car fleet. Cars would be tested against the crushable surface to assure that the stiffness of the vehicle front end is compatible with the fleet. The momentum and energy involved in this test condition would be closely matched to that of a collision between two cars of equivalent weights. This test, assuming a standardized weight of the deformable moving barrier, would, therefore, impose a greater severity test on smaller cars than on larger cars. If desired, geometric compatibility could also be addressed by selecting the shape of the deformable moving barrier, assuring that load paths are compatible with front, side, and rear structures.

However, this type of test imposes an added burden of complication in conducting the test. Preferably, both vehicles should be moving, necessitating that the test be conducted at mid-track and that the tow-release point be relatively close to the point of impact, or that some means of guidance be provided to ensure proper alignment at initiation of impact. Conducting the test with only one vehicle moving is not considered a viable option, since such a wide angle of film coverage is needed to follow the larger impact area since the struck car accelerates rearward to approximately one-half of the impact speed. With both cars moving, the cars come to rest near the point of impact. Any test using a deformable barrier has the disadvantage of requiring a new crushable honeycomb face assembly after every test.

### *NHTSA Crash Tests*

Given the lack of experience with the aforementioned test types and the lack of baseline car-to-car crash test data, NHTSA conducted a number of car-to-car and car-to-fixed barrier overlap tests to better understand frontal overlap crash behavior. The partial fixed barrier used in these tests was a flat barrier designed to engage 50 percent of the subject cars in frontal crash tests. Two different overlap configurations (63.5 percent and 90 percent) were used in the car-to-car tests. The subject vehicles in this test series were Toyota Celicas and Hyundai Excels. The model years used were 1987 and 1989, but there were no structural differences between these two model years. The first tests on these cars were 1987 NCAP tests. During NCAP testing, the Toyota was observed to prevent intrusion (crushing of the passenger compartment) better than the Hyundai, although both cars had similar crash pulses (acceleration-time history in the passenger compartment during a crash). A prior research program (4) was conducted using these same vehicle models and model years, because of their similarity in crash pulse and dissimilarity in intrusion characteristics. That program was conducted as a baseline exercise to review the potential for improvement in steering assembly characteristics for unrestrained occupants. Those research tests were conducted in full frontal barrier and 50-percent overlap barrier modes at 25 mph and 35 mph to better understand crash kinematics in those crash modes.

The test program covered in this paper began in 1989 and used restrained dummies, because restraint use (both manual and passive) was increasing as a result of Federal Motor Vehicle Safety Standard and 208, "Occupant Crash Protection." Vehicle manufacturers have since elected to install air bags in a variety of their lines; some have committed to installing air bags in all future production. While significant gains have been achieved in reducing injuries in crashes, much remains to be improved in restraints as well as vehicle structures. Toward this goal, NHTSA began examining frontal test configurations as a means of upgrading frontal crash protection.

In this research, four car-to-car tests using eight 1989 model Toyotas and Hyundais were conducted at 63.5-percent overlap and 90-percent overlap (i.e., 63.5 percent and 90 percent of the front fender-to-fender width was engaged upon impact). Both cars were moving at approximately 35 mph. Each test used a driver dummy in one car and a passenger dummy in the other. These tests were conducted to determine similarities and differences between car-to-barrier (full and partial) tests previously conducted and the car-to-car overlap tests. Table 1 shows the matrix of the test series used for comparison in this study.

**Table 1. Test Matrix of Car-to-Car and Car-to-Barrier Tests**

| | TEST SPEEDS (miles per hour) | |
|---|---|---|
| | **TOYOTA** | **HYUNDAI** |
| VSB 100% | 35.4 | 34.8 |
| VSB 50% | 34.7 | 34.7 |
| VTV 63.5% | 35.5 | 35.3 |
| VTV 90% | 34.8 | 34.2 |

VSB 100% = Vehicle-to-stationary barrier, 100 percent engagement.
VSB 50% = Vehicle-to-stationary barrier, 50 percent overlap.
VTV 63.5% = Vehicle-to-vehicle, 63.5 percent overlap.
VTV 90% = Vehicle-to-vehicle, 90 percent overlap.

### *Dummy Response*

Figures 1 through 4 compare the dummy responses for the restrained drivers and passengers only. Figure 1 shows the HIC (Head Injury Criterion) comparisons between the 35-mph tests using restrained dummies. The driver and passenger of the Toyota and the driver of the Hyundai all show consistent trends, with the 63.5-percent overlap car-to-car and the full barrier tests producing almost identical HIC's. Substantially higher HIC's (1.5 to 2.1 times greater) are observed for the 90-percent crash mode. This difference can be attributed to higher intrusion combined with a relatively severe crash deceleration pulse (discussed in the next section). The only inconsistent response was that the Hyundai passenger exhibited a much higher HIC in the full barrier test than in either of the other two crash conditions. This is probably due to the dummy's head striking his knee in the NCAP test, but not in the other tests. Observations from these crash test results indicate that HIC is influenced similarly by crash pulse and intrusion. Intuitively, one would expect higher intrusion, as seen in the 63.5-percent overlap tests, to cause higher HIC's than the full barrier tests. The reason this was not true is that the dummy trajectory was off center to the left of the stiffer portion of the wheel in all offset testing, particularly in the 63.5-percent overlap. In a real-world crash in which the trajectory of the vehicle may be lateral as well as frontal, the occupant might easily have impacted the center of the hub—with fatal consequences.

Figure 2 shows the chest acceleration responses for all four dummies and three crashes. The chest responses also show a clear and consistent trend for the Toyota driver and passenger and for the Hyundai driver. The response for these three dummies was highest in the 90-percent overlap car-to-car and lowest in the full barrier, with the 63.5-percent car-to-car dummy response falling between the two. This suggests a correlation between chest response and intrusion, as well as between chest response and crash pulse,with intrusion providing greater correlation. This is because in the 63.5-percent overlap crash, intrusion (discussed in following sections) was only slightly higher than in the 90-percent overlap crash, yet the crash pulse (see next section) was much softer than the other crashes. The exception to the consistency is again the Hyundai passenger. In this car, the 63.5-percent overlap car-to-car test yields the highest dummy chest response, with the 90-percent only slightly lower and the full barrier producing the lowest response. This slight deviation is of little concern, since the chest response still appears to be strongly influenced by intrusion and crash pulse.

Figure 3 shows the left femur maximum force, and Figure 4 shows right femur maximum force. While these data are not as consistent across the board as the head and chest responses, the average of the right and left femur force is consistently higher for the 63.5-percent overlap test—with the 90-percent next and the full barrier lowest (with the exception of the Toyota passenger). The Toyota femur forces are very low (less than 600 pounds) and all crashes are similar, possibly indicating no intrusion or no knee contact. These data indicate a strong correlation between femur forces and intrusion of the dash, with very little, if any, dependence on crash deceleration pulse severity.

***Deceleration Response of Vehicle Structure***

Four crash conditions are compared to evaluate crash deceleration responses (crash pulses). These are all approximately 35-mph crashes. Two crashes were car-to-car, conducted at 63.5-percent and 90-percent overlap, and the other two were fixed barrier tests conducted at 50-percent and 100-percent (full barrier) overlap. Table 1 shows the test matrix.

Figure 5 shows the crash pulses for the four Celica tests. Note that the highest peak deceleration occurs in the 50-percent overlap fixed barrier test, followed closely by the full barrier test. The 90-percent car-to-car is next, then the 63.5-percent overlap car-to-car crash,

**Figure 1. Comparison of Head Injury Criterion (HIC)**

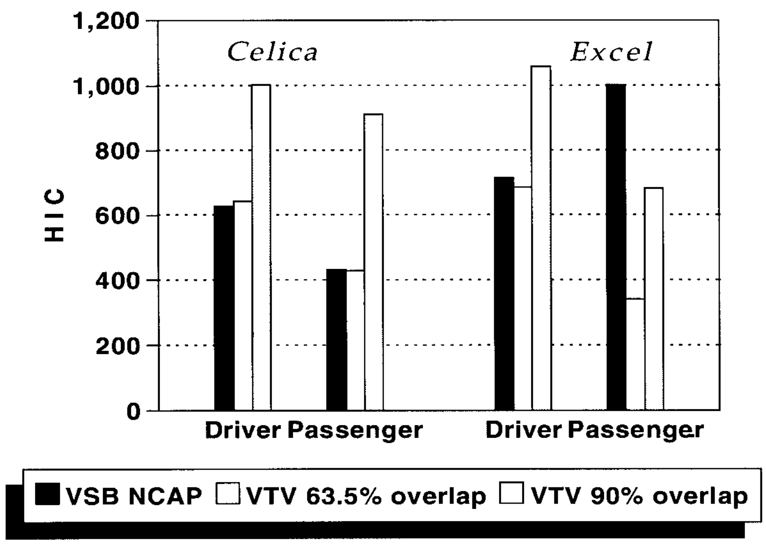



**Figure 2. Comparison of Chest 3 MS Clip**

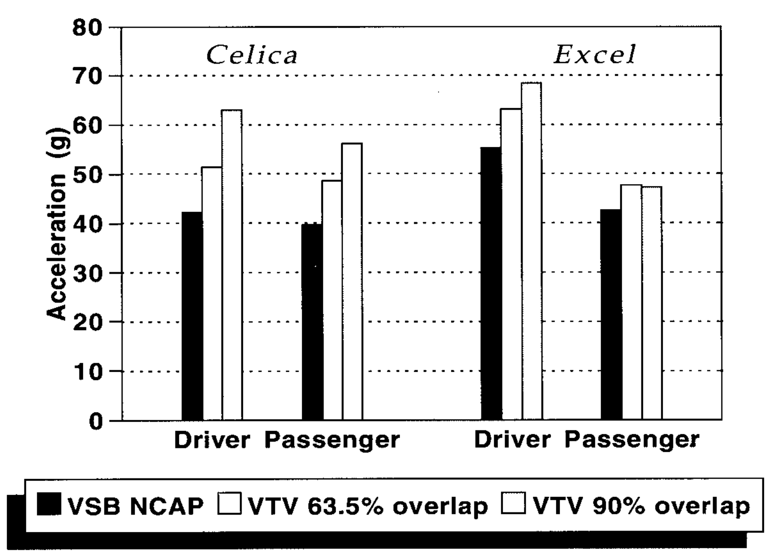


**Figure 3. Comparison of Left Femur Force (Pounds)**

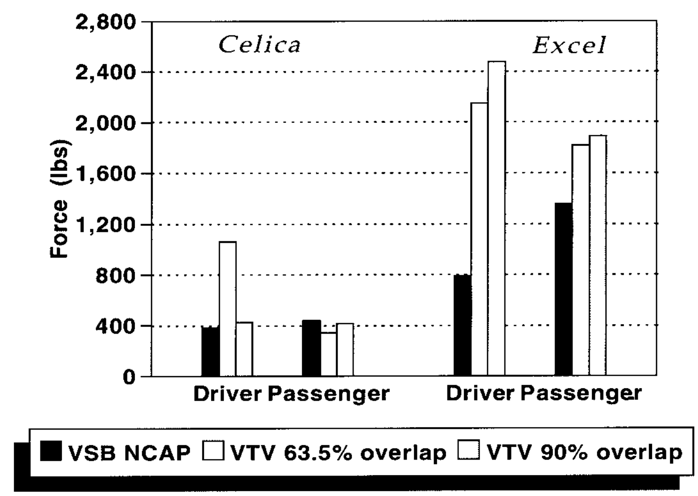



**Figure 4. Comparison of Right Femur Force (Pounds)**

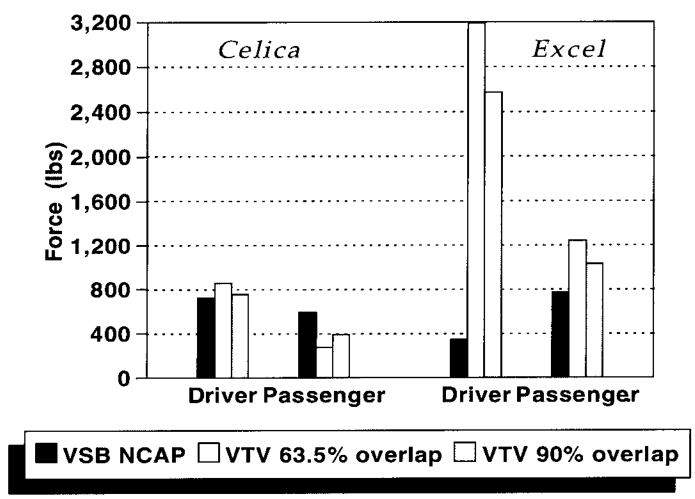
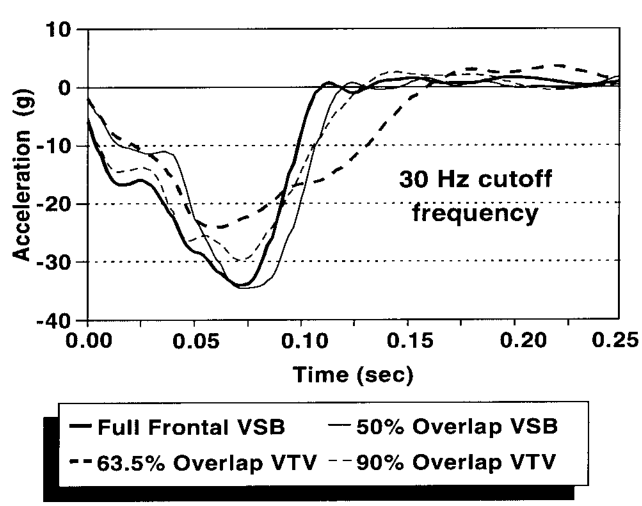



**Figure 5. Crash Pulses for Celica Tests**




representing the "softest" crash pulse. Peak acceleration is not the only indicator of crash pulse severity; perhaps equally important is the *duration* of impact. For this study, duration is calculated from the instant of impact to the time at which the velocity curve first reaches zero. The vehicle may still be decelerating at this time, but forward motion over ground has stopped, the vehicle motion has begun to reverse, and the dummy has already contacted the interior. Figure 6 shows the velocity curves. From this figure it can be seen that the shortest crash pulse is the full barrier test, followed by 90-percent overlap and 50-percent fixed barriers, which are fairly close together. Finally, the test with the longest duration is the 63.5-percent overlap car-to-car test.

