

NHTSA's VEHICLE AGGRESSIVITY AND COMPATIBILITY RESEARCH PROGRAM

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ABSTRACT

The National Highway Traffic Safety Administration's vehicle aggressivity and compatibility research program explores the global evaluation of vehicle crashworthiness designs as a means of minimizing injuries in the design vehicle while simultaneously minimizing injuries in the vehicle's collision partners. The program pursues both an analytic investigation of fleet wide vehicle performance as the basis for global optimization and pursues an experimental component as the foundation for validation of computer models and tools. This paper presents an overview of this research program along with a summary of the results achieved to date.

INTRODUCTION

The crashworthiness performance of passenger vehicles traditionally has been evaluated on the results of well defined laboratory crash tests. These tests, by their nature, focus on evaluating and minimizing injuries to the occupants in the subject vehicle. However, pursuing an optimal crashworthiness performance without regard to the crashworthiness performance of the collision partners can lead to very aggressive, incompatible vehicle designs. Particularly, design modifications which minimize injuries in one vehicle have the potential of actually accentuating injury levels in the vehicle's collision partner.

The purpose of this research program is to investigate the problems of vehicle compatibility in multi-vehicle crashes. The initial focus of the program is to identify and characterize compatible vehicle designs that will result in correspondingly large reductions in crash related injuries. While not a new idea, both the National Highway Traffic Safety Administration (NHTSA) and other international government agencies have recently renewed efforts to study compatibility as a means of reducing crash-related injuries below those levels achievable by equipping the fleet with safety belt and supplementary air bag restraints.

In the United States, there are several important research initiatives which are considering compatibility specifically and the overall fleet wide crashworthiness of vehicles more generally. First, within the last three years, the NHTSA Motor Vehicle Safety Research Advisory

Committee's Crashworthiness Subcommittee established a special working group on Vehicle Aggressivity and Fleet Compatibility. This working group was established as a result of the concern about the structural modifications being made by vehicle manufacturers in response to frontal offset crash testing being conducted throughout the world. These modifications included strengthening the vehicle structure in order to reduce the level of intrusion observed in the offset crashing. The stiffened structures have the potential of increasing the severity of side impact crashes. Also, there has been a recent concern over the increasing use of light trucks and vans (LTVs) as personal use vehicles. In the United States, LTVs have accounted for over one-third of new vehicle purchases. This group of vehicles generally is heavier and has stiffer structures than the passenger cars. The working group is developing a system model for evaluating vehicle crashworthiness on a fleet wide basis with the goal of identifying desirable vehicle characteristics for the various vehicle types and weight classes that will lead to improved fleet performance in the fleet crash environment. A second initiative in the United States is the Partnership for a New Generation of Vehicles (PNGV) program, which has the goal of developing new technologies to triple fuel economy and to reduce exhaust emissions while maintaining crashworthiness performance. To achieve this goal, it is anticipated that a forty percent reduction in vehicle weight may be required in the PNGV vehicles. The introduction of such a downsized vehicle could lead to a safety problem due to the mass differences. Also, power train technologies are under consideration that may result in vehicle construction that is different than that utilized for present day vehicles. Finally, the Advanced Research Programs Administration (ARPA) of the Department of Defense is directing the development of new generation of electric vehicles (EVs) which will meet a strict zero emission vehicle criteria. Some of the vehicles under development have ultra-light and ultra-stiff structures which may prove extremely aggressive. ARPA and NHTSA are conducting a joint program to evaluate the crashworthiness of these EVs.

The NHTSA's vehicle aggressivity and compatibility program explores the global evaluation of vehicle impact designs as a means of minimizing injuries in the design

vehicle while simultaneously minimizing injuries in its collision partners. The program pursues both an analytic investigation of fleet wide vehicle performance as the basis for global optimization, and an experimental component as the foundation for validation of computer models and tools. This paper presents an overview of this research program along with a summary of results achieved to date.

PROGRAM GOALS

The goals of the agency's research program are two-fold. The near-term goal is to identify and demonstrate the extent of the problem of incompatible vehicles in multi-vehicle collisions. The focus of this goal is to identify and characterize compatible vehicle designs with the overall objective that improved vehicle compatibility will result in correspondingly large reductions in crash related injuries. Based on the findings of the near-term efforts, the longer term goal will be to support improvements in vehicle compatibility. The longer term goal is develop test procedures that evaluate vehicle aggressivity and compatibility and that would lead to the development of appropriate countermeasures that reduce the aggressivity and increase the vehicle compatibility.

The objectives of the first phase of research are to identify those vehicle structural categories, vehicle models, or vehicle design characteristics which are relatively incompatible (i.e., too "hard" or too "soft") based upon accident statistics and crash test data; to develop a comprehensive computer simulation package for the system-wide crashworthiness evaluation of vehicle structures and occupant restraints; and to experimentally and analytically demonstrate the relationship between occupant injury and vehicle structural compatibility.

GENERAL TASK DESCRIPTIONS

This program is composed of the following six tasks: problem definition; global safety systems optimization model; frontal-side compatibility; compatibility of low mass, ultra-stiff electric vehicles; evaluation of compatible crush zone; and geometric compatibility. These are described as follows:

Problem Definition

Accident data is being examined to determine the extent of the aggressivity and compatibility problem and to explore the relationship between vehicle design and fleet compatibility through correlation of accident statistics and vehicle design parameters (e.g., hood profile, mass, and frontal stiffness) extracted from crash test data or physical

measurements. For this study, aggressivity is defined to be the number of fatalities/injuries in the vehicles struck by the subject vehicle divided by the number of subject vehicle registrations. This metric will measure the probable outcome in the struck vehicle, given that a multi-vehicle accident has occurred with the subject vehicle. The subtasks include:

Aggressivity Ranking - This task is to use the Fatal Accident Reporting System (FARS) and the National Accident Sampling System (NASS) accident statistics databases to rank all passenger vehicles, cars and LTVs, by their relative aggressivity. The results of this rating will be examined to determine the relative aggressiveness of different vehicle body types, to quantify the effect of weight incompatibility, and to search for differences in aggressiveness among vehicles of the same weight class.

Development of Alternate Aggressivity Metrics - One obstacle to quantifying the aggressivity of a vehicle is the lack of an accepted measure of aggressivity. As previously mentioned, aggressivity has been defined as the number of fatalities/injuries in the vehicle struck by the subject vehicle divided by the number of subject vehicle registrations. Several improvements to this measure have been proposed. This task is evaluating several variations on the base aggressivity metric to include the effect of "other car" restraint usage, normalizing on accident severity, and restricting the metric to prescribed accident modes, e.g., frontal-side impacts and frontal-frontal impacts.

Correlation of Vehicle Design vs. Aggressivity - This task is examining the relationship between vehicle aggressivity and measurable vehicle design parameters. The study is focusing on mass, geometrical, and structural aggressivity factors. Geometrical factors include the hood profile, sill height, and bumper height. Structural factors include the frontal stiffness as determined from crash tests and engine location (transverse right or transverse left). Structural stiffness are being determined from SISAME model syntheses from frontal-barrier crash tests [1]. Sources of geometrical data will include the NHTSA Vehicle Parameter Database [2].

Frontal-Side Compatibility vs. Side Impact Injury - The task is examining the relationship between compatibility and occupant injury in side impacts. In the early 1980s, the Vehicle Research and Test Center (VRTC) conducted an extensive side impact crash test program in which Volkswagen Rabbits were side struck with modified moving deformable barriers (MDBs). This program showed a strong correlation between occupant response and MDB stiffness and profile. This study will determine if the accident statistics support a similar finding [3].

Door Sill-Bumper Height Incompatibility - This task is examining the effect of incompatibility between bumper height/vehicle hood profile and door sill height. This task was begun in 1990 at Volpe National Transportation Systems Center (VNTSC) under sponsorship of NHTSA. The effort investigated the correlation between occupant injury as reported in NASS and vehicle sill-bumper mismatch as inferred from vehicle specification sheets and measurement.

