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AIRBAG TEST CONDITIONS BASED ON REAL-WORLD CRASH EXPERIENCE

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16. Abstract

To establish a crash test matrix for developing and evaluating an airbag restraint system, an analysis was made of existing information on motor vehicle accidents, biomechanical principles of occupant protection, and principles of occupant restraint systems. Evaluations of airbag restraint systems by means of crash tests usually center upon the test conditions of FMVSS 208 (flat barrier crash testing of Part 572 test dummies at 30 mph with impact angles from 0° to 30°). But those conditions specified in FMVSS 208 may not adequately represent the possible real-world crash exposure that a production airbag might face on U.S. highways. This report suggests a supplemental crash test matrix to represent more completely the real-world conditions an airbag restraint system evaluation program must consider.

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1.0 INTRODUCTION

An analysis was conducted to assess existing information on motor vehicle accidents, biomechanics of occupant protection, and the principles of occupant restraint systems in order to establish a crash test matrix for the development and evaluation of an airbag restraint system.

The crash test evaluation of airbag restraint systems usually centers upon the test conditions of FMVSS 208. This involves flat barrier crash testing at 30 mph with impact angles from 0° to 30°, using 50th percentile male test dummies (Part 572). The limited crash conditions specified in FMVSS 208 may not be adequate to reflect the possible real-world crash exposure that a production airbag system might face on the highways of the United States. It is the intent of this report to suggest a supplemental crash test matrix that would reflect more completely the real-world conditions that an airbag restraint system evaluation program must consider.

2.0 REVIEW OF REAL-WORLD ACCIDENT DATA

The data base chosen to provide the information for analyzing the real-world crash exposure of an airbag system is the data collected by the National Crash Severity Study (NCSS). The NCSS was a major accident data collection program of the National Center for Statistics and Analysis (NCSA) of the National Highway Traffic Safety Administration (NHTSA). Data collection began on January 1, 1977, and terminated on March 31, 1979.

In the NCSS study, accidents were investigated in seven geographic areas within the continental United States, selected so that the aggregate of the areas closely resembles the urbanization distribution of the entire country. Within each area, a stratified sampling plan was used to gather detailed information on passenger cars, light trucks, and vans, as well as their occupants, in accidents severe enough to require that the vehicles be towed from the scene. A total of 11,386 accidents (weighted total=54,318) involving 14,805 towed passenger cars (weighted total=67,281), 24,976 vehicle occupants (weighted total=106,121), and 917 fatalities (weighted total=917) were collected in the NCSS study. A more complete description of the NCSS study can be found in Ricci, ed. (1).*

For this analysis, the summary data on passengers cars (1) were reviewed from the standpoints of impact direction, object struck, instantaneous change in vehicle velocity (called delta V), and injury types for crashes that would be of relevance to airbag occupant restraint systems. Airbag systems are generally felt to be most effective in crashes that are of the frontal type and whose severity is sufficiently great that serious injuries would likely occur if the system were not activated. With that in mind, the following analyses were conducted to obtain an overview of the relevant crash data.

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*Numbers in parentheses denote references listed at the end of this report.

2.1 Impact Direction

The principal direction of force (PDOF) to an impacted vehicle is broken down into "clock directions" or 30° increments. This PDOF is not necessarily the same as the area of the vehicle damaged. For example, it is possible to have an 11 o'clock (30° to the left) impact vector into the side or the front of the car. The PDOF does, however, give a general picture of the vector orientation of the major deceleration of the occupant compartment. If we combine the left and right clock directions other than 12 o'clock (0°), we find the distribution of impact directions, presented in Table 1, grouped according to occupant injury levels.