Figure 7 shows another measure of crash pulse severity: dynamic displacement of the occupant compartment relative to a fixed point on the ground. Looking at maximum dynamic displacement from this figure, the order of the crash pulses from softest (most dynamic displacement) to stiffest is the 63.5-percent overlap, the 50-percent overlap, the 90-percent overlap, and the full barrier impact. This order is the same as obtained when ranking by duration, except for one minor difference: the four tests are grouped in pairs, with the full frontal and 90-percent overlap grouped together and the 50-percent and 63.5-percent grouped together. By duration/velocity ranking the 50-percent and 90-percent were grouped together near the middle of the other two extremes—63.5-percent (longest duration) and full barrier (shortest duration).

It can be concluded for the Celica that the 63.5-percent and the 90-percent impacts produce similarly shaped crash pulses of higher severity in the largest overlap percentage. The 50-percent and full barrier pulses also bear some resemblance. In terms of peak acceleration, the 50-percent barrier appears to be an anomaly, producing the highest peak. The other measures of crash pulse severity are in the order expected, with the full engagement more severe than the 50-percent overlap. By two out of three of the measures of crash pulse severity, the 50-percent fixed barrier lies between the 63.5-percent and 90-percent overlap car-to-car barriers. This was as expected when the test conditions were chosen.

However, the 50-percent barrier produces the highest peak acceleration. This may be explained by the fact that the compartment experiences more crush in the 50-percent overlap car-to-barrier test than in the 90-percent overlap car-to-car test. This compartment crush difference is caused by a major load path through the wheels, due to a rigid link from the suspension to the occupant compartment. This link adds tremendous rigidity between the compartment and either tire during a crash. The rigid barrier forces the tire rearward during impact, whereas a striking car yields and crushes to conform to the excessive stiffness of the tire contact area. Any advantage gained by this method of reducing intrusion in a car-to-car impact is somewhat reduced by allowing intrusion from other sources, such as rearward movement of the engine. Intrusions, which will be discussed in the next section, may be compared in Figures 11-13.

Looking at the Hyundai Excel crash pulses, Figures 8-10 show consistent results. All three measures of crash pulse severity show their decreasing order as: full barrier, 90-percent overlap, 50-percent overlap, and 63.5-percent overlap. This order was expected prior to testing and was the same as resulted from two out of the three measures for the Toyota. Further inspection of the four crash pulses in these figures reveals similarity between the 50-percent and 63.5-percent tests, and an almost identical match between the full barrier and the 90-percent overlap test. The similarity between the 50 percent and 63.5 percent begins to deviate at approximately 50 milliseconds. At this point in the car-to-car test the structures begin to disengage by lateral motion induced by the non-symmetrically deformed front bumpers and the forces imposed by the engines.

### *Intrusion—Steering Wheel Effects*

Figures 11-14 show comparisons of steering wheel intrusion parameters for the two barrier and two car-to-car impacts. Figure 11 shows maximum displacement rearward with respect to the rest of the compartment as measured dynamically by film analysis. The value of horizontal intrusion shown in this figure is the maximum value recorded before the dummy's head contacted the steering wheel rim or hub (usually 1-5 milliseconds before contact). In the car-to-car overlap tests the intrusion continued after dummy head contact initially occurred. In the car-to-barrier tests this phenomenon was not observed since the unrestrained dummies continued loading the steering column—causing more stroke and less observable intrusion.

The time of maximum intrusion is shown in Figure 12. Note the similarities in maximum intrusion time even though the fixed barrier tests used unrestrained dummies and the car-to-

**Figure 6. Velocity-Time Curves for Celica Tests**

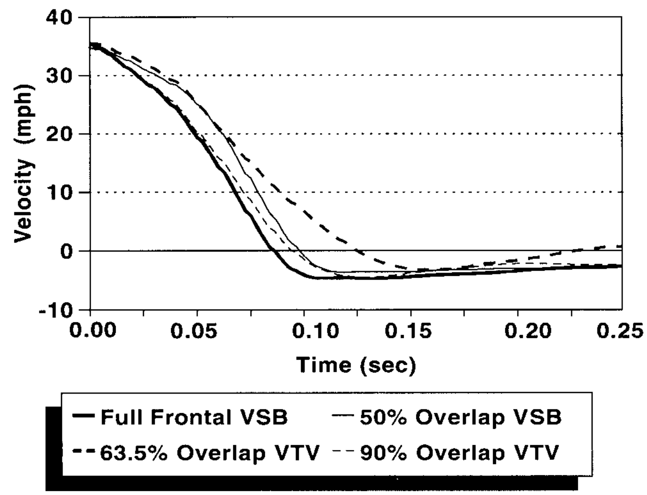



**Figure 7. Displacement-Time Curves for Celica Tests**

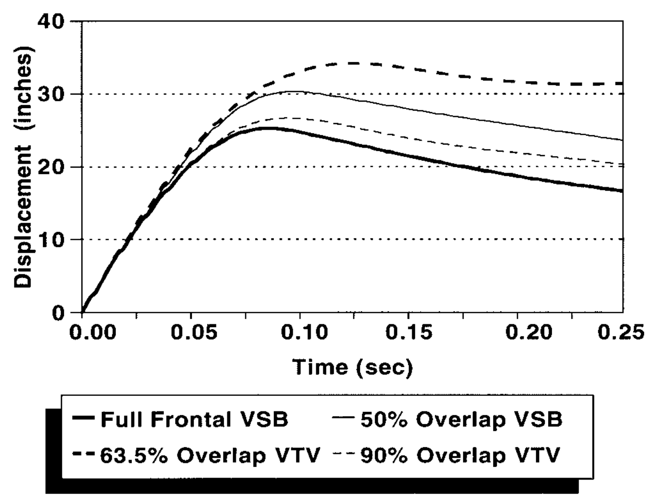



**Figure 8. Crash Pulses for Excel Tests**

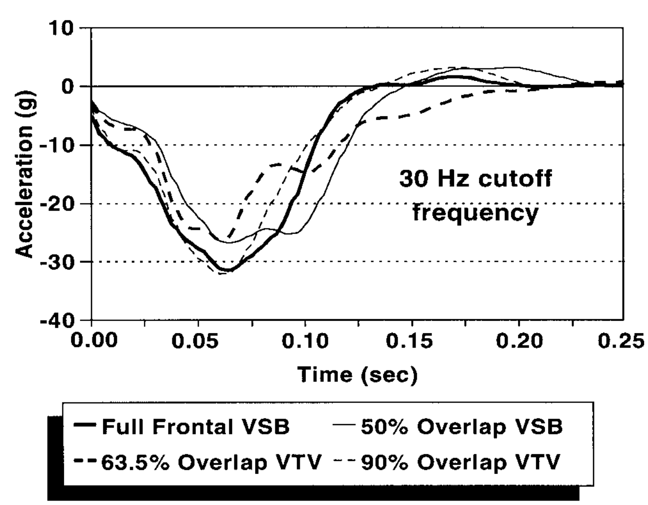


**Figure 9. Velocity-Time Curves for Excel Tests**

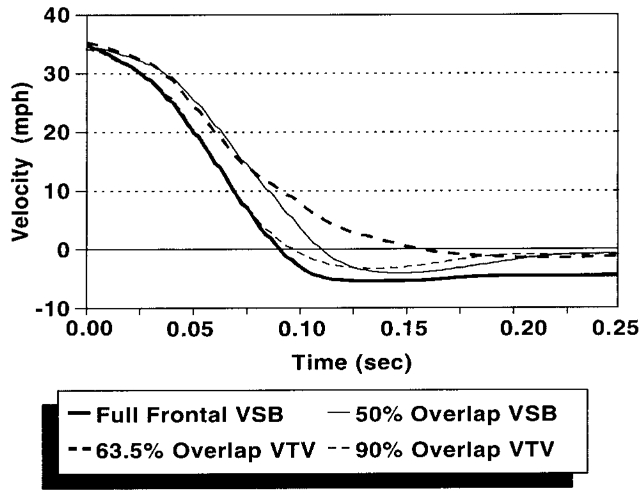



**Figure 10. Displacement-Time Curves for Excel Tests**

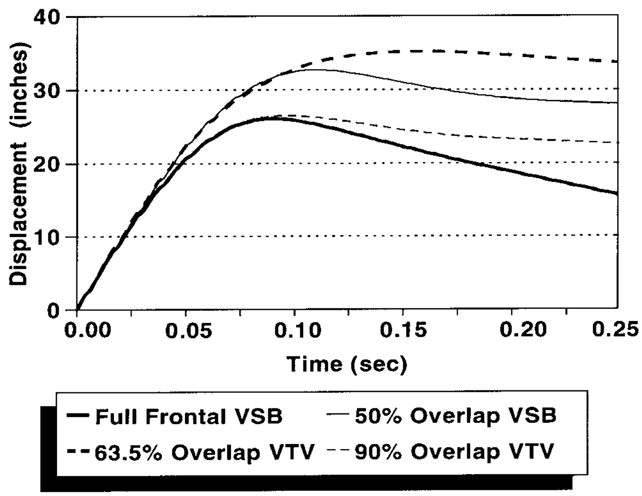
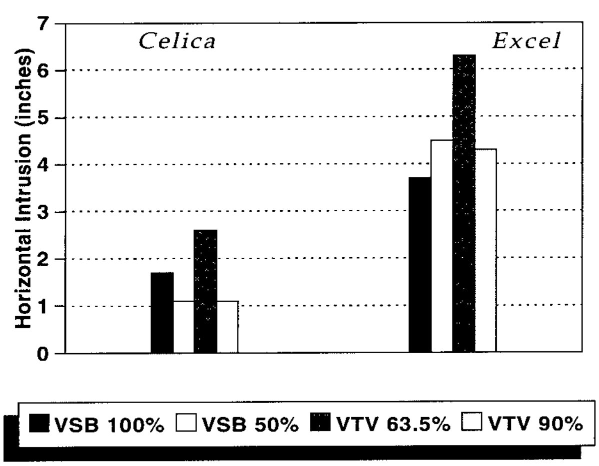



**Figure 11. Maximum Rearward Horizontal Dynamic Displacement of Steering Wheel**




car tests used restrained dummies. (Different restraint conditions were used because each set of tests was conducted under a separate project with slightly different objectives.)

Figure 13 shows the intrusion velocity, the maximum value of the velocity of the steering wheel with respect to the compartment, which occurs prior to the time of maximum rearward displacement. The Hyundai had the highest intrusion velocity and, of the four test conditions, the 63.5-percent car-to-car had the highest intrusion velocity. The second highest intrusion velocity was seen with the 90-percent overlap car-to-car tests. The third- and fourth-rated test condition depends on the car used. Of the remaining two test conditions the Excel performed more poorly with the 50-percent fixed barrier but the Celica performed more poorly in the full barrier. This intrusion behavior of the Celica was not expected; it can be explained by the Celica's unusual structure (also see discussion in previous section). In most cars, intrusion of the occupant compartment is caused primarily by rearward motion of the engine into the firewall. In the Celica, a major load path is through the wheels, due to a rigid link from the suspension to the occupant compartment. In addition, there is a crushable load path from the center bumper height to the compartment floorplan. In the barrier test the engine also contributes to intrusion. The combination of these load paths causes earlier and more extensive intrusion in the full barrier test because all are simultaneously engaged by the flat-barrier surface.