Global Safety Systems Optimization Model

In this task, a large scale systems model is being developed to evaluate vehicle crashworthiness based on the safety performance of the vehicle when exposed to the entire traffic accident environment, i.e., across the full spectrum of expected collision partners, collision speeds, occupant heights, occupant ages, and occupant injury tolerance levels. Optimal crash countermeasure designs must successfully balance two potentially conflicting objectives: (1) maximizing passenger protection in the vehicle under design, and (2) optimizing compatibility with other vehicles in the fleet mix. To meet these objectives, vehicle crashworthiness should be evaluated, not just on the basis of a few test configurations or test speeds, but also on the safety performance of the vehicle when exposed to the entire traffic accident environment; i.e., across the full spectrum of expected collision partners, collision speeds, occupant heights, occupant ages, and occupant injury tolerance levels. Note that, as in the real world accident environment, this will expose the design vehicle both to vehicles less compatible and vehicles more compatible with the design vehicle.

The means of evaluating vehicle crash performance on a system-wide basis was first accomplished by the Safety Systems Optimization Model developed by Ford Motor Company and later enhanced by the University of Virginia [4,5]. Starting with SSOM as a foundation, the VROOM (Vehicle Research Optimization Model) computer model, as proposed below, will take full advantage of recent dramatic improvements in vehicle and occupant models, newly developed injury criteria, and a comprehensive projection of the accident environment for the years 2000-2005. Where possible, VROOM will also explore the feasibility of implementing promising algorithms from the Volkswagen ROSI system-wide optimization model [6].

In this task, a large scale systems model is being developed for global evaluation of vehicle impact designs as a means of minimizing injuries in the design vehicle while simultaneously optimizing performance in crashes with its collision partners.

Enhanced Vehicle Models - During the last few years, the availability of the DYNA-3D finite element (FE) code has triggered a revolution in vehicle and occupant impact modeling. Unlike the lumped-mass models traditionally used in crashworthiness research, DYNA-3D models allow the complex dynamics of vehicle structural impact to be described with uncompromised detail and simulated with vastly improved fidelity to real world crash events. Both the vehicle manufacturers and NHTSA have comprehensive efforts underway to develop increasingly complex FE models of vehicle structures, occupant restraints, and occupants.

The objective of this task is to incorporate these promising new vehicle models into VROOM. The new vehicle FE models will be utilized in two ways. First, the models will be used to study vehicle-vehicle compatibility in a specific accident configurations, with specific collision partners, and specific impact speeds. However, while FE models are potentially very accurate and geometrically fidelic, FE models are prohibitively expensive to execute for global design optimization. A typical VROOM run requires 100,000 simulations. Even at an unrealistically fast 8 hours for a FE simulation of a car-to-car accident on a parallel machine, an optimization based exclusively on FE models would require nearly 800,000 hours (nearly 100 years) to complete.

The second application for the FE models will be to generate sophisticated, and faster running, lumped mass models for optimization. Optimization using lumped mass models will provide broad design directions (e.g., double the aft frame stiffness) for improved crashworthiness. After optimization, these lumped mass results can be used to design modified vehicle components and corresponding FE models for an optimized structure.

Because only a limited number of validated FE models are currently available to NHTSA, VROOM will initially consist of a mix of FE models and the more traditional lumped-mass models extracted from crash test data. To enable near-term analyses with VROOM, initial efforts are being focused on constructing lumped-mass SISAME models of late model passenger vehicles. Simultaneously, this task is developing and adapting FE vehicle models for use in VROOM. Specific subtasks are as follows:

1. Develop Generic Models of Late Model Year Vehicles

- This task will construct DYNA-3D and SISAME models for generic vehicles in each of the five VROOM weight categories: <2,000 lb, 2,500 lb, 3,000 lb, 4,000 lb, >5,000 lb. A FE and a lumped mass model(s) are being developed for the reference vehicle, the Ford Taurus, to be suitable for use in simulating frontal-barrier, full frontal-frontal, frontal-

frontal offset, and frontal-side impacts. Initial lumped mass models will be developed based upon available crash test data. After completion of FE models, enhanced lumped mass models will be extracted from FE simulations.

2. Develop Models of the PNGV Vehicles - The Partnership for a New Generation of Vehicles (PNGV) has selected three target vehicles: the Ford Taurus, the Dodge Intrepid, and the Chevrolet Lumina. This task is developing FE and lumped-mass models of these three vehicles.

All models will provide simulation of frontal-barrier, full frontal-frontal, frontal-frontal offset, and frontal-side impacts. The models will be exercised to develop approximating functions for input to VROOM. Initial lumped mass models are being developed from the available crash test data. After completion of FE models, enhanced lumped mass models will be extracted from FE simulations.

3. Vehicle-specific Models - Rather than represent all vehicles with the generic vehicle models described above, this task will investigate the possibility of increasing VROOM accuracy by augmenting the generic models with models specific to high-volume vehicles (e.g., the Chrysler minivan or the Honda Accord). Under this systems model, each high volume vehicle would be characterized by its own model, while less frequently encountered vehicles would be represented by one of the generic models.

4. Other FE Models - This task will develop and extend other FE models for use in VROOM and for use as the basis for experimentally evaluating the relationship between aggressive structures and occupant injuries.

Enhanced Occupant Models - Improved occupant models are being constructed for installation in VROOM. Like the vehicle models described above, VROOM will initially consist of a mix of lumped-mass MADYMO models and DYNA-3D models. Initial efforts are concentrated on providing MADYMO models to complement the lumped-mass SISAME models. Simultaneously, modeling development will proceed to construct FE models of both crash test dummies and human occupants.

LTV Models - SSOM was developed in the 1970s when the fleet mix was dominated by passenger cars. Reflecting this fleet mix, the SSOM model accident environment is limited to passenger cars grouped into four different weight categories. This task is extending the VROOM package to include LTVs as well as passenger cars. The LTV segment will be disaggregated into several

individual LTV body types to include pickup trucks, minivans, full-size vans, and sport utility vehicles. The following tasks are to be accomplished: (1) update accident statistics for the combined car/LTV fleet, (2) construction of generic vehicle and occupant models for each LTV category, and (3) validation of models against actual accident experience.

Updated Biomechanical Transforms - Injury criteria in SSOM are currently limited to Head Injury Criterion (HIC) and Chest Severity Index. This task will update the biomechanical transforms to include the Thoracic Trauma Index (TTI), pelvic fracture criteria, and lower extremity injury criteria. Injury criteria which are based on occupant age, gender, or stature may also require modification of the accident environment description to include the corresponding probability distributions.

Additional Impact Modes - The accident environment in SSOM is currently described by the majority of potential accident configurations or impact modes. However, a number of less frequent accident modes are not represented in the model. This task will add the following accident modes to VROOM: (a) Front-Rear, (b) Front-Side (oblique), (c) Front-Side (T-type collision), and (d) Side-Roadside object/barrier Collisions.

Additional Collision Partners - This task will add two new categories of collisions to VROOM: Heavy Trucks and Pedestrians.

Improved Accident Statistics - This task is developing a projection of accident statistics for the years 2000-2005 for use in VROOM. One challenging aspect of this task is the development of the distribution of impact speeds based on NASS delta-Vs.

Review of Safety Performance Requirements - Currently, SSOM optimizes vehicle designs without regard to FMVSS regulations, e.g., the FMVSS No. 208 frontal barrier crash test. Conceivably, SSOM could recommend a vehicle design which minimizes injuries but fails a FMVSS requirement. This task will evaluate the relationship between FMVSS regulations and optimal crashworthiness design. Should FMVSS regulations lead to sub-optimal designs, this task will evaluate various countermeasures to produce improved safety performance.

Frontal-Side Impact Compatibility

This task is developing a problem definition statement, and is developing test conditions and test devices for crash tests which explore the effectiveness of increasing compatibility in reducing occupant responses for the side impact crash mode. The objective of this task is to determine the relationship between occupant responses in

side struck vehicles and variation in the striking vehicle front-end characteristics.

VROOM Evaluations - The effect of striking vehicle compatibility on side impact injuries will be evaluated using VROOM. The simulation will include both the effect of striking vehicle stiffness, weight, and profile as well as occupant height and age. VROOM evaluations and optimization of the striking vehicle front structure will be conducted to determine the effect of variations in stiffness and profile, and to suggest potential countermeasures.