TABLE 1

DISTRIBUTION OF IMPACT DIRECTION FOR VARIOUS OCCUPANT INJURY GROUPINGS

Impact Direction (PDOF)	All Occupants	AIS 2+	AIS 3+	Fatal
12 O'Clock (0°)	27.3%	34.1%	32.7%	34.4%
1 & 11 O'Clock (±30°)	22.5%	21.0%	20.0%	16.6%
2 & 10 O'Clock (±60°)	14.8%	17.0%	20.2%	19.2%
3 & 9 O'Clock (±90°)	2.4%	3.2%	3.6%	6.1%

The data in Table 1 indicate that the ±30° test conditions of FMVSS 208 would cumulatively include 50% to 55% of the occupants involved in all the NCSS crashes. The question of when the PDOF pertains more to side impact than to front impact has not really been addressed in the literature. The revision proposed by NHTSA to FMVSS 214 for side impact include a ±60° impact PDOF. Thus, one might conclude that the division between frontal impact and side impact should occur when the PDOF is at ±45°. This would give equal frontal and lateral components to the impact vector. Interpolation of the cumulative frequency data from Table 1 indicates that approximately 63% of the occupants injured at the level of AIS 3 or greater would be included for PDOF directions between ±45°. Thus, it is reasonable to extend the range of the PDOF for airbag crash testing to include directions up to ±45° in order to increase the coverage of real-world accident victims.

2.2 Type of Object Struck

Table 2 shows the distribution of NCSS accidents by accident type for the same injury groups.

TABLE 2

DISTRIBUTION OF ACCIDENT TYPE FOR
VARIOUS OCCUPANT INJURY GROUPINGS

Accident Type	All Occupants	AIS 2+	AIS 3+	Fatal
Single Vehicle/Fixed Object	19.5%	31.6%	31.8%	29.4%
Two Vehicles/Head-On	10.8%	16.2%	17.8%	20.8%
Two Vehicles/Side	36.7%	27.6%	27.2%	25.2%
Three or More Vehicles	11.7%	9.5%	8.5%	7.2%

A few comments need to be made about this breakdown of the data. The two-vehicle/side-impact data invariably include one side-impacted vehicle and one frontally-impacted vehicle in each crash. Thus, only half of the data pertain to frontal impacts. These frontal impacts would most likely be different than those occurring in two-vehicle/head-on crashes, in terms of both the vehicle-to-vehicle interaction and the delta V of the frontally-impacted vehicle. An estimate of the relative frequency of frontal impact for occupants in these crashes, obtained by simply dividing all "side" data by two, produces numbers of occupants injured at the AIS2+, AIS 3+, and fatal levels that are somewhat lower than those in two-vehicle/head-on crashes.

Similarly, the single-vehicle/fixed-object data include all impact directions. An estimate of the relative frequency of frontal impact for occupants in these crashes can be made by taking 63% of the single-vehicle/fixed-object data based on the relative frequency of ±45° PDOF given in section 2.1. This would produce relative frequencies for each injury group of about 18% to 20%, which would be similar to the relative frequencies of the two-vehicle/head-on category.

As a result of the above considerations, it appears that injuries in frontal (±45°) crashes occur with similar frequency in the NCSS data in vehicle-to-fixed object, head-on vehicle-to-vehicle, and vehicle-to-side-vehicle types. The implications for crash test evaluation of airbag restraint systems are that equal emphasis should be placed on vehicle-to-fixed object tests and to both types of vehicle-to-vehicle tests. Also, the fact that front-to-side-vehicle type frontal crashes occur with similar frequency to the other two types of frontal crashes should be considered in setting the threshold level for initiation of airbag deployment, because these front-to-side crashes would tend to have lower delta V's and decelerations than head-on or fixed-object crashes.

2.3 Vehicle Velocity Change (Delta V)

The NCSS study contains 20,279 (weighted total) frontal-damage passenger cases. Table 3 gives information on occupants injured among the 31,431 occupants in these crashes in two different ways. One way is to give the percentage of all occupants injured for velocity changes up to 35 mph and 40 mph, respectively (cumulative frequency). The other way is to give the percentage of occupants injured in the various injury groupings among those involved in crashes with velocity changes specifically of 35 mph and 40 mph (injury rate).

TABLE 3

DISTRIBUTION OF VEHICLE VELOCITY CHANGES FOR
VARIOUS OCCUPANT INJURY GROUPINGS

Delta V	AIS 2+		AIS 3+		Fatal	
	Cum. Freq.	Injury Rate	Cum. Freq.	Injury Rate	Cum. Freq.	Injury Rate
35 MPH	87%	50%	78%	33%	50%	11%
40 MPH	92%	58%	85%	43%	60%	20%

These data indicate that a crash velocity change of 40 mph instead of 35 mph nearly doubles the fatal injury rate as well as producing a 10% increase in the cumulative frequency of the occurrence of fatalities. Significant increases in the cumulative frequencies and injury rates for the AIS 2+ and AIS 3+ levels also result when considering the 40 mph level instead of the 35 mph level.