Figure 14 shows the maximum vertical steering wheel displacement in each test. From this figure it is apparent that the Hyundai in the fixed barrier test had more vertical displacement. In the Celica the only crash test that produced a significant amount of vertical steering wheel intrusion was the 50-percent barrier test. It is uncertain whether this is due to loading from the unrestrained occupant via the dummy's knees or due to structurally induced intrusion, such as from the engine, or from crushing of the structure.

In summary, the intrusion can be said to be more severe in the car-to-car tests than in the car-to-barrier tests. Intrusion measured in terms of velocity agrees fairly well with the intrusion measured in terms of displacement. Figures 13 and 14 show that intrusion measurements for the Hyundai are greater than for the Celica.

### *Summary and Conclusions*

It can be shown from this limited test series that intrusion as measured at the steering wheel in partial overlap car-to-car crashes is typically of a higher magnitude than in car-to-full barrier crashes. Intrusion resulting from a narrower overlap impact (63.5 percent) produced more intrusion than a wider overlap impact (90 percent). However, there was no consistent correlation between the 50-percent fixed barrier and the car-to-car overlap tests. The 50-percent overlap barrier test resulted in approximately the same horizontal intrusion displacement, but slightly lower intrusion velocity than did the 90-percent car-to-car overlap test. Therefore, to simulate the intrusion seen in a car-to-car test via an offset barrier test requires a narrower engagement with the barrier than the actual overlap of interest. To more accurately simulate intrusion extent and velocity may require more sophisticated test tools, such as a deformable moving barrier, a partial fixed barrier or a deformable fixed barrier.

Comparing the crash pulses for the Hyundai, the 50-percent barrier crash pulse is close to, but more severe than, the 63.5-percent overlap car-to-car test pulse. In the Celica, the 50-percent barrier crash pulse is very similar to the full barrier and closer to the 90-percent overlap, than the 63.5-percent car-to-car pulse. This means that to match the crash pulse and intrusion occurring in a car-to-car test with a barrier test, one requires a narrower impact overlap with the barrier. This is consistent with the need to match intrusion alone by a narrower engagement with the barrier. However, the percentage difference required to match crash pulse and intrusion may vary from car to car. Additionally, the percentage difference required to match intrusion may not be the same as that required to match crash pulse.

Because of the relative inconsistency between the two car models in matching the car-to-car test with the car-to-barrier test, it is doubtful that one overlap fixed barrier percentage can be used with every model to replicate structural and occupant responses precisely in a given overlap car-to-car impact. Whether this objective is feasible is a matter of continuing debate, since it is also recognized that full frontal fixed barrier crashes cannot always replicate a car-to-car full frontal test. Even though not all possible testing configurations were used, insight was gained for consideration of other potential test configurations.

**Figure 12. Time of Maximum Displacement of Steering Wheel**

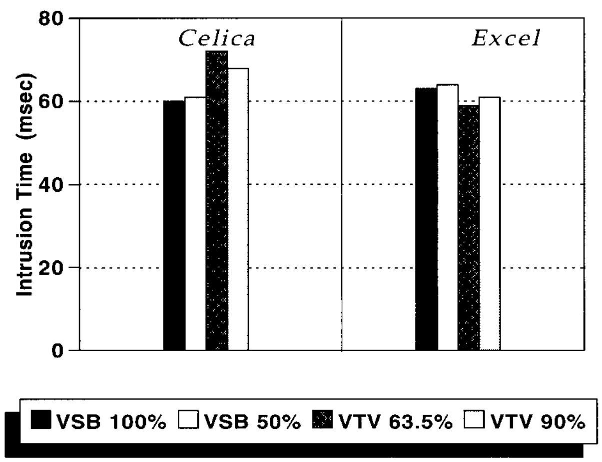



**Figure 13. Maximum Rearward Horizontal Velocity of Steering Wheel**

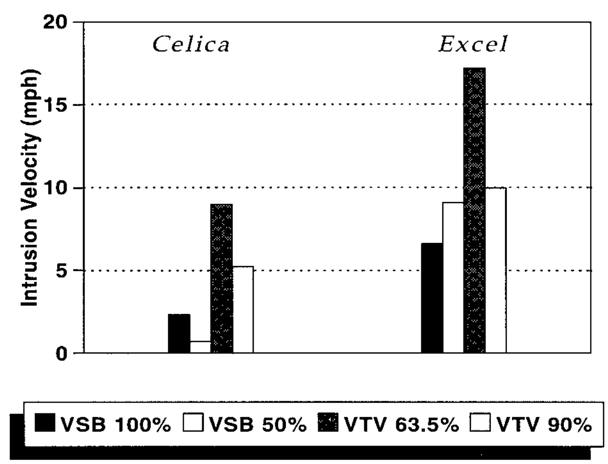
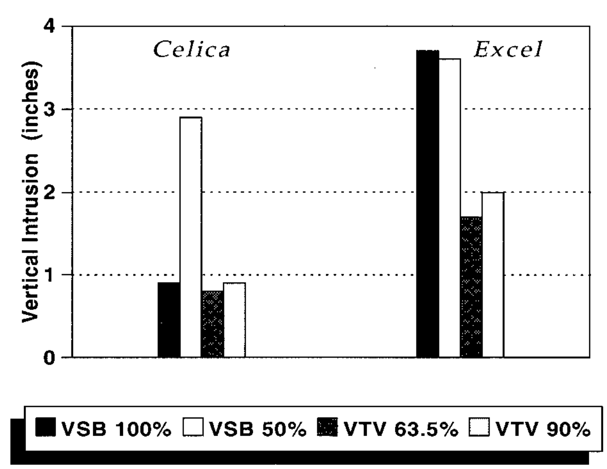



**Figure 14. Maximum Upward Dynamic Displacement of Steering Wheel**



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## About the Authors


***Carl L. Ragland, Jr.***, has been a research engineer with NHTSA since 1977. His accomplishments include developing the deformable barrier used in the FMVSS 214 side impact standard and designing the load cell barrier used in NHTSA's frontal testing. As a program manager, he has conducted numerous crash test programs and published the analysis and results in various journals. He is currently researching occupant and vehicle structural responses in frontal offset crashes. His 22 years experience in design, testing, and analysis of structures includes work at Ford Motor Company, Duke Power Company, and Value Engineering Laboratory. Mr. Ragland received his Bachelor of Science degree in Civil Engineering from Old Dominion University in 1970.

***Gayle Dalrymple*** has been with the U.S. Department of Transportation for 7 years. She spent the first 6 years at the Volpe National Transportation Systems Center, where she participated in NHTSA crash testing and vehicle structural analysis. She also did assessments of the state of the art in the use of electric vehicles and the safe transportation of persons using wheelchairs. She is currently with NHTSA's Crash Avoidance Division, Office of Vehicle Safety Standards. She received her Bachelor of Science degree in Mechanical Engineering from the University of Michigan in Ann Arbor, Michigan, in 1980, and is currently writing her thesis for the Master of Science degree in Applied Mechanics from the University of Virginia.

# Data Analysis of the Speed-Related Crash Issue

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*Abstract*

Speeding has been recognized for decades as both a significant and complex highway safety issue. Using the most recent data available, this paper examines the size of the "speeding problem" in the United States and identifies characteristics most often associated with speed-related crashes. Data from the National Accident Sampling System, the Fatal Accident Reporting System, the Crash Avoidance Research Data File, the National Crash Severity Study, and the Indiana Tri-Level Study were used in conducting the analysis. Information pertaining to crash avoidance, crash severity, and related crash characteristics (alcohol, vehicle type, roadway condition, etc.) were examined. Of particular interest is the use of an innovative methodology to estimate the economic impact of speed-related crashes on society. The results of the study clearly indicate that the speed issue warrants priority attention. Speeding was found to be involved in 12 percent of all police-reported crashes and one-third of all fatal crashes. The authors estimate that speed-related crashes cost society more than $19 billion each year. The study also identifies specific aspects of the issue that should be focused upon in considering potential countermeasures.

### *Introduction*

"Speed Kills" has been an important slogan for highway safety for several years. While the slogan is clearly true, the issue that must be addressed by highway safety programs is much more complex. To effectively address the issue of speeding, it is imperative to know the size of the speed-related crash problem, where speed-related crashes most often occur, why they occur, and who is most likely to be involved in such crashes. Accordingly, the National Highway Traffic Safety Administration (NHTSA) undertook an analysis of several crash data files to ascertain this information. This paper presents the results of the analysis and examines the speed issue in terms of crash causation, severity, characteristics, and societal costs.

### *Crash Causation Data*

Data from the Crash Avoidance Research Data file (CARDfile) (1), the Indiana Tri-Level study (2), and the Fatal Accident Reporting System (FARS) (3) were examined by the authors to determine the relative role of speeding in crash causation. Other than data from the Indiana Tri-Level Study, the crash data presented in this paper are based on police-reported information, not detailed investigations. The police-reported data are generally not as accurate as data provided by field investigations or crash reconstructions. This should be kept in mind when interpreting the results discussed below.

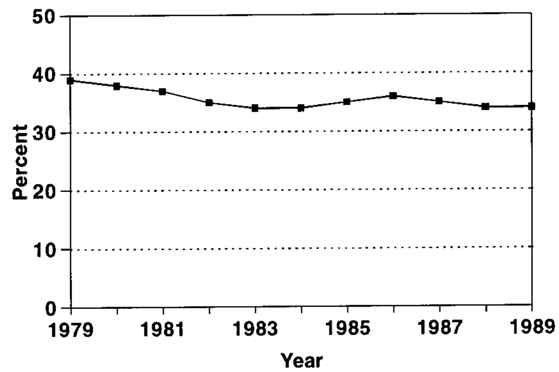
NHTSA developed CARDfile to help identify problems and countermeasures in the general area of crash avoidance research. CARDfile electronically combines the annual crash data files of six states into a common format. For purposes of this analysis, data from the 1986 CARDfile were used. The 1986 CARDfile data describe about 1.4 million crashes involving about 2.4 million vehicles and drivers. Data from additional years of CARDfile were not included, both to simplify the analysis and because previous analyses have shown that distributions obtained for a single year of data closely reflect distributions based on several years of data.

CARDfile was analyzed to determine the magnitude of the role of speed in crash causation. Table 1 compares the relative involvement of speed and other driver errors in contributing to the occurrence of crashes.

As illustrated in Figure 1, speed was a factor in close to 12 percent of the crashes in CARDfile. It was the most prevalent driver error-related cause contributing to crash occurrence.

A similar analysis of data from the Indiana Tri-Level Study was also performed by the authors. In the Tri-Level study, crashes were examined at three levels: police accident reports (level A), on-scene investigation of crashes by teams of

**Figure 1. Speed-Related Fatal Crashes**




Source: Fatal Accident Reporting System.

**Table 1. Driver Error Involvement in Crash Causation**

| CRASH TYPE | CRASHES IN WHICH FACTOR WAS INVOLVED[a] (percent) |
|---|---|
| Speed-Related[b] | 11.6 |
| Right-of-Way Violation | 8.7 |
| Following Too Closely | 8.0 |
| Ignore Traffic Control | 7.1 |
| Asleep/Inattention | 4.1 |
| Improper Passing | 2.4 |
| Failure To Signal | 0.9 |

[a]Data based on police accident reports from six states and are not nationally representative.

[b]Speed-related means that in the police officer's judgment speed contributed to the cause of the crash. Up to three factors could be coded for each crash.

Source: CARDfile 1986.

**Table 2. Rank of Causal Factors by Range of Involvement**

| CAUSAL FACTOR | RANGE OF INVOLVEMENT (percent) |
|---|---|
| Improper Lookout | 13.0 - 23.1 |
| Excessive Speed[a] | 7.1 - 16.9 |
| Inattention | 8.4 - 15.0 |
| Slick Roads | 3.8 - 14.1 |
| Improper Evasive Action | 4.5 - 13.0 |

[a]Excessive speed means too fast for conditions. It was not determined with reference to the prevailing speed limit.

Source: Indiana Tri-Level Study, 1979.

technicians (level B), and in-depth investigations of subsets of crashes by multidisciplinary teams (level C). Also, there were three levels of certainty that a causal factor contributed to the occurrence of a crash—definite, probable, and possible. For purposes of this analysis, only investigation levels B (2,258 cases) and C (420 cases) and certainty levels "definite" and "probable" were used.

The leading crash-causation factors (driver, environment, and vehicle-related factors) were identified and ranked. Here, "cause" means a contributing factor without which the crash would not have occurred. Each crash could have multiple causes. The factors were ranked by the range of their estimated involvement, considering the estimated percentage of involvement at level B definite, level B probable, level C definite, and level C probable. The highest and lowest figures for each causal factor were then used to represent its overall range of involvement.