Dummy Selection - A side impact dummy must be selected for use in side impact crash testing. The SID, BioSID, EuroSID, and SID2S could be considered. The primary criterion for this selection is the suitability of the dummies for this type of testing. Lowering of the striking vehicle profile may produce loading to the dummy below the thoracic region, perhaps in a direction different from that of the dummy's primary response axis. The response sensitivities of the dummies will be examined and compared through HYGE sled testing.

Testing - Based on the compatibility ranking and on the results of the VROOM optimization, at least two values for each of front end stiffness, bumper height, and hood profile will be selected. Up to eight different MDB fronts will be designed and fabricated which combine these characteristics. A side impact test will then be conducted using each of the MDB fronts. The struck car will have been previously tested with the appropriate dummy, and will marginally meet the requirements of the dynamic crash test of FMVSS No. 214. The same struck car will be used throughout this series of tests, and other impact conditions will be as specified in FMVSS No. 214. The results will be used to determine the effect that different striking vehicle front end characteristics have on side struck vehicle occupant responses.

Demonstrations - Based on the results of the aforementioned testing and the fleet characterization, specific front end characteristics will be selected for additional testing. At least two different vehicles will be selected (and modified if necessary) which combine these characteristics. The characteristics chosen will likely represent the upper and lower bounds of the side impact performance spectrum, as well as the optimal characteristics identified in the optimization studies, if different. If it is not feasible to modify existing vehicles to meet the required design requirements, then simulated fronts will be designed with the required characteristics, if different from those tested previously. Several frontal load cell barrier (FLCB) tests to determine front end stiffnesses will likely be required. A side impact crash test will then be conducted using each of these vehicles. The struck car,

dummy, and test conditions will be the same as those used in the aforementioned testing. The results from these tests are intended to further validate the findings of the parameter study and the MDB crash tests. If vehicles are used, these tests also help to demonstrate practicability.

Compatibility of Low Mass, Ultra-Stiff Electric Vehicles

This task is to explore the aggressivity of the new generation of electric vehicles being developed under ARPA sponsorship in a joint research program. ARPA is directing the development of new generation of electric vehicles which will meet a zero emission vehicle criteria. Some of the vehicles being developed have ultra-light and ultra-stiff structures which may prove extremely incompatible with the fleet. In Europe, "city" cars are already at the prototype stage which weigh under 600 kg of mass, but are designed with ultra-stiff, ultra-aggressive frontal structures to protect the occupants. Under this task, NHTSA is conducting a joint research program with ARPA to evaluate the crashworthiness and compatibility of EVs.

Evaluation of Compatible Crush Zone

This task is investigating the feasibility of one recent European proposal to mandate front-end stiffness for the first 700 mm of crush as a means of regulating fleet compatibility. More recently, the European Experimental Vehicles Committee has convened a working group (Working Group 15 - Improvement of Crash Compatibility between Cars) to investigate the following topics: overall identification of compatibility problems with respect to injuries and countermeasures, determine parameters which can affect the compatibility, and determine the methods for evaluating compatibility such as the analysis of deformation patterns of deformable elements. This task will analytically investigate the feasibility of setting force-deflection requirements on the fleet by performing a VROOM optimization to determine the optimal force-deflection levels for this crush zone, and determining the expected benefits of a compatible crush zone regulation.

Geometric Compatibility

This task will examine the extent and consequences of geometric incompatibilities. This task will investigate the feasibility of adapting the VROOM methodology to determining the effect of geometric incompatibility. Studies to be conducted under this task include the correlation of door sill height and bumper height, and the

correlation between occupant injury guard rail/vehicle frontal profile incompatibility. This task will investigate the use of three-dimensional lumped mass models and FE models to analytically evaluate geometric compatibility.

RESULTS

The aggressivity of a specific vehicle is controlled by its weight, its structure, and the driver behavior. Comparison of vehicle-vehicle aggressivity is challenging because these three factors vary widely between any two given models. However, by comparing only vehicles within a given vehicle category (i.e., subcompact cars, compact cars, midsize cars, large cars, minivans, full size vans, small pickups, full size pickups, and sports utility vehicles), the effects of weight can be minimized. Presumably all vehicles within a single vehicle category are of approximately the same weight.

But just as importantly, limiting the comparison of specific vehicles to within a vehicle category should reduce the complexity of the vehicle to vehicle variation in driver behavior (e.g., speeding). Presumably, the vehicles within a given category are operated by drivers sharing the same demographics. For example, minivans are typically driven for family transportation and the drivers are assumed to share similar driving behavior patterns. Similarly, sports performance cars are assumed to be operated by drivers who share similar driving characteristics.

This study first presents a fleet wide ranking in which all vehicle models are compared. This ranking will be dominated by the overwhelming effect of vehicle weight on the outcome of vehicle-vehicle collisions. In order to investigate structural aggressivity, a fleet wide ranking with model rankings for each vehicle category is presented.

Technical Approach

This initial study uses the Fatal Accident Reporting System Database (FARS) to rank order all passenger vehicles, cars, light trucks, and vans, by their relative aggressiveness. The ranking will show that vehicles of the same weight class and body type (e.g. minivans) will display approximately the same aggressivity. The results of this rating will be examined to (1) determine the relative aggressivity of different vehicle body types, and (2) to quantify the effect of weight incompatibility, and (3) to search for differences in aggressivity among vehicles of the same weight class.

This study examined the 1991-93 FARS database to tabulate, for each vehicle, the number of fatalities in the subject vehicle and in the other vehicle. FARS provides a comprehensive census of all U.S. traffic accident related

fatalities. The scope of our analysis was constrained to cars, light trucks, and vans under 10,000 pounds in weight. The focus was further narrowed to two vehicle collisions in which the vehicles were either cars or LTVs in which a fatality had occurred.

The net result of the FARS analysis will be to provide absolute numbers of occupant fatalities resulting from multi-vehicle accidents. To develop an aggressivity risk factor or metric (rather than evaluate the subject vehicles by the absolute number of fatalities in the other vehicle), our study will normalize the absolute number of fatalities in the other vehicle by the size of the subject vehicle population. In particular, we have normalized the number of fatalities in the other car per million registrations of the subject vehicle as shown below:

$$\text{Aggressivity Metric} = \frac{\text{Deaths in Other Vehicle}}{(\text{Total Registrations in Subject Vehicle}) / 1,000,000}$$

Findings

This section presents the findings of the FARS analysis in terms of absolute numbers of fatalities in the other vehicle, as a rank ordering of all vehicles by Aggressivity Metric, as a rank ordering of all vehicle categories, and as a rank ordering of all models within each vehicle category.

Fatalities in the Other Vehicle - The results of the FARS analysis are presented in Figure 1 in rank order by total number of fatalities in the other vehicle for the top 20 vehicles. The fatality totals are an annual average computed over 1991-93. Note that four out of the top five vehicles on this plot are LTVs. LTVs are heavier and structurally stiffer than their passenger car counterparts, and might be expected to perform aggressively in a collision.

However, these absolute numbers must be used with caution, as they have not been normalized by the number of vehicle registrations. Although the Ford F-Series Pickup and the Chevrolet Pickup are the top two vehicles on the list, both trucks are extremely popular and have large populations in the fleet. To more accurately gauge aggressivity, we can not only measure total number of fatalities but divide this total by the size of the subject vehicle population.

Overall Fleet Aggressivity Ranking - In Figure 2, the total number of deaths in the other vehicle has been normalized by the estimated number of vehicle registrations over the 1991-93 time period. This plot is limited to current production vehicle models with at least 100,000 registered vehicles. For this study, a current production

vehicle model is defined to be a vehicle model which was in production in the 1991-93 time frame. Note, however, that the totals for each vehicle include all vehicles of each model whether produced during the 1991-93 or earlier.