Choosing a crash test vehicle delta V of 40 mph would appear to be a suitable goal for increasing the protective capabilities of a vehicle. However, it must be kept in mind that the delta V values in the NCSS data are not equivalent to barrier crash delta Vs. The acceleration levels association with barrier crashes tend to be higher than those for car-to-car crashes at the same delta Vs. This is attributed to the complete and uniform contact that the flat barrier produces against the front of the test vehicle. Thus, a 40 mph delta V level in terms of real-world crash severity may be represented by a lower delta V in an equivalent barrier crash test. The 35 mph barrier crash velocity used by Honda in previous testing may be near this equivalence level.

2.4 Distribution of NCSS Injuries

The goal of any restraint system is to prevent serious and fatal injuries. In meeting this goal it is possible that some injuries may be produced by the restraint system itself and that many lower level injuries may not be prevented. Choosing the crash test severity levels for evaluating a restraint system requires a decision as to what level of injury will be judged acceptable and what levels of injury are to be prevented. Currently, it is generally felt that the AIS 3 level is an acceptable injury level for the upper crash severity limit of the vehicle.

In view of this, the NCSS data on the most frequent injuries common at AIS levels of 4, 5, and 6 can provide insight into the types of injuries that are to be prevented. Table 4 presents the distribution of injuries to the major body regions for AIS 3 and the higher three AIS levels.

The three most frequently involved body regions at AIS 4, 5, and 6 are the head, abdomen, and thorax. These would most likely be well

TABLE 4

DISTRIBUTION OF AIS=3,4,5,6 INJURIES BY BODY REGION

Body Region	AIS 3	AIS 4	AIS 5	AIS 6	AIS 4,5,6
Head	10.2%	24.7%	38.3%	29.7%	30.1%
Abdomen	8.3%	29.9%	30.7%	1.4%	26.3%
Thorax	36.6%	19.2%	25.4%	23.1%	21.9%
Leg	26.1%	16.5%	0.2%	0.0%	8.6%
Neck	4.2%	1.3%	4.0%	43.4%	7.9%
Arm	12.8%	7.3%	0.0%	0.0%	3.8%
Back	1.9%	1.0%	1.1%	0.9%	1.0%

protected by an effective airbag system. Note that at the AIS 3 level the leg represents a significant portion of the injuries, second only to the thorax. It would be valuable for a restraint system that diminished the occurrence of head, thoracic, and abdominal injuries to also minimize leg injuries, even though they are usually classified as AIS 4 and below.

3.0 DISCUSSION OF FACTORS INFLUENCING AIRBAG DESIGN AND PERFORMANCE

The role of an occupant restraint system is to couple the occupant tightly to the vehicle so that he can ride down the crash using the vehicle's energy absorbing capabilities while at the same time preventing, insofar as possible, contact of the occupant with the interior of the vehicle. A third function of a restraint system is to distribute or limit the loads produced by the crash on the occupant's body. While all of these functions can be provided for in principle, the critical factors that come into play in the actual specification of restraint performance levels are the mechanical response characteristics of the human body under such loading conditions and the limits of mechanical loading that can be reliably applied without serious injury. Such information is known as the biomechanical impact response and tolerance of the human body. The lack of adequate knowledge of such factors has impeded the progress of restraint system design, particularly with respect to innovative approaches to occupant restraint. To put it in simple terms, an engineer must know the mechanical characteristics and failure modes of the subject that is to be protected just as much as those of the structures or systems that are being designed to do the protecting. Given a desired upper crash velocity level, it is the limits of the human body to withstand the type and magnitude of the loads produced on it by the restraint system that dictate the actual performance levels of the vehicle crashworthiness structures.