Table 2 shows that "excessive speed" was the second most prevalent factor contributing to crash occurrence in the Tri-Level study. The mid-point of the range of involvement (7.1 to 16.9 percent) for "excessive speed" is 12 percent, which corroborates the CARDfile estimate that speed is involved in close to 12 percent of all crashes occurring in CARDfile states.

Tri-Level data were also analyzed by crash type (e.g., head-on, angle, sideswipe, rear-end, and single-vehicle). For each crash type, the top causal factors were ranked by the percentage of crashes in which they occurred. Table 3 shows that "excessive speed" ranked as one of the top ten contributing factors for each crash type. This is especially noteworthy given that approximately 50 factors could be considered in each crash case. Of further significance, "excessive speed" was the first or second most prevalent cause listed for the two most severe crash types—head-on and single-vehicle crashes. This suggests not only that "excessive speed" is a leading cause of motor vehicle crashes, but that it is most prevalent in the more severe crash types.

FARS data were used to determine the role of speed in contributing to fatal crash causation. FARS is a census of people who die within 30 days of a motor vehicle crash as a result of injuries received during the crash. The data are prepared by the states from death certificates, hospital records, police reports, and other sources and are compiled by NHTSA into a national data file. For FARS data, "speed-related" was defined as "driving too fast for conditions or in excess of the posted speed limit," and "high-speed police chase." (Note that these are qualitative variables that are subject to interpretation on the part of the data coder. Quantitative variables such as travel speed and posted speed were not used because there are a substantial number of cases for which this information is unknown.) These data indicate that in 1989, approximately one-third of all fatal crashes were speed-related. This percentage has declined from a high of 39 percent in 1979. Since 1982, the proportion of speed-related crashes has basically remained stable, as shown in Figure 1.

**Table 3. Ranking of Excessive Speed by Crash Type**

| CRASH TYPE | RANKING | RANGE OF INVOLVEMENT (percent) |
|---|---|---|
| Single-vehicle | 1 | 22.1 - 39.3 |
| Head-on | 2 | 12.7 - 22.0 |
| Sideswipe | 2 | 10.8 - 14.9 |
| Angle | 10 | 3.4 - 8.8 |
| Rear-end | 10 | 2.9 - 6.6 |

Source: Indiana Tri-Level Study, 1979.

### *Crash Severity Data*

The laws of physics tell us that the energy of impact delivered to vehicle occupants in a collision increases non-linearly with impact speed. Simply stated, crash severity increases (disproportionately) with vehicle speed.

To determine real-world crash experience, the authors conducted an analysis of data from the National Accident Sampling System (NASS) (4) and the National Crash Severity Study (NCSS) (5). Through the use of field investigation teams, NHTSA's NASS system collects detailed data on a nationally representative sample of all police-reported crashes. (The system was revised in 1987 and now consists of two components, the General Estimates System (GES) and the Crashworthiness Data System (CDS).) NCSS was a NHTSA data-collection program that was conducted between 1977 and 1979. Crashes were investigated in seven geographic locations across the country. Detailed information was collected on more than 11,000 "tow-away" crashes—i.e., crashes so severe that the vehicle could not be driven from the crash scene.

In Table 4, the percentage of occupants sustaining Abbreviated Injury Scale (AIS) 2+ and 3+ injuries is given for various Delta V levels. AIS is a system for rating the severity of individual injuries. AIS levels range from 1 for a minor injury to 6 for an injury that is not currently survivable. Delta V is a computed estimate of

**Table 4. Injury Rates by Crash Severity,[a] Comparison of NCSS and NASS (1982-1989)**

| TOTAL DELTA V (mph) | AIS 2+ | | AIS 3+ | |
|---|---|---|---|---|
| | NCSS | NASS | NCSS | NASS |
| 1-10 | 2.4 | 4.5 | 0.7 | 1.0 |
| 11-20 | 9.5 | 10.6 | 3.5 | 2.6 |
| 21-30 | 25.3 | 29.2 | 13.9 | 11.1 |
| 31-40 | 51.8 | 53.4 | 37.2 | 27.9 |
| 41-50 | 70.3 | 67.2 | 58.3 | 40.6 |
| Over 50 | 64.7 | 69.3 | 56.9 | 54.3 |

[a]Rate equals the number of occupants at a certain Delta V level (in 10-mph increments) injured at specific AIS levels (AIS 2+ or AIS 3+) divided by the total number of occupants involved in crashes at that level of Delta V times 100. Rate does not include cases in which either the Delta V level or the AIS level was unknown.

Sources: NASS 1982-86, and 1988-89 (CDS). Includes only tow-away cases. There was no statistically representative NASS file in 1987. (See Appendix for sample sizes and standard errors.) NCSS, 1979. Data are limited to tow-away crashes involving passenger cars and light trucks. Data are not nationally representative.

the instantaneous change in velocity of the vehicle during the impact phase of the crash.

Both NCSS and NASS data show a consistent and dramatic increase in injury severity as Delta V level increases. For instance, people involved in crashes with a Delta V of 50 mph or greater are more than 50 times more likely to sustain an AIS 3+ injury than those involved in a crash with a Delta V of 10 mph or less. Clearly, the crash data are evidence that real-world crash experience follows the laws of physics.

In terms of crash severity, the most critical real-world measure is how many injuries and fatalities result from speed-related crashes. To determine this, the authors analyzed data from the GES file, FARS, and CARDfile. First, GES was referenced to obtain nationally representative estimates of the number of occupant injuries for the various police-reported injury severity levels. CARDfile, because of its large number of cases, was referenced to determine the proportion of occupant injuries for each injury-severity level that is speed-related. The CARDfile percentages were then applied to the overall GES estimates and FARS data to derive the number of speed-related occupant injuries for each injury-severity level. The FARS file was then used to obtain the total number of motor-vehicle crash fatalities and the number that were speed-related (Table 5).

From the information in Table 5, the authors estimate that in 1989, 15,558 people died in speed-related crashes and more than 80,000 sustained incapacitating injuries. The injury estimates may be conservative because they do not include cases in which the occupant's injury severity level was not known. No attempt was made to include "unknowns," because it cannot be assumed that the injury severity level distribution for such cases is the same as for cases in which the injury severity level is known. Recognize that many of these crashes also involved other contributing factors, such as alcohol, slick roads, and driver inattention. Note also that involvement of speed as a contributing factor increases with injury severity. Only 11 percent of vehicle occupants who were coded as *possible injury* were involved in a speed-related crash, while more than one-third of fatally injured occupants were involved in a speed-related crash.

### *Crash Characteristics*

An analysis of the 1989 FARS file was conducted by the authors to identify the characteristics most associated with speed-related crashes. FARS data were used because FARS is a census of all fatal crashes; and the level of investigation by the police for fatal crashes is generally greater than for less severe crashes. As a result, the following analysis is descriptive of fatal crash situations and may not be indicative of other crash severity levels.

**Manner of Collision.** Speed-related fatal crashes most often involve only a single vehicle. Almost 70 percent of all drivers involved in speed-related fatal crashes were involved in single-vehicle crashes. The next highest percentages are for head-on crashes (12 percent) and angle crashes (11 percent). For fatal crashes that were not speed-related, only 35 percent of the drivers were involved in a single-vehicle crash, while 30 percent were involved in an angle crash and 23 percent were involved in a head-on crash.

**Table 5. Distribution of Injuries in Speed-Related Crashes by Injury Severity Level**

| INJURY SEVERITY LEVEL | NUMBER[a] | SPEED-RELATED[b] (percent) | TOTAL |
|---|---|---|---|
| No Injury[c] | 12,610,000 | 10.2 | 1,286,220 |
| Possible Injury | 1,719,000 | 10.9 | 187,371 |
| Non-Incapacitating Injury | 943,000 | 14.6 | 137,678 |
| Incapacitating Injury | 481,000 | 17.1 | 82,251 |
| Fatal Injury[d] | 45,500 | 34.2 | 15,558 |

[a]National totals are from 1989 GES. (See Appendix 1 for sample sizes and standard errors.)
[b]Speed-related percentage derived from CARDfile (1984-1986).
[c]The estimate for non-injured people is considered to be low because some states only list injured persons.
[d]Fatal crash statistics are from FARS, 1989.

**Vehicle Type.** FARS data indicate that among vehicle types, speed-related crashes are most frequently associated with motorcycle drivers. More than 45 percent of all motorcycle drivers involved in fatal crashes were speeding. The involvement of speed in fatal crashes for motorcycles is almost twice as great as for drivers of the next vehicle types, passenger cars and light trucks (23 percent). Speeding was found to be much less likely for drivers of medium and heavy trucks involved in fatal crashes (11 percent).

**Alcohol Involvement.** Alcohol involvement was found to be prevalent in drivers involved in speed-related fatal crashes. Approximately 41 percent of all drivers under the influence of alcohol who were involved in a fatal crash were speeding. Of all drivers involved in speed-related fatal crashes, about 56 percent were under the influence of alcohol. Conversely, of all drivers involved in fatal crashes that were not speed-related, only 24 percent were under the influence of alcohol.

**Safety Belt Usage.** Manual safety belt usage (lap belt or lap and shoulder belt) for drivers involved in speed-related fatal crashes was found to be only 19 percent. This compares to a usage rate of 37 percent for drivers involved in non-speed-related fatal crashes. The number of cases involving vehicles equipped with automatic restraints was insufficient for development of reliable estimates.

**Motorcycle Helmet Usage.** Little difference was found in motorcycle helmet usage for speeders and non-speeders. Of all motorcycle drivers involved in speed-related fatal crashes, 40 percent were wearing helmets. In fatal motorcycle crashes that did not involve speed, 44 percent of the motorcycle drivers were wearing helmets.

**Roadway Type.** About 34 percent of all fatal crashes on known roadway types were speed-related. The percentages varied considerably by road type, with the percentage of those speed-related being greater in rural settings, except for "Other Principal Arterial Roads," where it was greater in urban settings. Approximately 36 percent of all fatal crashes on rural roads were speed-related, whereas only 30 percent of those on urban roads were speed-related. While rural roads account for only 40 percent of all vehicle miles traveled, they account for 61 percent of all speed-related fatal crashes. Finally, the highest percentage of speed-related fatal crashes among the roadway types was on "Local Roads/Streets" and "Collectors" (39 percent).

**Roadway Surface Condition.** About 14 percent of all fatal crashes occur on wet roads. It makes no difference whether the crash is speed-related (14 percent) or not (14 percent). Of all fatal crashes occurring on dry roads, about one-third are speed-related. The same is true for fatal crashes occurring on wet roads.

**Roadway Alignment.** Speed-related crashes account for only 27 percent of all fatal crashes on straight roadway sections, but constitute 54 percent of all fatal crashes occurring on curves. Approximately 40 percent of all speed-related fatal crashes occur on curves, whereas only 18 percent of the fatal crashes that are not speed-related occur on curves.

**Time of Day.** While only 27 percent of all daytime fatal crashes are speed-related, 39 percent of nighttime fatal crashes involve speed. Sixty-four percent of all speed-related fatal crashes occur at night, and 50 percent of all fatal crashes not involving speed occur at night.

**Sex and Age.** Male drivers were more likely than female drivers to be involved in speed-related fatal crashes. About 25 percent of all male drivers involved in fatal crashes were speeding. The percentage for female drivers involved in fatal crashes was only 16 percent. Speed-related fatal crashes were also most associated with young drivers. Further, the relative proportion of speed-related crashes was found to decrease with increasing driver age. Approximately 37 percent of all drivers aged 14-19 years involved in fatal crashes were speeding. The percentage for drivers 70 and over involved in fatal crashes was only 7 percent. The percentages for the various age groups were as follows: 14-19 (37 percent), 20-29 (30 percent), 30-39 (22 percent), 40-49 (16 percent), 50-59 (12 percent), 60-69 (10 percent), and 70+ (7 percent).

**Number of Vehicle Occupants.** FARS data indicate that the number of vehicle occupants does not affect a person's propensity to speed. The percentage of vehicles with only one occupant was about the same for vehicles that were speeding (56 percent) as it was for vehicles that were not speeding (59 percent).