The most striking feature of Figure 2 is that 19 of the top 20 most aggressive vehicles are light trucks and vans. Of the nineteen LTVs, seven are sports utility vehicles, nine are pickup trucks, two are full-sized vans, and one is a minivan. The most aggressive vehicle of those surveyed was the full-size Chevrolet Blazer with an Aggressivity Metric of 122 other vehicle fatalities per million Blazer registrations. The Chevrolet Blazer is a large sport utility vehicle with an estimated curb weight of 4,700 pounds. The aggressivity of the Blazer is likely due to both its weight and the structural stiffness typical of a sports utility vehicle designed for off-road use.

Only one vehicle in the list of top twenty aggressors is a passenger car. The Chevrolet Camaro, with an Aggressivity Metric (AM) of 86, is a mid-sized performance sports car approximately 3,200 pounds in weight. The aggressivity of the Camaro may be more the result of the way a sports car is driven, rather than due to any structural or weight factor. Other metrics may provide a measure of aggressivity that may better handle effects such as driver behavior. In Table 1, two other metrics besides the measure selected for this study are presented for the identified 20 most aggressive vehicles. These measures are the ratios of (1) the other vehicle fatalities divided by the subject vehicle fatalities and (2) the other vehicle fatalities divided by the subject vehicle fatal accidents. Both of these measures rank the Camaro near the bottom for these 20 vehicles. In other words, the high Camaro fatalities may involve more frequent crashes and the vehicle itself may not be as aggressive as Figures 1 and 2 imply. Figure 3 provides a graphical representation of the measure using the ratio of the other vehicle fatalities divided by the subject vehicle fatalities. In this figure, the percent of the fatalities in the other vehicle and in the subject vehicle are shown. Any value of other vehicle fatalities above 50 percent indicates that the subject vehicle may be more aggressive.

Aggressivity Ranking by Vehicle Type - Aggressivity is a strong function of vehicle weight and vehicle type. Nineteen of the twenty most aggressive vehicles shown in Figure 2 are LTVs. One way to better illustrate the degree of crashworthiness incompatibility within the fleet is to compare the average Aggressivity Metric of the different categories of vehicle types. Figure 4 presents the registrations-averaged AM for each category of light truck, van, and passenger car. The categories assigned to each vehicle are as tabulated by the 1993 Automotive News

Market Data Book [7]. Our study groups luxury, near luxury cars, and large cars into a single large car category.

As shown in Figure 4, full-size pickups were found to be the most aggressive vehicle category with an AM = 86. This category was followed closely by Sport Utility Vehicles (AM = 72), full-sized Vans (AM= 67), and Small Pickups (AM=59). Minivans were the least aggressive of all LTV groups with an average AM = 46. The AM of passenger cars was significantly lower and ranged from AM=24 for subcompacts to AM=42 for large cars.

Vehicle weight is not always the overriding factor dictating aggressivity as clearly demonstrated by Figure 4. Mid-sized cars (e.g. the Ford Taurus) and small pickups (e.g. the Toyota pickup) both have approximately the same curb weight of 3,000 pounds. However, mid-sized cars have a modest AM of 39 while small pickups have a dramatically higher AM of 59. We theorize that the higher aggressivity of the small pickup class is due to both its higher structural stiffness and its higher hood and bumper height.

Among cars, the Aggressivity Metric is a strong function of vehicle weight. AM for the large car category (e.g., Oldsmobile 98) is 42 and drops to an AM of 24 for the subcompact category (e.g., the Nissan Sentra). The conservation of momentum in a collision places smaller cars at a fundamental disadvantage when the collision partner is a heavier vehicle. The importance of car size in providing occupant protection has been demonstrated in several studies of the U.S. accident statistics [8].

Aggressivity Ranking by Vehicle Model - This section will compare the aggressivity of different models within a given vehicle category to identify specific vehicle models which vary significantly from the category average.

1. Minivans - The average AM of minivan vehicle category is 46. Figure 5 presents the within category variation for that group. AM varies from a high of 67 for the Chevy Astro Van to a low of 25 for Pontiac Trans Sport. Note the consistency of the AM across corporate twins: the Trans Sport and the Lumina APV are corporate twins and both have AM=25. The Plymouth Voyager and Caravan have AM=36 and 44 respectively. However, we have not controlled for all variations as two other twins, the Chevy Astro (AM=67) and GMC Safari (AM=47), do not have similar AM's. This dissimilarity may reflect the fact that the Chevy Astro Van is a popular cargo van as well as a minivan.

2. Vans and Pickups - Figure 6, 7, and 8 show that only modest variation is observed in the full-sized van, small pickup category, and full-size pickup categories. In the van class, the exception is the VW Vanagon

which has AM = 31 significantly lower than the full-sized van average AM of 57. However, the VW Vanagon also has a significantly different structure than other full-sized vans in the group.

3. Sports Utility Vehicles - As shown in Figure 9, the Sport Utility Group displays dramatic variation in aggressivity between specific models. The most aggressive vehicle of those surveyed in the entire car/truck fleet is the Chevy Blazer, a member of the Sport Utility group, with an AM of 122 (71 percent above the group average). The least aggressive of the sport utility vehicles is the Isuzu Trooper with an AM of only 41 (43 percent below the group average). Future studies will explore the vehicle design variations which account for this tremendous variation.

4. Passenger Cars - Figures 10, 11, 12, and 13 show the within-group variation for the subcompact, compact, mid-sized, and large categories of passenger cars. As hypothesized earlier, comparison of cars in this manner should minimize the effect of vehicle weight and driver behavior, and allow the examination of structural differences between models. Within group variation is presented below:

Passenger Car Category	AM Low	AM Hi	AM Avg
Subcompacts	15	52	24
Compacts	18	62	38
Mid-Size	11	86	39
Large	14	61	42

In all but the large car category, the most aggressive vehicle in each car category was a sports/performance car. In the subcompact category, the most aggressive car was the Geo Storm. In the compact category, the most aggressive car was the Ford Mustang. In the mid-sized category, the most aggressive car was the Chevrolet Camaro. It is interesting to note that the large car with the lowest AM (14), the Volvo 240 (weight = 3000 lb) had an aggressivity metric slightly lower than the least aggressive subcompact (AM = 15), the Geo Sprint (<2000 lb). This demonstrates again that vehicle weight is not always the overriding contributor to aggressivity.

FUTURE WORK

This paper has presented the first results of a NHTSA study which is attempting to characterize the problem of fleet

incompatibility and vehicle aggressivity. As further steps in investigating vehicle aggressivity, a number of areas for future work have been identified:

Alternative Metrics

One obstacle to quantifying the aggressivity of a vehicle is the lack of an accepted measure of aggressivity. For the purposes of this initial study, aggressivity was defined as the registration-weighted number of fatalities in the ‘other’ vehicle. In ranking the top 20 most aggressive vehicles, two other metrics (determined by using the ratio of the other vehicle fatalities divided by the subject vehicle fatalities and the ratio of the other vehicle fatalities divided by the subject vehicle fatal accidents) were presented to demonstrate other possible metrics. Several improvements to these measures have been proposed and will be evaluated in future efforts. Proposed variations on the basic aggressivity metric include:

1. Normalizing by number of accidents instead of number of registrations
2. Normalizing for the effect of restraint usage in either vehicle
3. Normalizing for accident severity
4. Examining the metric in prescribed accident modes, e.g., frontal-side impacts or frontal-frontal impacts
5. Examining rollovers and full ejections from either vehicle
6. Limiting the other vehicle fatality count to cases where the subject vehicle was the striking vehicle

Ranking Refinements

NHTSA currently has a research effort under way to further refine the aggressivity ranking presented in this paper. This second phase effort will investigate 1991-95 FARS, and will perform a more refined breakdown of vehicle models. The current study groups vehicle models simply by nameplate. The follow-on study will group vehicles by platform design within nameplate. This will allow the study to capture, for example, any design differences between the 1986 Ford Taurus and the 1996 Ford Taurus.

Correlation of Vehicle Design with Aggressivity

This task will examine the relationship between vehicle aggressiveness and measurable vehicle design parameters. This future task will focus on mass,

geometrical, and structural compatibility factors. Geometrical factors will include hood profile, sill height, and bumper height. Structural factors will include frontal stiffness as determined from crash tests and engine location (transverse right or transverse left). Structural stiffness will be determined by extracting discrete element models from frontal-barrier crash tests.