In a frontal crash, an airbag restraint system has several theoretical advantages over the lap/shoulder belt restraint system. First, the airbag provides a much larger area to restrain the occupant and thus can apply larger total loads to the body for a given unit loading. Second, the airbag can load the head as well as the rest of the body and can thereby control the motion of the head in a manner that belt systems cannot. A third possible advantage is the ability to increase the stopping distance of the occupant by providing controlled forward motion within the occupant compartment during the crash. This feature can be designed into belt systems also. The above advantages were referred to as theoretical advantages because it depends to a great extent upon the severity of the crash velocity level as to whether or not such features are actually necessary to prevent severe or fatal injury to the vehicle occupants. The crashworthiness features of the vehicle structures must be capable of adequately doing their job of managing the crash energy and preventing occupant compartment intrusion at a particular design crash velocity before such additional features as load distribution on the body, control of head motion, and increased stopping distance are needed. The basic function of the restraint system is still to provide ride down of the crash and to prevent uncontrolled interior contacts. Real-world accident investigation data has found that, for crashes in which the vehicle crashworthiness structures have remained effective, the proper use of a lap/shoulder belt poses no serious threat of injury to the occupant. These crash severity levels appear to include the conditions of the present FMVSS 208.

Thus, it appears that the biomechanical advantages of the airbag are not strictly necessary for safe occupant protection in survivable vehicle crashes with the present level of crashworthiness in today's cars. Only as the crashworthiness level (that is, the survivable crash velocity) is raised to higher levels with future vehicle designs might it become necessary to provide the additional frontal crash protective features of the airbag. At just what level this occurs depends to a great degree upon a good knowledge of the biomechanical factors involved in human tolerance to impact injury.

The airbag is a restraint system that is designed to do one particular job very well. That job is to provide passive protection for a well-placed (that is, seated, forward-facing, centered, and back in the vehicle seat) vehicle occupant in a primarily frontal force crash in which the major crash events take place while the airbag remains inflated. The airbag is mounted in the forward structure of the vehicle and therefore depends to some extent upon the structural integrity of the forward structure, including the windshield, in the case of the passenger airbag. Windshield retention in vehicle crashes is an important factor in keeping unrestrained occupants inside the car and is covered by FMVSS 212. However, outside objects can disrupt the windshield integrity during a crash and thus might compromise the performance of a passenger airbag. An analysis of the Collision Performance and Injury Report (CPIR) accident data files for frontal crashes with impact forces between 10 and 2 o'clock yielded 5,705 vehicles of which 991 broken windshields occurred. Of these, 412 were caused by occupant contact, 358 were broken by other than occupant contact, and 221 were of unknown cause. This means that 6.3% to 10.1% of the crashes may have represented a problem for passenger airbag performance.

The out-of-position occupant presents another factor for consideration in the design and performance of airbag restraint systems. This situation can occur for both the driver (2) and for the passenger (3,4). Prevention of dangerous out-of-place occupant interactions with the rapidly inflating airbag has significant influences on inflation characteristics, bag folding patterns, and system placement. The out-of-position child occupant generally presents the most severe restriction on design parameters.

4.0 DISCUSSION OF BIOMECHANICAL FACTORS

The problem of describing the mechanical response, injury mechanisms, and tolerance to force of the human body is paramount in restraint system design. As attempts are made to upgrade and optimize the performance of restraint systems, the greater the need for more complete and accurate data on the biomechanics of the human body. Biomechanical knowledge can be useful in many ways in restraint system design and evaluation. The information can be used to set design criteria for load limits produced by the restraint system, such as the collapse load of the energy-absorbing steering column or the breaking load of the HPR windshield, while it can also be useful in specifying the response of a human surrogate, such as a dummy or a mathematical model. Finally, it can be used to assess the injury potential of a particular restraint system through the use of injury criteria.

There are several problems related to the biomechanical use of the present type of test dummies specified for use in FMVSS 208 (the so-called Part 572 dummy). Such test dummies had their origins in dummies that were intended to simulate the shape and mass distribution of the average (50th percentile) male human body. The articulations of these dummies were only crudely representative of the human linkages, and there was no attempt at simulating the mechanical response of such critical structures as the head, neck, and chest. Most of the features of the Part 572 dummy were developed to improve the repeatability and reproducibility of the dummy, the first priority of any test device. As a result, the Part 572 dummy gives exaggerated values of accelerations and forces generated under some of the impact situations typical of restraint systems testing. These discrepancies are the result of a lack of what is known as biomechanical fidelity. An additional complicating factor is that the injury criteria used in FMVSS 208 were based on biomechanical impact data obtained with human cadavers. As a result, the limited injury criteria put forth in FMVSS 208 (head, chest, and femur injury criteria) were obtained with the best available surrogate of the human body but are interpreted with a surrogate (Part 572 dummy) that does not necessarily respond in the same manner as the human body.