**Previous Violations.** An analysis of drivers with previous citations shows that in all cases,

**Table 6. Drivers in Fatal Crashes by Previous Violations and Speed-Related Involvement**

| | PERCENT | |
|---|---|---|
| PREVIOUS VIOLATION | Speed-Related | Non Speed-Related |
| Speeding Conviction | 34 | 28 |
| Moving Violation | 27 | 21 |
| DWI Conviction | 12 | 8 |
| Suspension | 23 | 15 |

Source: FARS, 1989

**Table 7. Economic Costs per Injury by MAIS Level**

| | 1990 DOLLARS |
|---|---|
| MAIS 1 | 6,145 |
| MAIS 2 | 26,807 |
| MAIS 3 | 84,189 |
| MAIS 4 | 158,531 |
| MAIS 5 | 589,055 |
| Fatal | 702,281 |

**Table 8. Economic Loss per Injury (Police-Reported)**

| | 1990 DOLLARS |
|---|---|
| No Injury | 1,681[a] |
| Possible Injury (C) | 7,947 |
| Non-Incapacitating Injury (B) | 11,640 |
| Incapacitating Injury (A) | 39,583 |
| Killed (K) | 702,281[b] |

[a]There is an injury cost because in some cases where the police officer reported no injury, subsequent information (such as the hospital report) showed that the victim sustained an injury of some AIS level. Estimate does not include property damage costs.

[b]The number of K injuries is derived from FARS; therefore, it was not necessary to convert the costs.

a greater percentage of drivers involved in speed-related fatal crashes had previous violations as compared to those involved in fatal crashes that were not speed-related (Table 6).

### *Economic Cost of Speed-Related Crashes*

An innovative approach was employed to estimate the economic impact of speed-related motor vehicle crashes. This approach involves the conversion of Maximum Abbreviated Injury Scale (MAIS) levels to police-reported injury severity levels, and applying economic cost estimates to the injured occupant totals for each injury severity level.

Estimates of cost are based on a recent assessment of economic costs by MAIS levels carried out by NHTSA's Office of Plans and Policy (6). The figures are based on the sums of the following categories of economic costs: property damage, medical costs, lost productivity, emergency services, legal/courts, and other administrative costs. The estimates are shown in Table 7.

Using 1982-1986 NASS data, NHTSA's National Center for Statistics and Analysis (NCSA) converted MAIS injury levels to police-reported injury severity levels. This allows one to apply the above MAIS cost estimates to police-reported injury severity levels. Using injury totals from NASS and the economic cost estimates in Table 7, an average cost for police-reported injury level was computed, as shown in Table 8.

To calculate the total economic loss to the country from speed-related crashes, the occupant injury estimates described in the Crash Severity section of this paper were multiplied by the corresponding cost figures (Table 9).

By this estimate, speed-related crashes cost society more than $19 billion in 1989. This estimate is "conservative" because: (1) it does not include cases in which the injury level was not known; (2) the estimate for non-injured people is low because some states list only injured persons; and (3) the cost figures address economic loss only and do not consider the intrinsic value of life and health above and beyond economic considerations.

### *Summary of Data Analysis*

The priority setting process for highway safety programs centers on the observed incidence of a given factor's involvement in contributing to the occurrence of crashes, injuries, and fatalities. The use of real-world crash data provides

## Table 9. Estimated Economic Cost of Speed-Related Crashes, 1989

| TYPE OF INJURY | NUMBER | 1990 DOLLARS COST PER INJURY | 1990 DOLLARS TOTAL (thousands) |
|---|---|---|---|
| No Injury | 1,286,220 | 1,681 | 2,162,136 |
| C Injuries | 187,371 | 7,947 | 1,489,034 |
| B Injuries | 137,678 | 11,640 | 1,602,572 |
| A Injuries | 82,251 | 39,583 | 3,255,741 |
| K Injuries | 15,558 | 702,281 | 10,926,087 |
| Total Societal Cost of Speed-Related Injuries | | | 19,435,570 |

insight critical to the conduct of meaningful analysis and safety improvement. As previously stated, the purpose of this analysis was to use current crash data files to estimate the size of the speed problem and identify pertinent crash characteristics most often associated with speed-related crashes.

The results of this analysis clearly indicate that the speed issue warrants priority attention. Excessive speed is one of the most prevalent factors contributing to crash occurrence. Speed is a factor in approximately 12 percent of all police-reported crashes, and the prevalence of its role appears to increase with crash severity. While only 10 percent of vehicle occupants sustaining no injury were involved in a speed-related crash, more than one-third of all fatally injured occupants were involved in a speed-related crash. The authors estimate that in 1989 about 15,558 fatalities and 80,000 serious injuries occurred in speed-related crashes. The economic cost of these crashes exceeded $19 billion. The results of this analysis also suggest that the specific aspects of the issue that should be focused on when considering potential countermeasures include: (1) single-vehicle crashes; (2) alcohol involvement; (3) nighttime driving; (4) rural roads; (5) low safety-belt usage; (6) motorcycles; (7) male drivers; (8) young drivers (under 30); and (9) drivers with previous traffic violations.

### *References*


(1) National Highway Traffic Safety Administration. "Crash Avoidance Research Data File" (1984-1986 data).

(2) "Tri-Level Study of the Causes of Traffic Accidents," Prepared for the National Highway Traffic Safety Administration, May 1979.

(3) National Highway Traffic Safety Administration. "Fatal Accident Reporting System" (1979-1989 data).

(4) National Highway Traffic Safety Administration. "National Accident Sampling System" (1982-1986, 1988 data).

(5) National Highway Traffic Safety Administration. "National Crash Severity Study" (1977-1979 data).

(6) L.J. Blincoe and B.M. Faigin, "The Economic Cost of Motor Vehicle Crashes, 1990," National Highway Traffic Safety Administration (Washington, DC, September 1992).


## About the Authors

***Noble N. Bowie, Jr.*** has been with NHTSA for 8 years and is currently Chief of the Agency's Strategic Planning Division, where he is responsible for directing the strategic planning function and its activities. This includes developing forecasts and projections, examining key issues, and studying organizational and management alternatives. Before coming to NHTSA, he worked for 4 years in the Federal Highway Administration's (FHWA) Office of Motor Carrier Safety. During his tenure with FHWA he conducted a number of special studies and regulatory evaluations of proposed or existing Federal Motor Carrier Safety Regulations. He has authored or co-authored several published reports including, "Report to Congress on Heavy Truck Ride Quality," "An Analysis of NHTSA Data Needs," and "Moving America More Safely." He also represented NHTSA in the development of the Department of Health and Human Services' "Healthy People 2000." This document contains a national strategy for significantly improving the health of the Nation over the coming decade. He received his Masters Degree in Safety Management from West Virginia University in 1979.

***Marie Walz*** is a mathematical statistician in NHTSA's National Center for Statistics and Analysis. In this capacity, she is involved in the areas of vehicle restraint systems, alcohol involvement in fatal crashes, child restraint use, and the 65-mph speed limit on rural interstate roads. Her other activities include reviewing papers for data accuracy and statistical appropriateness. She received her Bachelor of Arts in Psychology from Miami University in 1980, her Master of Arts in Counseling Psychology from Wright State University in 1981, and her Master of Science in Quantitative Psychology from Ohio State University in 1986.

## *Appendix*

### Sample Sizes and Standard Errors for NASS Data in Table 4

| TOTAL DELTA V (mph) | PERCENT | AIS 2+ STANDARD ERROR[a] | PERCENT | AIS 3+ STANDARD ERROR[a] | TOTAL SAMPLE SIZE |
|---|---|---|---|---|---|
| 1-10 | 4.5 | 1.4 | 1.0 | 0.95 | 10,814 |
| 11-20 | 10.6 | 1.9 | 2.6 | 1.1 | 15,364 |
| 21-30 | 29.2 | 6.3 | 11.1 | 4.2 | 4,238 |
| 31-40 | 53.4 | 14.5 | 27.9 | 18.4 | 1,031 |
| 41-50 | 67.2 | 39.1 | 40.6 | 40.5 | 224 |
| Over 50 | 69.3 | [b] | 54.3 | [b] | 102 |

[a]The standard errors were derived from a single year, 1984. These estimates are probably larger than sample errors from all years of NASS in this analysis. Multi-year sampling error estimates are currently being developed. For more information on the sample design and estimation methodology, contact NHTSA's National Center for Statistics and Analysis.

[b]Sample size is insufficient to allow calculation of sampling error.

### Sample Sizes and Standard Errors for NASS Data in Table 5

| INJURY SEVERITY LEVEL | FREQUENCY | SAMPLE SIZE | STANDARD ERROR (thousands) |
|---|---|---|---|
| No Injury | 12,610,000 | N/A[a] | N/A[a] |
| Possible Injury | 1,719,000 | 13,345 | 91 |
| Non-Incapacitating Injury | 943,000 | 11,632 | 56 |
| Incapacitating Injury | 481,000 | 5,718 | 60 |
| Fatal Injury[b] | 45,500 | N/A[c] | N/A[c] |

[a]No confidence bounds were derived for this figure because some states list only injured persons. Therefore, as noted in the paper, the estimate of non-injured occupants is considered low.

[b]Fatal crash statistics are from FARS, 1989.

[c]Standard errors are not derived for FARS data because the file is a census of all fatal crashes, not a sample.

# Recent Research Reports

This section briefly summarizes recent selected research reports by NHTSA staff and contractors. It includes reports published from May 1991 through August 1992. These reports are available from the National Technical Information Service, Springfield, VA 22161.

## Evaluation of the Effectiveness of Occupant Protection—Federal Motor Vehicle Safety Standard 208—Interim Report

*NHTSA, Office of Plans and Policy, June 1992*

NHTSA continually reviews existing and proposed Federal Motor Vehicle Safety Standards and other regulations in light of current circumstances and motor vehicle safety requirements. The Agency is evaluating the effectiveness of occupant protection. Safety Standard 208 combines a nationwide effort to increase the use of safety belts with a requirement that automatic occupant protection, such as air bags or automatic belts, be phased into passenger cars and light trucks. The Interim Evaluation report, published in June 1992, showed that the use of belts climbed from 14 percent in 1983 to 59 percent in 1991. Fatality risk of occupants in cars equipped with air bags plus manual belts, at 1991 use rates, is 23 percent lower than in "baseline" cars equipped only with manual belts, at 1983 use rates.

DOT HS 807 843, NTIS number PB93-182632.

## The Economic Cost of Motor Vehicle Crashes, 1990

*by Lawrence J. Blincoe and Barbara M. Faigin, NHTSA, Office of Plans and Policy, September 1990*

This report presents the results of an analysis of motor vehicle crash costs for 1990 and the costs of alcohol-related crashes. The total economic cost of motor vehicle crashes and injuries that occurred in 1990 was $137.5 billion. This total represents the present value of lifetime costs for 44,531 fatalities, 5.4 million non-fatal injuries, and 28 million damaged vehicles, in both police-reported and unreported crashes.

Lifetime losses of $50.5 billion in marketplace and household productivity accounted for the largest share of total costs (36.8 percent). Property damage costs of $45.7 billion were the second largest share of total motor vehicle crash costs. Medical expenses were the third highest cost category, totaling $13.9 billion. Each fatality resulted in a discounted lifetime economic cost of $702,000. Alcohol-related crashes resulted in economic costs of $46.1 billion, 33.5 percent of 1990 costs; 81 percent of all alcohol-related costs occurred in crashes where a driver or pedestrian was legally impaired (≥0.10 percent BAC).

The economic costs do not include values for pain and suffering and lost quality of life, although the report also documents those costs.

DOT HS 807-876, NTIS number PB93-123578.

## Source of Payment for the Medical Cost of Motor Vehicle Injuries in the United States

*by Joan S. Harris, NHTSA, Office of Plans and Policy, January 1992*

This report uses hospital discharge reports from selected states to identify motor-vehicle injuries and determines both charges and sources of payment for the injuries. Motor-vehicle-injured patients are compared to those hospitalized for other reasons. Trends by three payer types (those with private insurance, those whose costs are paid by government programs, and other) are analyzed for length of hospital stay and total charges.

Based on the sample states, the report estimates that total U.S. medical expenditures in 1990 for persons hospitalized for motor vehicle injuries was $6.5 billion, with government health care reimbursement programs paying nearly $2 billion of that total. This represents the hospital charges for the estimated 360,000 patients who used 2.5 million days of inpatient care. Length of hospital stay comparisons showed that motor-vehicle-injured patients whose care was paid by government programs remained hospitalized for longer periods than those with private insurance, and the cost of their care was commensurately higher.

DOT HS 807 800, NTIS number PB92-174226.

## Contributions of Vehicle Factors and Roadside Features to Rollover in Single-Vehicle Crashes

*by Kenneth W. Terhune, Arvin/Calspan, Buffalo, NY, March 1991*

This exploratory study examined a small sample of single-vehicle crashes from the National Accident Sampling System (NASS), to suggest how vehicle factors and roadside features interact in generating rollovers. According to the study: (1) sideslopes and ditches were the roadside features with the highest rollover rates; (2) vehicle factors were related to overturn rates mainly with the most hazardous roadside features; (3) the combined data for the cars and light trucks of the sample indicate that overturn rates were inversely related to stability factors; (4) wheelbase was inversely related to rollover rates; (5) when controlling for wheelbase and stability factor, light trucks had substantially higher overturn rates; and (6) wheelbase and vehicle type were related to pre-crash vehicle modes (skidding, spinning, etc.), which in turn were related to rollover rates.