CONCLUSIONS

This paper has investigated the problem of vehicle aggressivity in two-vehicle traffic accidents. Using the other vehicle fatalities per registered subject vehicle as a measure of a vehicle's aggressivity, the examination of U.S. accident statistics shows a striking incompatibility between LTVs and passenger cars crash performance. As measured by this aggressivity metric, LTVs as a class are twice as aggressive as passenger cars. This mismatch in crash performance has serious consequences for the traffic safety environment as approximately half of all passenger vehicles sold in the U.S. are LTVs. The effect of this tremendous degree of fleet incompatibility is not measured directly by frontal-barrier crash tests and will be the focus of future NHTSA research.

The aggressivity metric used in this study provides an initial analysis of the data. Other metrics will be examined in order to control for confounding factors such as driver behavior, crash severity, and other considerations which may affect the fatality outcome.

REFERENCES

1. Mentzer, S.G., Radwan, R.A., and Hollowell, W.T., "The SISAME Methodology for Extraction of Optimal Lumped Parameter Structural Crash Models," SAE Paper No. 920358, February 1992.
2. McCullough, Catherine A., Hollowell, William T., and Battisti, Peter, "Applications of NHTSA's Vehicle Parameter Database," SAE Paper No. 950360, March 1995.
3. Monk, M. and Willke, D., "Striking Vehicle Aggressiveness Factors for Side Impact," Final Report for Project SRL-92, Report No. DOT HS-806-917, January 1986.
4. Ford Motor Company, Safety Systems Optimization Model, Final Report, U.S. Department of Transportation, Contract No. DOT HS-6-01446, November 1978.
5. White, K.P., Gabler, H.C., Pilkey, W.D., and Hollowell, W.T., "Simulation Optimization of the Crashworthiness of a Passenger Vehicle in Frontal Collisions Using Response Surface Methodology," SAE Paper No. 850512, March 1985.
6. Zobel, R., "Economically Justified Passenger Protection Results of Simulation," SAE Paper No. 850516, 1985.
7. _____, 1993 Automotive News Market Data Book, Crain Communications, Inc., Detroit, MI., 1993.
8. Evans, Leonard, "Car Size and Safety: A Review Focused on Identifying Causative Factors," Proceedings of the 14th International Technical Conference on Enhanced Safety of Vehicles, Paper No. 94-S4-W28, Munich, Germany, May 1994.

Table 1. Top 20 Aggressors

Vehicle	1991-93 Fatal Accidents	1991-93 Subject Vehicle Fatalities	1991-93 Other Vehicle Fatalities	Other Vehicle Fatalities per Million Registered Vehicles	Other Vehicle Fatalities / Subject Vehicle Fatalities	Other Vehicle Fatalities / Fatal Accident
Chevrolet Blazer-full size	213	54	206	122	3.81	0.97
Toyota 4-Runner	94	32	78	105	2.44	0.83
Dodge Dakota	191	71	157	103	2.21	0.82
Jeep Comanche	49	14	44	99	3.14	0.90
GMC Jimmy full size	47	11	49	99	4.45	1.04
Nissan Pathfinder	62	19	48	97	2.53	0.77
Ford F-series PU	2474	606	2341	94	3.86	0.95
GMC C,K,R,V-series PU	599	166	561	86	3.38	0.94
Chevrolet Camaro	601	322	433	86	1.34	0.72
Ford Explorer/ Bronco	329	101	298	82	2.95	0.91
Ford Bronco full size	203	42	191	81	4.55	0.94
Chevrolet C,K,R,V-series PU	2131	601	1942	80	3.23	0.91
GMC G-series Van	117	28	120	80	4.29	1.03
Ford E-series Van	671	140	628	77	4.49	0.94
Ford Ranger	702	337	491	71	1.46	0.70
Isuzu P'up/PU	111	51	75	70	1.47	0.68
Dodge D,W-series PU	384	118	352	67	2.98	0.92
Chevrolet Astro Van	228	78	187	67	2.40	0.82
Chevrolet S-10,T-10 PU	577	315	379	66	1.20	0.66
Chevrolet S-10 Blazer	307	122	249	66	2.04	0.81