The human body is a very complicated biomechanical structure. Its critical structures and their injury limits are not completely understood. Current research work is aimed at improving this situation, but in some regions, such as brain injury, it may be many years before an adequate understanding of all the possible modes of injury and their causes are achieved. The same is true to a lesser extent in the chest. The simplified injury criteria of FMVSS 208 represented the best available information at the time of its formulation, but it neglects other possible forms of injury, such as neck injury, because little is known quantitatively about the subject. Such incomplete specification of potential types of injury in a restraint system's performance standard requires that restraint system development be approached on a very conservative basis to ensure that a system that is aimed at preventing one type of injury does not produce another, possibly more serious, type of injury.

The GM Hybrid III dummy (5) has significant improvements in biomechanical fidelity over the Part 572 dummy. In addition, the Hybrid III dummy has provisions for advanced transducers in the neck, chest, and legs that can aid in the assessment of injury potential in body regions not possible with the Part 572 dummy. The problem of understanding the injury limits remains, however.

General Motors has also developed a modified three-year-old child dummy with improved instrumentation in the form of neck and chest load cells. This dummy was intended primarily for out-of-position test evaluation of airbag systems. The dummy may not have good biomechanical fidelity, since such data on children are lacking.

5.0 DISCUSSION OF CRASH TESTING FACTORS AND SUGGESTED CRASH TEST MATRIX

To test the protective performance of an occupant restraint system, it is most often necessary to simulate a vehicle crash to some degree, and to include a simulation of the vehicle occupants. Vehicle crashes can be simulated by a variety of techniques, including sled testing, component impact testing, and full-scale car crash testing. Each technique has various advantages and disadvantages. The most realistic techniques, actual crashing of cars into realistic objects (other car, tree, or roadside structure), suffer from a lack of precise control of the experiments and can result in problems of repeatability and reproducibility of test results. Techniques that offer more control can compromise the realism of the crash environment by eliminating vehicle crash motions, such as pitching and yawing, and their subsequent effect on occupant kinematics. Any test program will, of necessity, involve compromises between realism and repeatability.

The goals of an airbag restraint system development program can best be met by a combined approach using full-scale car crash tests for major system evaluation and supplementing them with selected sled tests for evaluation of special cases. The General Motors air cushion crash test program (5) used such an approach. The GM study had a number of criteria for selecting test conditions and configurations. These included selecting simulations of high-occurrence real-world accidents based on accident data, mileage and environmental effects, occupant size and position mix, and duplication of particular accidents in which their airbag-equipped vehicles had been involved.

In comparison to the GM study, the proposed Honda study would necessarily differ in two aspects. First, there are no real-world accidents to recreate involving airbag-equipped Honda cars, and second, the Honda system has been developed to exceed the requirements of FMVSS 208 by meeting the injury criteria at a crash speed of 35 mph. An additional factor, which can enhance the Honda study, is the availability of advanced adult and child dummies for evaluation of system performance.

The suggested test conditions and configurations for the Honda study are based on the information provided in the previous sections of this report and are intended to reflect real-world accident experience.

The suggested test matrix (shown in Table 5) considers the following factors:

a. Type of crash test (barrier, car-car, car-pole, or sled)
b. Impact angle (0°, 30°, 45°)
c. Impact velocity change (Delta V)
d. Occupant size
e. Occupant position

The various combinations of these conditions and configurations have been rated according to their relative importance in evaluating the overall performance of the system. The rating used the following code:

A = Essential Test
B = Important Test
C = Useful Test
D = Can Omit

General comments on the features of the test matrix follow.