DOT HS 807 735, NTIS number PB92-119031.

## Heavy Truck Occupant Restraint Use

***by M. Copenhaver and T. Wilkinson, CAE-Link Corp., Alexandria, VA, August 1991***

This study replicated a similar one conducted by Allison and Tarkir (1982). Seat-belt use data were collected from a sample of 4,771 heavy trucks at weigh stations located at Dumfries, VA; Lowell, IN; Slidell, LA; and Northbend, WA. Comparisons were made of seat-belt use by region, by carrier type, by trailer type, and by tractor type. Some carriers' drivers were noted to have significantly higher-than-average use rates. Seat-belt use rates appear to be determined more by individual choice rather than by type of vehicle. Results indicate that seat-belt use has increased from 6 percent in 1982 to 50 percent in 1991.

DOT HS 807 752, NTIS number PB92-115104.

## An In-Service Evaluation of the Reliability, Maintainability, and Durability of Antilock Braking Systems (ABS) for Heavy Truck Tractors

***by L.F. Klusmeyer, A.W. Gray, J.S. Bishop, M. Van Schoiack, J.M. Woods, and W.M. Mahmoud, Southwest Research Institute, San Antonio, TX, March 1992***

This 2-year project studied the reliability, maintainability, and durability of antilock braking systems (ABS) installed on 200 truck tractors that accumulated approximately 40 million revenue miles. Maintenance actions for all 200 ABS-equipped tractors and for 88 comparable tractors without ABS were monitored and recorded. ABS operation was monitored by on-board data recorders. The data collected in this program were generally positive relative to reliability, with some important caveats. Use of high-quality components, especially wiring and electrical connectors, and sustained attention to quality control and detailed aspects of the installation of the system are critical.

DOT HS 807 846, NTIS number PB93-113207.

## Performance Requirements for Large Truck Conspicuity Enhancements

***by P.L. Olson, K. Campbell, D. Massie, D.S. Battle, E.C. Traube, T. Aoki, T. Sato, and L.C. Pettis, University of Michigan Transportation Research Institute, Ann Arbor, MI, February 1992***

The purpose of this program was to define a range of minimally acceptable large truck conspicuity enhancements, using retroreflective materials, that could be used as a basis for revised Federal regulations.

Recommendations were developed for an upgraded marking system using retroreflective tape a minimum of 2 inches in width with a red and white pattern. A continuous or broken strip of this material is recommended along the bottom of the trailer on the sides, with a continuous strip along the bottom on the rear, together with white corner markers at the top where appropriate structure is available.

Recommendations are also offered for minimum retroreflective efficiency levels, taking into account the effects of environmental dirt, aging, and orientation of the marked vehicle.

DOT HS 807 815, NTIS number PB92-146182.

## NHTSA IVHS Plan

***NHTSA, Office of Crash Avoidance Research, August 1992***

This report to Congress describes a comprehensive Agency plan to support the safety-related aspects of Intelligent Vehicle Highway System (IVHS) research, development, and deployment. NHTSA will fulfill its mission by facilitating the development of safety-effective IVHS products and systems. This role encompasses five principal program thrusts: (1) building research tools and compiling a knowledge base; (2) identifying promising crash-avoidance opportunities; (3) demonstrating proof-of-concepts for crash avoidance/mitigation; (4) facilitating development of crash avoidance products toward commercialization; and (5) assessing the safety of mobility-enhancing IVHS concepts and systems. NHTSA's largest IVHS programs will develop advanced technology countermeasure performance specifications; i.e., recommended functional guidelines for optimal performance. The specifications will facilitate industry efforts to develop practical and commercially viable safety systems.

DOT HS 807 850, NTIS number PB93-182640.

## National Advanced Driving Simulator (NADS) Requirements Study, Volume I: Technical Summary

***by David H. Weir and Robert K. Heffley, Dynamics Research, Inc., Torrance, CA, September 1991***

Potential users of the National Advanced Driving Simulator (NADS), a planned state-of-the-art research simulator, were identified and surveyed. Organizations surveyed included vehicle and component manufacturers, state and Federal governments, and research groups. The main areas of interest for these potential users were shown to be vehicle safety, driver/vehicle interaction and human factors, and vehicle and component design and development.

The potential users surveyed indicated hourly cost ranges for simulator use. Tentative research priorities were identified from the survey results. Illustrative research problem statements and estimated cost comparisons were made, considering simulator and full-scale research methodologies.

DOT HS 807 825, NTIS number PB92-189711.

## National Advanced Driving Simulator (NADS) Requirements Study, Volume II: Final Technical Report

***by David H. Weir and Robert K. Heffley, Dynamics Research, Inc., Torrance, CA, September 1991***

This report expands and elaborates on points made in "National Advanced Driving Simulator (NADS) Requirements Study, Volume I:

Technical Summary" (DOT HS 807 825). The technical approach used is explained, and presentation and analysis of the survey results are given, as are raw data and a comparison of research methodologies. Pertinent simulator functional requirements are discussed, and possible high-priority research areas are identified and listed. Example research problem statements are selected and detailed. Also included are the presentation materials used in the site visits, an example survey form, and a list of potential users contacted.

DOT HS 807 826, NTIS number PB92-189729.

## National Advanced Driving Simulator (NADS) Requirements Study

*by R. Wade Allen, Anthony C. Stein, Jeffrey R. Hogue, David G. Mitchell, and Keith J. Owens, Systems Technology, Inc., Hawthorne, CA, November 1991*

This report documents a requirements analysis for a National Advanced Driving Simulator (NADS) facility. The study involved contacting potential users such as vehicle and component manufacturers, state and Federal governments, research groups, and simulation component manufacturers and researchers to determine functional requirements and cost trade-offs for a NADS. A wide range of applications for the NADS was developed, some of which require high-end capability. Research problem statements were also developed. High-end capability implies high operational costs, and several potential users indicated a willingness to pay such costs for selected applications.

DOT HS 807 827, NTIS number PB92-189737.

## Summary of Impoundment and Forfeiture Laws and Practices for DWI-Involved Drivers

*by R.B. Voas, National Public Services Research Institute, Landover, MD, June 1992*

In an attempt to reduce the occurrence of driving by DWI offenders who have had their licenses suspended, 32 states have passed one or more laws that directly affect the offender's vehicle or vehicle plates. Examples of sanctions include impoundment or forfeiture for the vehicle and impoundment or use of special markings for the vehicle plates. A NHTSA-sponsored study, containing a description of the laws, information on their limitations and use, and the feasibility of conducting an impact evaluation for one or more of the laws, was recently completed.

Contact with state, local officials, and others suggested that use of vehicle impoundment and forfeiture is rare, whereas special markings for vehicle plates have been used more often.

DOT HS 807 870, NTIS number PB93-157485.

## The Effects Following the Implementation of an 0.08 BAC Limit and an Administrative Per Se Law in California

*by Research and Evaluation Associates, Washington, DC, August 1991*

On January 1, 1990, California lowered the illegal blood alcohol concentration (BAC) from 0.10 to 0.08. On July 1, 1990, California also implemented an Administrative License Revocation (ALR) law (also known as an Administrative Per Se law). A study was conducted for NHTSA to determine the effects of the reduction in the BAC limit. Additional information was collected regarding the effects of the ALR law.

There were three main components of the study: a survey of the public; analyses of change in Driving Under the Influence (DUI) arrests and alcohol-related fatalities; and an assessment of the operational impact on the organizations involved with DUI offenders. Awareness of the new DUI laws in California is high. Most people are aware of the reduction in the BAC limit, and almost half know the provisions of the ALR law.

The analysis indicated fewer alcohol-related fatalities statewide than projected following implementation of the 0.08 law. NHTSA believes that this reduction is due not only to implementation of the 0.08 law but also to a combined effect of the publicity and enforcement focused on both 0.08 and ALR. Law enforcement agencies reported that there were no substantial procedural problems associated with the 0.08 law for the agencies that deal with DUI offenders.

DOT HS 807 777, NTIS number PB92-160126.

## Responsible Alcohol Service Programs Evaluation: Results of the TEAM Alcohol Management Program in Major League Baseball Stadiums

*by Robert Apsler and Wayne Harding, Social Science Research Enterprises, Lincoln, MA, June 1991*

Techniques for Effective Alcohol Management (TEAM) is a coalition of public and private organizations that promotes responsible alcohol use in sports arenas and other public facilities. TEAM programs are designed to reduce the incidence of drinking and driving at such facilities.

This NHTSA-sponsored research report describes an independent study of TEAM program operations in seven Major League baseball stadiums. Representatives of stadium management were interviewed, and survey data were collected from both employees and fans. Additionally, several stadiums provided some information about concession revenues before and after the TEAM programs were implemented.

Results from management interviews indicated that three factors were critical for successful TEAM implementation: strong management support, involvement of many categories of employees in program implementation, and repeated emphasis of alcohol policies by management and supervisors. Surveys of employees and fans also indicated strong support for the efforts, indicating that the programs were accepted as an effective tool in dealing with alcohol problems, and have helped reduce alcohol consumption by fans.

DOT HS 807 779, NTIS number PB92-129477.

## Lower BAC Limits for Youth: Evaluation of the Maryland .02 Law

***by Richard D. Blomberg, Dunlap and Associates-East, Norwalk, CT, March 1992***

This study was undertaken to determine the effects of special drinking-driving sanctions aimed at youth by evaluating a Maryland law which prohibits driving by those under 21 with a Blood Alcohol Concentration (BAC) of 0.02 or more. The study also examined the extent to which public information and education (PI&E) programs about the sanction would increase its effectiveness.

The research found that the Maryland .02 sanction for youth is a highly effective highway safety countermeasure. As initially implemented, the sanction was associated with a significant reduction of crash-involved drivers under 21 who police officers judged had been drinking. This reduction was attributed to the adoption of the sanction, the "normal" publicity attendant to the passage and implementation of the law, and the imprinting of new licenses with the words "Under 21 Alcohol Restricted." In six experimental counties, the law was accompanied by special public information and education. This was associated with an estimated reduction of about 50 percent in crash-involved-had-been-drinking drivers under 21. The additional project-generated PI&E, which emphasized the penalties for violation of the law, appeared to substantially increase the effectiveness of the sanction.

Technical Summary: DOT HS 807 859, NTIS number PB92-236157. Final Report: DOT HS 807 860, NTIS number PB93-157477.

## The Deterrent Capability of Sobriety Checkpoints: Summary of the American Literature

***by H. Laurence Ross, University of New Mexico, Albuquerque, NM, March 1992***

This study reviews the evaluation literature concerning police sobriety checkpoints in the United States. Nine studies were reviewed that contained reasonable evaluation criteria. Six of the nine studies showed significant positive effects of checkpoints.

The weaknesses of some of the study designs appear to be adequately overcome by the accumulation of positive, consistent findings that visible and well-publicized checkpoints are effective. Checkpoint programs multiply the occasions of interaction between drivers and law enforcement personnel to foster the perception that impaired drivers will be caught and punished. The available evidence supports the conclusion that checkpoints reduce impaired driving if they are conducted frequently and the public is made well aware of them.

DOT HS 807 862, NTIS number PB92-236165.

## Obstacles to Enforcement of Youthful (Under 21) Impaired Driving

***by D.F. Preusser, R.G. Ulmer, and C.W. Preusser, Preusser Research Group, Inc., Bridgeport, CT, February 1992***

Arrest rates of young drivers for impaired driving have been widely reported as low compared to those of older drivers. This study analyzed the arrest and crash data for young drivers nationwide. The study found that young drivers are being arrested for Driving While Impaired (DWI) at rates which are far below their incidence in alcohol-related driver fatal crashes, non-fatal alcohol-related crashes, and roadside surveys of driver impairment.

The report focuses on three primary topics: (1) an analysis of the arrest and crash data; (2) identification of the obstacles preventing effective enforcement of impaired driving by youth; and (3) identification of successful programs and strategies which overcome obstacles to enforcement. The report found that the time and places young people drink are different from those for the older population and are not generally where DWI enforcement resources tend to be deployed. A method for assessing youthful DWI enforcement is described.

DOT HS 807 878, NTIS number PB93-182608.

## A Collection of Recent Analyses of Vehicle Weight and Safety

***by T.M. Klein, E. Hertz, and S. Borener, NHTSA, Office of Research and Development, May 1991***

This report documents the results of an analysis of the effect of car weight on safety. The analysis encompassed a number of crash modes, including fatality risk in single-vehicle nonrollover crashes, serious injury and fatality risk in car-to-car crashes, and serious injury risk in collisions of cars with medium/heavy trucks. The analysis employed logistic regression methods to model the (conditional) risk of serious injury as a function of accident-level and person-level covariates. In these types of crashes, the analysis found statistically significant increases in injury rates ranging from 4 to 14 percent for the reduction in vehicle fleet average weight from 3,700 pounds to 2,700 pounds that occurred in passenger car weight in the 1970s and 1980s.