FIGURE 1. FATALITIES IN OTHER VEHICLES

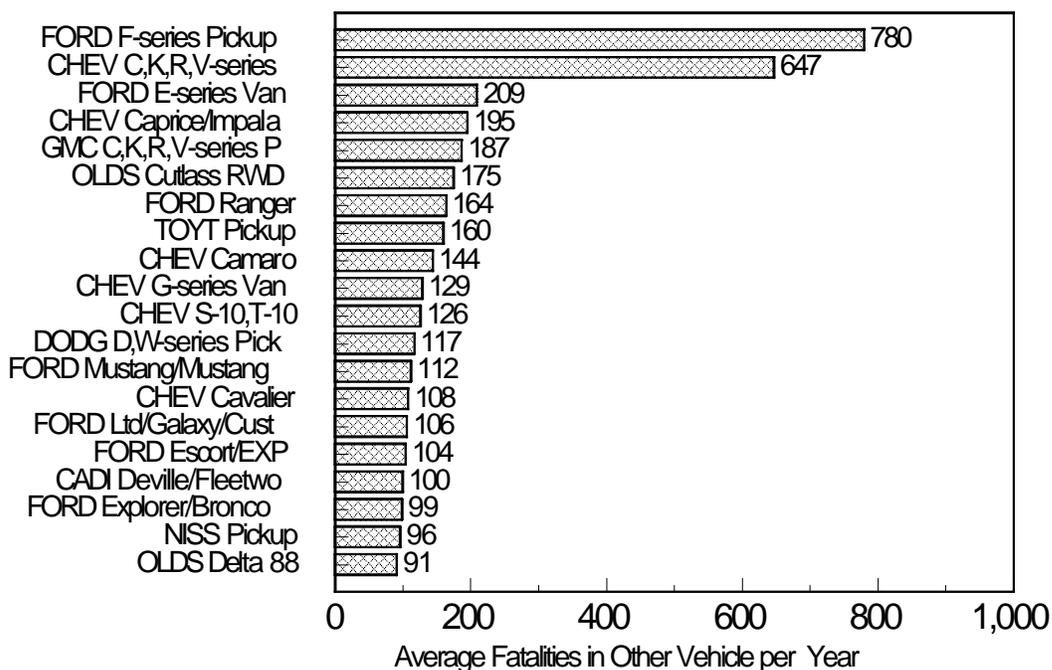


FIGURE 2. AGGRESSIVITY RANKING: TOP 20 VEHICLES

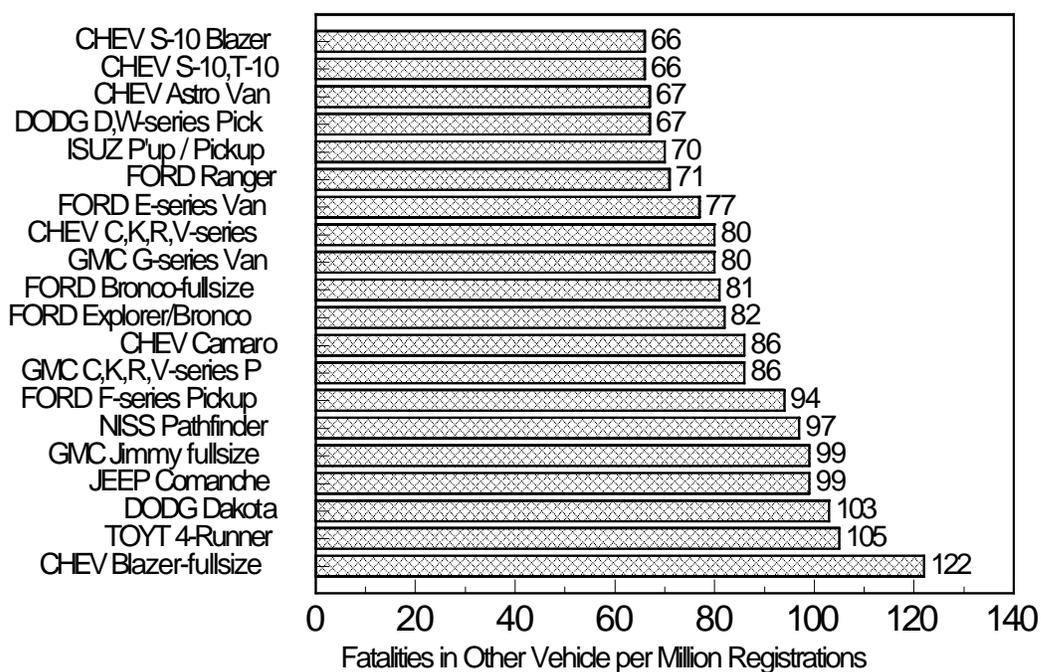


FIGURE 3. TWO VEHICLE COLLISIONS: OTHER VEHICLE/TOTAL FATALITIES

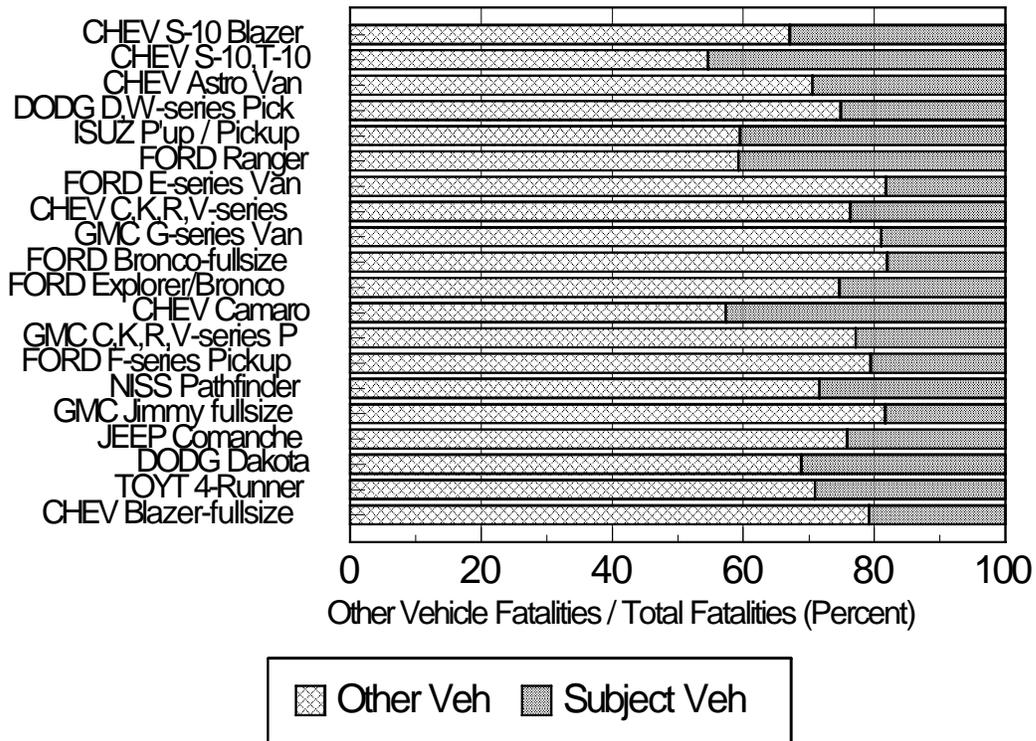


FIGURE 4. AGGRESSIVITY RANKING: LTVs vs CARS

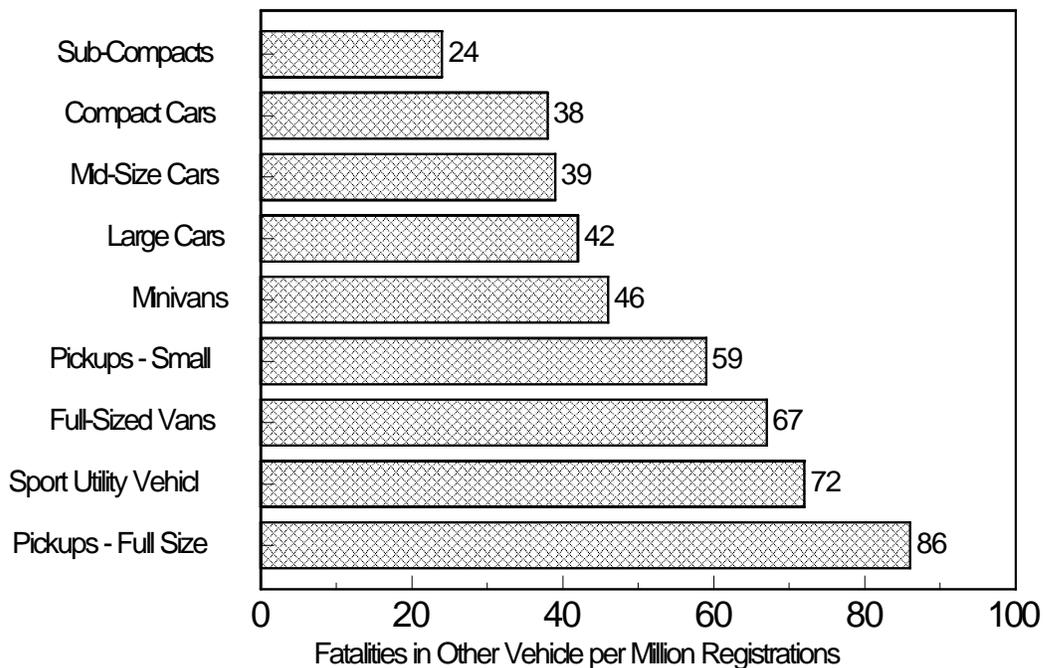