<u>Type A: Essential Tests</u>. Although barrier tests are not as realistic as car-car or car-pole tests in terms of real-world frequency, they do represent a repeatable and highly standardized test condition. The 0° / 35-mph barrier tests with the 50th percentile male Hybrid III dummy and the 5th percentile female and 95th percentile male dummies have been given a rating of A due to the combined importance of range of occupant size and increased biomechanical data needed for a complete evaluation of the system performance. Similarly, car-car tests at 0°/ 40-mph and 30° / 40-mph have been given A ratings also. From a repeatability and test control standpoint only one of the vehicles in the car-car tests should be moving, if possible. One car-pole test at 30°/35-mph has been added to evaluate the system performance under localized vehicle deformations. The A-rated sled tests are related to out-of-position occupants for the 50th percentile male and 3-year-old child dummies and a passenger-positioned 95th percentile male dummy. It is suggested that the out-of-position occupant tests be run first, and, based on suitable performance in those tests, the resulting system

TABLE 5

HONDA AIRBAG CRASH TEST MATRIX

Type of Crash	Impact Angle	Impact Velocity Change, ΔV (mph)	50TH PERCENTILE MALE HYBRID III DUMMY			95TH PERCENTILE MALE DUMMY			5TH PERCENTILE FEMALE DUMMY			3-YEAR-OLD CHILD DUMMY*	
			Driver Pos.	Pass. Pos.	Out of Pos.	Driver Pos.	Pass. Pos.	Out of Pos.	Driver Pos.	Pass. Pos.	Out of Pos.	Pass. Pos.	Out of Pos.
Barrier	0°	35	A	A	D	A	B	D	B	A	D	C	C
	30°	35	B	B	D	B	C	D	C	C	D	C	D
	45°	30	C	C	D	C	C	D	C	C	D	D	D
	0°	30	C	C	D	C	C	D	C	C	D	D	D
	30°	30	C	C	D	C	C	D	C	C	D	D	D
	45°	25	C	C	D	C	C	D	C	C	D	D	D
Car-Car	0°	40	A	A	D	B	A	D	A	B	D	C	C
	30°	40	A	A	D	A	B	D	B	A	D	C	D
	45°	35	B	B	D	B	B	D	B	B	D	D	D
	0°	30	C	C	D	C	C	D	C	C	D	D	D
	30°	30	C	C	D	C	C	D	C	C	D	D	D
	45°	25	C	C	D	C	C	D	C	C	D	D	D
Car-Pole	0°	35	B	C	D	C	C	D	C	C	D	C	C
	30°	35	B	A	D	A	C	D	C	C	D	C	D
	45°	30	C	C	D	C	C	D	C	C	D	D	D
	0°	30	D	D	D	C	C	D	C	C	D	D	D
	30°	30	D	D	D	C	C	D	C	C	D	D	D
	45°	25	D	D	D	C	C	D	C	C	D	D	D
Sled	0°	20**	C	C	A	D	D	B	D	D	B	C	A
	30°	20**	D	D	B	D	D	D	D	D	D	B	B
	45°	20**	D	D	C	D	D	D	D	D	D	B	C
	0°	35	B	B	A	B	A	B	B	B	B	C	A
	30°	35	B	B	B	B	B	D	B	B	D	B	B
	45°	35	C	C	C	C	C	D	C	B	D	B	C

*Specially modified with neck and chest load cells.

**Or threshold bag firing delta V.

A=Essential Test
B=Important Test
C=Useful Test
D=Can Omit

should then be evaluated with the 95th percentile male dummy sled test to ensure proper performance of the system.

Impact Angle. The impact angles have been chosen to reflect the information discussed in Section 2.1.

Impact Velocity Change. In all cases two different velocity levels have been suggested. This was done to allow for the establishment of system performance over a range of crash velocities rather than "tuning" a system for a particular velocity.

Occupant Size. The dummies suggested for use in this study were chosen for two basic reasons. The 95th percentile male and 5th percentile female dummies were chosen to represent the range of adult occupants to be protected by the system. The 50th percentile Hybrid III male and the 3-year-old child dummies were chosen to provide additional biomechanical data on the system performance for the properly positioned adult and out-of-position adult driver and child passenger. These dummies are commercially available and represent the best available devices for evaluating airbag performance.

Occupant Position. The longitudinal seat location of the dummies in the driver positions should correspond to dummy size, except for the out-of-position driver where a closer seating position or a slumped position may be chosen. Passenger-position dummies should be in a mid- to far-back seated location even for the 5th percentile female and child dummies. The out-of-position child dummy should be standing or kneeling close to the instrument panel.

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