DOT HS 807 677, NTIS number PB92-115930.

## Air Bag Deployment Characteristics

***by L.K. Sullivan and J.M. Kossar, NHTSA, Office of Research and Development, February 1992***

A study was conducted to examine inflation characteristics of several production air bag systems for the driver's side relative to factors that may be important to the likelihood of injuries occurring as side effects of the inflation process. Tests conducted in a static, non-crash environment consisted of two phases: (1) deployment of the air bags to determine inflation characteristics through analysis of high-speed films, and (2) deployment of the air bags with a 5th-percentile female dummy positioned in front of the restraints to permit observation of air bag/dummy interactions.

Four distinct air bag folding patterns were observed among the nine systems tested. Although peak air bag velocities were similar, the maximum displacements of the leading edge of the air bags were distinctly different for tethered and untethered systems. The air bag folding pattern and the presence of tethers appeared to have significant effects, both singularly and in conjunction, on the observed interactions with the small female dummy. Removal patterns of the powdered chalk from the dummy's face by the air bags' contact appeared to be primarily dependent on these two factors.

DOT HS 807 869, NTIS number PB93-130631.

## Upper Interior Head Protection, Volumes I and II

***by Donald T. Willke, NHTSA, Vehicle Research and Test Center, East Liberty, OH, November 1991***

About 4,000 fatalities and 9,300 serious injuries result each year from occupants' heads striking various upper interior structures. The magnitude of this problem has prompted both government and industry to address the issue of reducing head injuries due to contacts with these structures. NHTSA recently issued a notice of proposed rulemaking on this subject, based on extensive research conducted over the past several years. This two-volume report contains results and findings from much of the research.

In Volume I, "The Development of a Research Test Procedure," a research test procedure for use in evaluating the potential for head injury due to contacts with vehicle upper interior structures is presented. Included are discussions of the selection of a free-motion headform impactor (FMH) and the establishment of various test conditions, such as ranges for impact angles and locations.

In Volume II, "Fleet Characterization and Countermeasure Evaluation," the results of tests conducted to estimate the potential for head injury in the current U.S. fleet are presented. Also included are the results of tests to evaluate the effectiveness of padding as a countermeasure. In addition, this volume contains a comparison of the responses of the FMH to those of a full Hybrid-III dummy and an evaluation of the repeatability and reproducibility of the FMH.

DOT HS 807 865 and DOT HS 807 866, NTIS numbers PB93-113769 and PB93-113772.

## Evaluation of Booster Seat Suitability for Children of Different Ages and Comparison of Standard and Modified SA103C and SA106C Child Dummies

***by E.C. Hiltner, Transportation Research Center, East Liberty, OH, February 1990***

A sled test program was conducted to examine the suitability of shield type booster seats for children spanning the age and size ranges recommended by manufacturers, and to compare the performances of standard 3- and 6-year-old dummies with the performances of dummies that had University of Michigan-Transportation Research Institute (UMTRI) modified abdomens. Testing was conducted to approximate the FMVSS No. 213 test procedure.

For booster seat suitability, nine different booster seats were tested with dummies representing 9-month-old, 3-year-old, and 6-year-old children. FMVSS No. 213's HIC, chest acceleration, and head and knee excursion criteria were used for evaluation purposes only—these were not actual compliance tests.

The booster seats generally proved to be unsuitable for the 9-month-old dummy, with ejection occurring 78 percent of the time. All tests with the 3-year-old dummy fell within FMVSS No. 213 criteria boundaries; however, the booster seats generally did not provide adequate restraint for the 6-year-old—the dummy's head exceeded the 32-inch excursion criterion for seven of the nine seats, and structural failure occurred with two seats. The standard and modified 3- and 6-year-old dummies were tested with eight different booster seats. The differences in dummies' performances (i.e., head excursions, dummy ejection) were important, but they were not statistically significant.

DOT HS 807 844, NTIS number PB92-226331.

## Analysis of Hybrid III Lower Leg Instrumentation and an Associated Injury Criterion

***by Roger A. Saul and David S. Zuby, NHTSA, Vehicle Research and Test Center, East Liberty, OH, April 1992***

This report describes a series of static and dynamic tests conducted on the optimal Hybrid III lower leg instrumentation. The tests were conducted to determine the accuracy of the lower leg instrumentation measurements, the ability to calculate a maximum bending moment, and the feasibility of conducting a single-impact lower-leg calibration.

DOT HS 807 871, NTIS number PB93-182616.

## Development of a Facial Injury Test Procedure— Part I: Facial Injury Test Device Evaluation Part II: NASS Facial Injury Accident Data Analysis

***by Roger A. Saul and David S. Zuby, NHTSA, Vehicle Research and Test Center, East Liberty, OH, December 1991***

The work described in this report was initiated amid concerns that increased belt use would increase the frequency of facial injuries resulting from steering wheel contact. By 1986, three different devices had been developed to assess facial injuries. The Transport and Road Research Laboratory (TRRL) had developed a honeycomb test procedure and a safety steering wheel. Other devices were also being proposed by Transport Canada and Volvo/Collision Safety Engineering (CSE). The device proposed by Transport Canada was a methyl acrylic frangible dummy facial insert, while the Volvo/CSE device had piezoelectric pressure sensors incorporated into the dummy head form. These three devices were tested to determine the ability to assess injury under impact conditions that duplicated cadaver facial testing.

On the basis of the tests, the TRRL procedure was selected for further evaluation. The TRRL honeycomb procedure was evaluated in both static and dynamic loadings. The procedure was then used to evaluate the TRRL safety steering wheel and production steering wheels. The honeycomb test procedure indicated that the safety steering wheel would be expected to produce fewer facial injuries than standard production wheels. Comparison with cadaver tests, however, indicated that the safety wheel provided little benefit over standard production wheels, bringing the validity of the TRRL honeycomb procedure into question.

Finally, an analysis of NASS 1981-85 accident data was conducted to reveal facial injury severities and mechanisms occurring for belt-restrained drivers as a result of steering wheel contact. The results showed that more than 90 percent of all facial injuries were AIS 1 severity, that 20 percent of the injuries were facial fractures, and that 35 percent of the facial fractures were broken, fractured, or missing teeth.

DOT HS 807 855, NTIS number PB92-239474.

## Evaluation of Chest Deflection Measurement Band

***by Alena V. Hagedorn, Transportation Research Center, and Howard B. Pritz, NHTSA, Vehicle Research and Test Center, East Liberty, OH, July 1991***

The External Peripheral Instrument for Deformation Measurement (EPIDM), also known as the "chest band," was evaluated to determine its effectiveness in reproducing the cross-sectional shape of the chest during safety testing. The standard 16-gauge chest band was evaluated, and a 37-gauge chest band prototype was then procured for comparison. The two chest bands were tested under static and dynamic conditions to ascertain the impact of additional strain gauges on the performance of the device. The results of the tests revealed that the 37-gauge chest band is capable of reproducing complex shapes, as may be encountered in vehicle safety testing, while the standard 16-gauge chest band does not have enough gauges for accurate shape reconstruction.

DOT HS 807 838, NTIS number PB92-203884.

## Newborn Infant Dummy Development and Evaluation

***by Edward Hiltner, NHTSA, Vehicle Research and Test Center, East Liberty, OH, February 1991***

Three dummies representing newborn infants were evaluated for use in testing infant automotive safety restraints. Two existing dummies were procured and another was developed for the purpose of the evaluation. The dimensions of each dummy were compared to the anthropometric and anthropomorphic characteristics of an approximately 50th-percentile newborn infant. Repeated crash simulations on a high-acceleration sled were performed to study each dummy's response in rearward facing and car bed type safety restraints.

DOT HS 807 738, NTIS number PB92-187764.

## Evaluation of the BioSID and EuroSID-1, Volumes I through VI

***by David S. Zuby, Transportation Research Center, East Liberty, OH (Vols. I, III, IV, V, VI), and Donald T. Willke, NHTSA, Vehicle Research and Test Center, East Liberty, OH (Vol. II), July 1991***

In the October 1990 rule to upgrade Federal Motor Vehicle Safety Standard Number 214 (FMVSS 214), the NHTSA side impact dummy (SID) was specified for use in the required side impact crash tests. Two alternative SID development efforts were in progress at that time. The EuroSID-1 is the result of a 2-year European effort to improve the original EuroSID, which NHTSA had previously evaluated. More recently, General Motors, in conjunction with the Society of Automotive Engineers, initiated the development of the BioSID. In July 1989, NHTSA began a research program to evaluate the BioSID and compare it to the SID. This six-volume report contains the results of that effort.

In Volume I, "Padded Wall Comparison Tests: BioSID, EuroSID-1, and SID," a comparison of the responses of the three dummies in a series of 32-km/hr sled tests is presented. In this series, each dummy was subjected to rigid and padded-wall impacts, using a wide range of padding stiffness. In Volume II, "Analysis of the SID and BioSID Side Impact Crash Tests," a comparison of SID and BioSID responses in FMVSS 214 type crashes is presented.

Other aspects of the program included establishing preliminary calibration response requirements for the BioSID (Volume III, "BioSID Calibration Data Analysis"), evaluating the repeatability and reproducibility of the BioSID (Volume IV, "BioSID Repeatability and Reproducibility"), and evaluating the durability of the BioSID through the extensive test program (Volume V, "BioSID Durability Analysis").

Finally, BioSID responses were compared to the appropriate International Standards Organization's (ISO) guidelines (Volume VI, "Comparison of the BioSID s/n 01 & 02 Dynamic Responses with ISO Recommendations for Side Impact Dummy Responses").

Volume I, DOT HS 807 807, NTIS number PB92-230273;
Volume II, DOT HS 807 808, NTIS number PB93-182624;
Volume III, DOT HS 807 809, NTIS number PB92-230283;
Volume IV, DOT HS 807 810, NTIS number PB92-230291;
Volume V, DOT HS 807 811, NTIS number PB93-183341;
Volume VI, DOT HS 807 812, NTIS number PB92-230309.

## Light Vehicle ABS Performance Evaluation

***by E. Hiltner, C. Arehart, and R. Radlinski, NHTSA, Vehicle Research and Test Center, East Liberty, OH, December 1991***

This report describes tests conducted on ten light vehicles (seven passenger cars, two light trucks, and one van) to evaluate the improvement in braking performance and vehicle control resulting from each vehicle's antilock braking system (ABS). Tests were conducted on both four-wheel systems (systems that control the brakes on all four wheels) and rear-axle-only systems (systems that control only the rear axle brakes). The tests compared stopping distances and vehicle stability with and without the ABS system operational for various vehicle and surface conditions.

The results showed that in all cases evaluated, the ABS system provided benefits by improving vehicle stability. Also, in all of the four-wheel system tests, there was an improvement in vehicle directional control. On all the surfaces tested except gravel, the stopping distance with ABS was better or the same as without the system. These results, however, are for a skilled test driver; a "typical" driver in an emergency situation would likely not be able to match the performance of the ABS system.

DOT HS 807 813, NTIS number PB92-161884.

## The Effect of Aftermarket Linings on Light Vehicle Braking Performance

***by R. Radlinski, NHTSA, Vehicle Research and Test Center, East Liberty, OH, July 1991***

This report describes testing to determine the effect of installing aftermarket linings on light vehicles. The study was conducted in two phases. In the first phase, approximately 300 in-use vehicles were rented from consumers and tested to determine their braking efficiency. In the second phase, four vehicles were instrumented and equipped with various sets of original equipment (OE) and aftermarket linings. Braking efficiency and fade resistance were measured after the linings were burnished.

The results of the first phase did not show significant differences between the braking efficiencies of vehicles equipped with OE linings and those equipped with aftermarket linings. The number of vehicles tested with aftermarket linings, however, was relatively small. The second phase of testing showed that some of the aftermarket linings resulted in a degradation in braking efficiency, caused rear wheels to lock before fronts, or reduced fade resistance compared to the OE linings.

DOT HS 807 835, NTIS number PB92-188580.

## Vehicle Dynamics Simulation and Metric Computation for Comparison with Accident Data

***by Gary J. Heydinger, Transportation Research Center, East Liberty, OH, March 1991***

This document describes a program of simulating vehicle handling responses and computing a large variety of dynamic response metrics (measures of vehicle response). The simulation program was performed at NHTSA's Vehicle Research and Test Center. The objective of the work was to compute, via digital computer simulation, vehicle response metrics for the purpose of comparison with accident statistics.