FIGURE 5. AGGRESSIVITY RANKING: MINIVANS

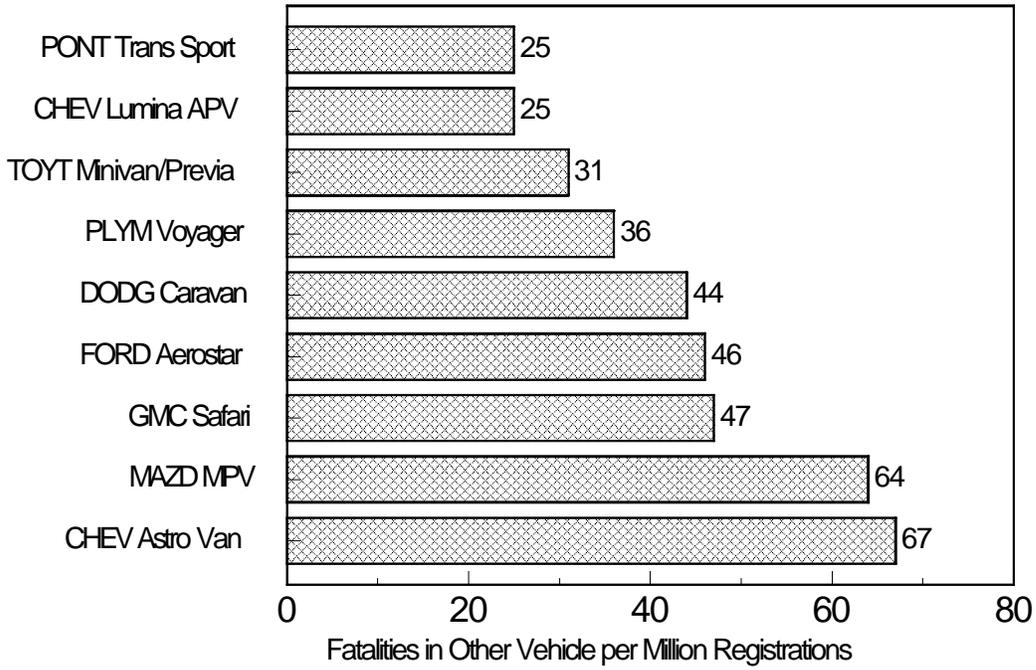


FIGURE 6. AGGRESSIVITY RANKING: FULL SIZED VANS

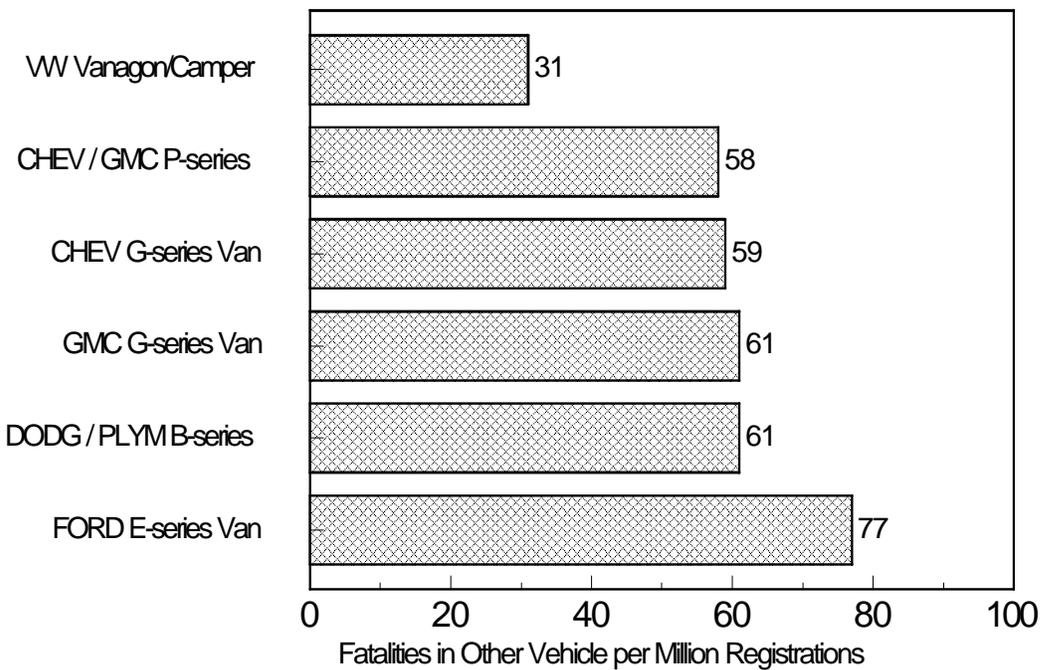


FIGURE 7. AGGRESSIVITY RANKING: SMALL PICKUP TRUCKS

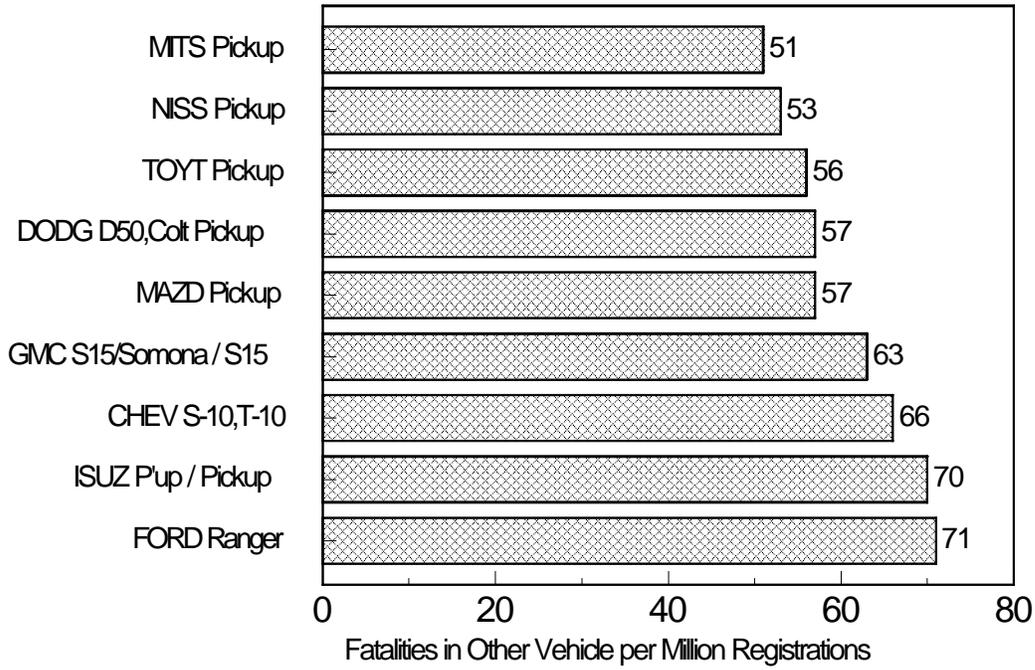


FIGURE 8. AGGRESSIVITY RANKING: FULL SIZE PICKUP TRUCKS

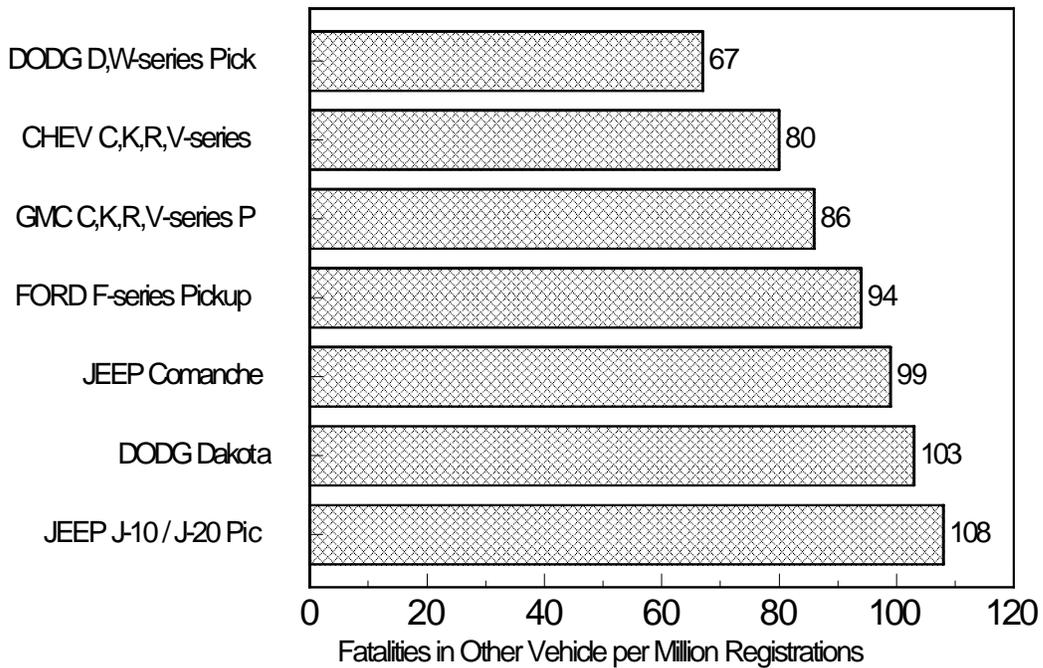


FIGURE 9. AGGRESSIVITY RANKING: SPORT UTILITY VEHICLES