This report describes the vehicle dynamics simulation used for generating the directional response metrics. The report outlines the procedures used for determining the vehicle parameters required for use in the simulation model, and the vehicle maneuvers that were simulated in order to generate response metrics. Lastly, the report provides a description of the actual metrics computed, as well as descriptions of the understeer plots and frequency response curves generated for each vehicle.

DOT HS 807 828, NTIS number PB92-185008.

## Evaluation of NHTSA Light Vehicle Handling Simulations

***by Jeffrey P. Chrstos and Gary J. Heydinger, Transportation Research Center, East Liberty, OH, August 1992***

The focus of the evaluations described in this report is each simulation's ability to accurately predict light vehicle responses during flat road handling and crash avoidance maneuvers. Each simulation is first described on an analytical basis. The overall modeling approach is described, along with detailed descriptions of the modeling of the vehicle subsystems. For each simulation, any areas found to be inadequately modeled are reported. The ability of each simulation to predict flat road vehicle responses is evaluated by comparing the simulation predictions to experimentally measured vehicle responses. Comparisons are made in both the time and frequency domains.

DOT HS 807 868, NTIS number PB93-113710.

## Analysis of VASCAR

***by J. Gavin Howe, Transportation Research Center, East Liberty, OH, May 1991***

This study is part of an effort by NHTSA to determine the accuracy of the VASCAR-plus speed measurement device. VASCAR-plus is used extensively for speed law enforcement by state and local police. VASCAR-plus calculates average speed using the basic formula: Speed = Distance/Time.

The VASCAR-plus manual claims an overall speed measurement accuracy of ±1 percent, but the accuracy was recently challenged. This study determined the accuracy of VASCAR-plus time, distance, and speed measurements. Two VASCAR-plus units were electronically tripped (no human operator) to determine timing accuracy. Six VASCAR-certified officers participated in a study to determine VASCAR-plus distance measurement accuracy. Eight VASCAR-certified officers participated in a series of studies to determine VASCAR-plus speed measurement accuracy. The results of show that VASCAR-plus does not have an overall speed measurement accuracy of ±1 percent, but that a +2 mph upper 90th percentile tolerance limit (95 percent of the speed errors are less than +2 mph) is achievable when the speed measurement is 4 seconds for stationary methods (angular and parking), and 5 seconds for moving methods (following and approaching from the rear).

DOT HS 807 748, NTIS number PB92-125178.

# Recent Research Contracts

This section identifies recently negotiated contracts and interagency agreements for research activities. It identifies the contractor, project title, contract number, and NHTSA contact person. It also briefly describes the purpose of the research activity.

## Contracts Awarded by the Office of Crashworthiness Research:

The *Performance Evaluation of Crash and Sled Testing Data* interagency agreement was awarded to the Volpe National Transportation Systems Center to provide for crash testing in offset frontal and other crash modes, with several dummy sizes and at test speeds around 35 miles per hour.

Contract No. HS-176(30).
For information, contact
Carl Ragland at (202) 366-4728.

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The *Moving Deformable Barrier Side Impact Testing for LTVs* contract was awarded to Mobility Systems and Equipment to evaluate side impact performance of light trucks and vans and to investigate potential new test procedures.

Contract No. DTNH22-87-C-07168.
For information, contact
H. Clay Gabler at (202) 366-4705.

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The *Rollover Studies* interagency agreement was awarded to Wright-Patterson A.F.B. to conduct rollover crash tests and computer modeling of occupants' motion during rollover.

Contract No. DTNH22-90-X-07357.
For information, contact
Arnold Johnson at (202) 366-4716.

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The *Evaluation of High Performance Frontal Crash Tests* interagency agreement was awarded to the Volpe National Transportation Systems Center to develop computer simulation models of offset frontal crashes, using crash test data for model validation.

Contract No. HS-176(39).
For information, contact
Carl Ragland at (202) 366-4728.

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The *Crashworthiness Accident Data Analysis* contract was awarded to Comsis Corporation to provide analytical support for problem identification, definition of injury mechanisms, and development of test procedures and countermeasures for several crashworthiness programs.

Contract No. DTNH22-88-C-07116.
For information, contact
Catherine McCullough at
(202) 366-4734.

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The *Develop a Finite Element Model of a Passenger Vehicle* contract was awarded to EASI, Inc. to develop a finite element model of a 1990 model year Ford Taurus for analysis of frontal and offset frontal crash tests.

Contract No. DTNH22-92-R-07323.
For information, contact
Stephen Summers at (202) 366-4712.

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The *Crashworthiness of Lightweight Automotive Structures* cooperative agreement was awarded to West Virginia University to develop and implement a comprehensive modeling and test program to demonstrate light-weight, superior performance automotive structures.

Contract No. DTNH22-92-Y-07423.
For information, contact
H. Clay Gabler at (202) 366-4705.

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The *Motor Vehicle Impact Injury Mechanisms in Children* cooperative agreement was awarded to Children's National Medical Center to collect injury information and crash data to assist in evaluating child restraint systems.

Contract No. DTNH22-91-Y-07350.
For information, contact
Nopporn Khaewpong at
(202) 366-4703.

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The *Injury Causes and Cost of High Speed Car Crashes* cooperative agreement was awarded to the Trauma Center, University of Medicine and Dentistry of New Jersey, to collect information on injuries to lower extremities and crash data to investigate injuries to adult occupants in severe crashes.

Contract No. DTNH22-92-Y-07340.
For information, contact
Nopporn Khaewpong at
(202) 366-4703.

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The *Further Development and Evaluation of Functional Capacity Index* grant was awarded to Johns Hopkins University to develop an index to assess changes in human functional capacity—e.g., walking, bending, eating, and cognition—as a result of injuries sustained in a motor vehicle crash.

Contract No. DTNH22-89-Z-06019.
For information, contact
Stephen Luchter at (202) 366-2576.

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The *Modeling and Analysis of Human Thorax During Crashes* interagency agreement was awarded to the Volpe National Transportation Systems Center to develop a finite element model of the human thorax and investigate its response to loads imposed by restraint systems.

Contract No. HS-176(38).
For information, contact
Mike Kleinberger at (202) 366-4698.

## Contracts Awarded by the Office of Driver and Pedestrian Research (now the Office of Program Development and Evaluation, Office of Traffic Safety Programs):

The *Driving Practices/Performance Capability in Iowa 65+ Rural Study* interagency agreement was awarded to the National Institute on Aging. Its purpose is to conduct a survey of older drivers in rural Iowa regarding driver practices by piggybacking on a continuing survey of their health status.

Contract No. DTNH22-91-X-07471.
For information, contact
John Eberhard at (202) 366-5595.

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The *Problem Drinker Assessment Instrument Validation* contract was awarded to Mid-America Research Institute to validate both adult and adolescent problem drinker assessment instruments. This study obtains recommendations from experts in alcohol screening and abuse to establish validation criteria. It then compares the performance of subjects on various screening (assessment) instruments against the validation criteria.

Contract No. DTNH22-90-C-07287.
For information, contact
James Frank at (202) 366-5593.

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The *Insurance Sanctions as a Countermeasure for DWI* contract was awarded to the Mid-America Research Institute to determine whether a reduction in driving after drinking occurs when information is presented to the general driving public about the heavy insurance penalty consequences associated with a DWI conviction.

Contract No. DTNH22-89-C-07007.
For information, contact
Marvin Levy at (202) 366-5597.

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The *Motivating Anti-DWI Behavior Using Existing Values* contract was awarded to the Pacific Institute for Research and Evaluation to identify important existing values of youths and adults, and to determine what anti-drinking and driving messages and incentives can be linked to their values to motivate them to avoid alcohol-impaired driving.

Contract No. DTNH22-91-C-07005.
For information, contact
Amy Berning at (202) 366-5599.

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The *Norms—Decision Basis* contract was awarded to the National Public Services Research Institute to identify the basis of people's drinking and driving decision and to determine which specific changes are needed for persons to accept anti-DWI principles as norms of behavior.

Contract No. DTNH22-91-C-07128.
For information, contact
Amy Berning at (202) 366-5599.

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The *Review and Analysis of Community Traffic Safety Programs* contract was awarded to Preusser Research Group. Community Traffic Safety Programs (CTSPs) are local organizations devoted to solving one or more of the community's traffic safety problems. This project is to examine CTSPs on a nationwide basis to identify information that will enable NHTSA to develop new CTSPs and enhance existing ones.

Contract No. DTNH22-91-C-07017.
For information, contact
Alfred Farina at (202) 366-5585.

## Contracts Awarded by the Office of Crash Avoidance Research:

The *Human Factors Evaluation of Vehicle Subsystem Performance* contract was awarded to CAE-Link Corporation to measure the extent of headlight mis-aim on a sample of vehicles in use, including cars, pickups, and vans, and also to measure voltages on rear stop lamps.

Contract No. DTNH22-90-D-07010.
For information, contact
Michael Perel at (202) 366-5675.

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The *Effects of Light Truck and Roadside Characteristics on Rollover* contract was awarded to the University of Missouri at Columbia to investigate the dynamics of several vehicles in maneuvers leading to rollover, and to compare them with computer simulation results.

Contract No. DTNH22-89-C-07005.
For information, contact
José Bascuñana at (202) 366-5674.

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The *Quantitative Characterization of Vehicle Motion Environment* cooperative agreement was awarded to the University of Michigan Transportation Research Institute to develop a portable system to capture the time histories of vehicles in a specific section of highway, including, for example, sizes, positions, and yaw angles, and to analyze their time-varying motions.

Contract No. DTNH22-92-Y-07319.
For information, contact
Paul Spencer at (202) 366-5668.

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The *Heavy Vehicle Driver Workload Assessment* contract was awarded to Battelle Memorial Institute to develop workload evaluation protocols that could be applied to new technologies being implemented in heavy vehicles—e.g., navigation, trip logging, and communication.

Contract No. DTNH22-91-C-07003.
For information, contact
Michael Goodman at (202) 366-5677.

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The *Visibility from Vehicles Research* contract was awarded to the Ketron Division of the Bionetics Corporation to develop a test protocol for evaluating vehicle indirect visibility systems—e.g., mirrors—in terms of driver performance.

Contract No. DTNH22-91-C-07000.
For information, contact
Michael Perel at (202) 366-5675.

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The *In-vehicle Crash Avoidance Warning Systems: Human Factors Considerations* contract was awarded to Comsis Corporation to develop human factors guidelines for electronic warning systems that can help alert drivers to impending collisions.

Contract No. DTNH22-91-C-07004.
For information, contact
Michael Perel at (202) 366-5675.

The *Vehicle-based Driver Status/Performance Monitoring* contract was awarded to Virginia Polytechnic Institute to develop, using a driver simulator, vehicle-based detection algorithms for reduced driver performance, especially drowsiness.

Contract No. DTNH22-91-Y-07266.
For information, contact
Ronald Knipling at (202) 366-4733.

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The *Multipin Tractor/Trailer Electrical Connector* contract was awarded to Cole Hersee Co. to develop a prototype design for a multipin tractor/trailer electrical connector and to produce ten sets for evaluation. This design is to provide increased electrical power and signalling/control capability.

Contract No. DTNH22-91-C-07070.
For information, contact
Robert Clarke at (202) 366-4664.

The *Heavy Truck Crashworthiness—Joint Industry/Government Project* contract was awarded to the Society of Automotive Engineers to develop the basis for SAE-recommended practices and test procedures to gauge the crashworthiness performance of heavy truck occupant restraints, interior components, and cab structures.

Contract No. DTNH22-91-C-07297.
For information, contact
Robert Clarke at (202) 366-4664.

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The *Truck Tire Characterization—Joint Government/Industry Effort* contract was awarded to the Society of Automotive Engineers to measure characteristics of heavy truck tires under several conditions—including speed, load, tire wear, and turn angle (zero to six degrees)—in an indoor laboratory facility and on an outdoor surface.

Contract No. DTNH22-92-C-17189.
For information, contact
James Brittell at (202) 366-5678.

The *Development of a Portable Driver Data Acquisition System for Human Factors Research* interagency agreement was awarded to the U.S. Department of Energy, Oak Ridge National Laboratory, to design and construct a prototype of a data acquisition system for incorporation in any vehicle to collect human factors/driver performance data.

Contract No. DTNH22-92-X-07453.
For information, contact
Michael Goodman at (202) 366-5677.

## Contracts Awarded by the Volpe National Transportation Systems Center for NHTSA

The *SBIR Clipboard Computer* contract was awarded to Data Analysis & Testing Associates to develop and test portable hand-held clipboard computers with supporting software and services for automating traffic accident data collection.

Contract No. DTNH22-90-X-07131.
For information, contact
Sam Luebbert at (202) 366-2676.

U.S. Department
of Transportation

**National Highway
Traffic Safety
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