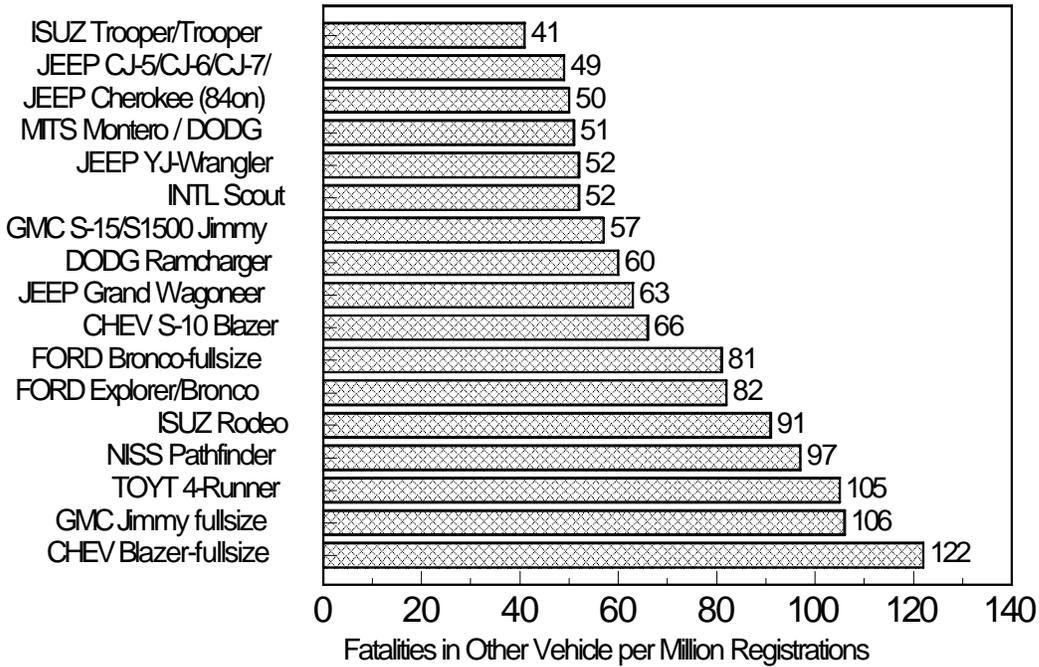


FIGURE 10. AGGRESSIVITY RANKING: SUBCOMPACT CARS

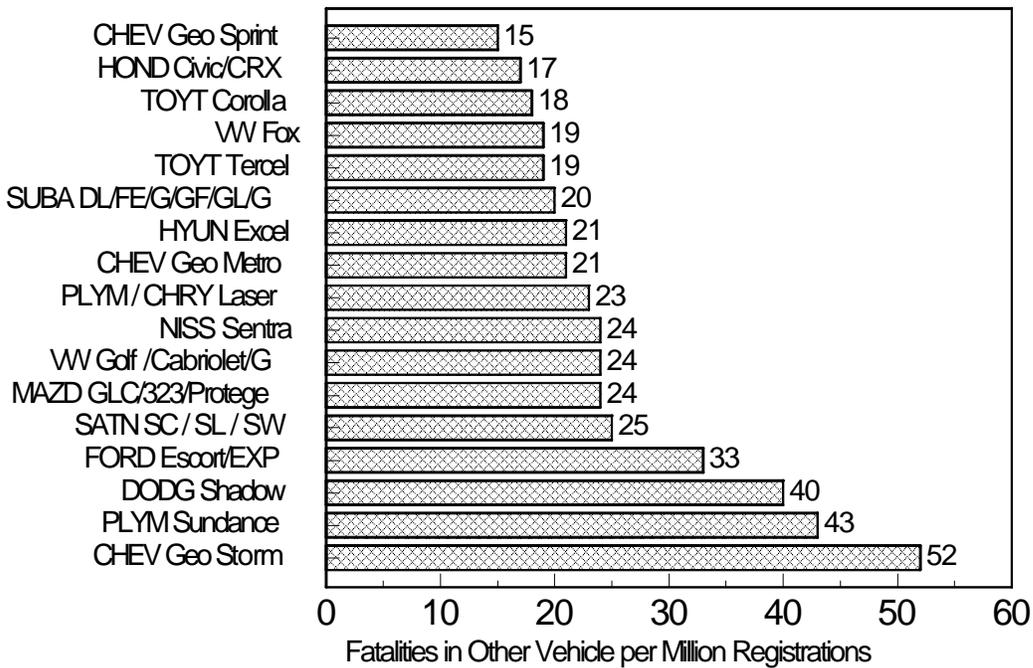


FIGURE 11. AGGRESSIVITY RANKING: COMPACT CARS

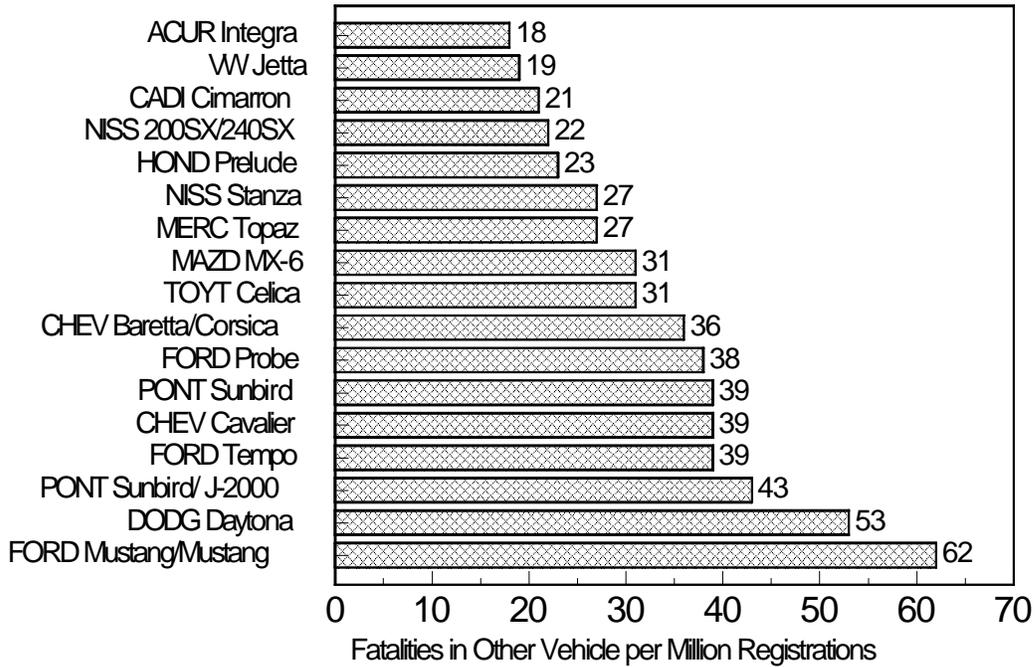


FIGURE 12. AGGRESSIVITY RANKING: MID-SIZE CARS

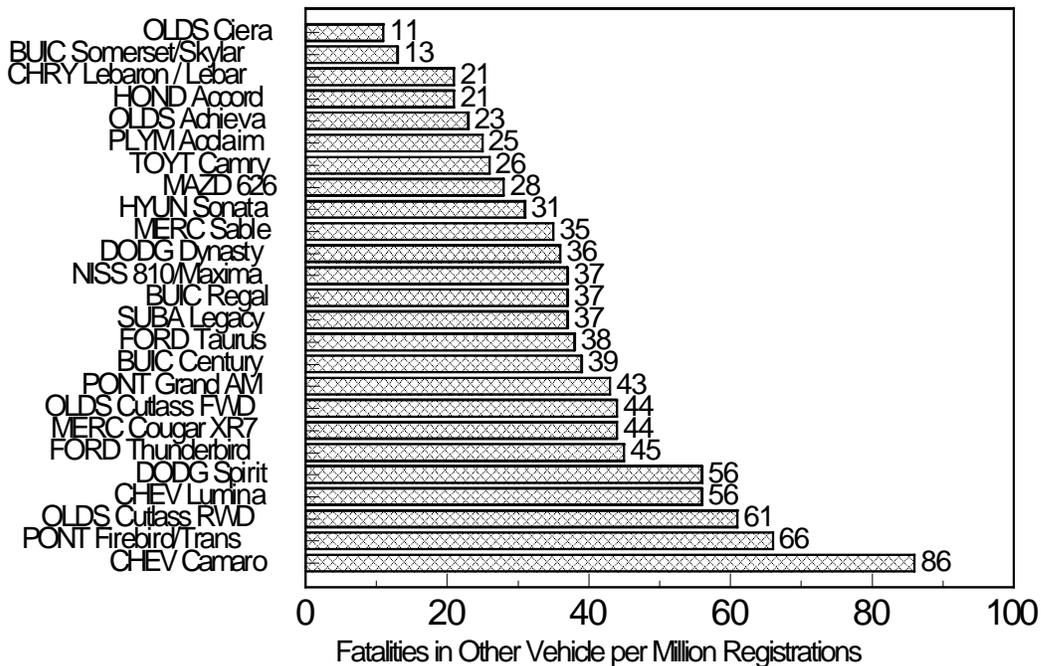


FIGURE 13. AGGRESSIVITY RANKING: LARGE CARS

