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Car Crash Compatibility: The Prospects for International Harmonization

Hampton C. Gabler
Rowan University

Brian N. Fildes
Monash University Accident Research Centre

ABSTRACT

Crash incompatibility between disparate classes of passenger vehicles is an issue of growing global concern. There is widespread consensus, both in the U.S. and internationally, that any regulation or test procedure focusing on crash compatibility should be a globally harmonized standard. However, this may prove to be a challenging effort due to huge differences in U.S. and international fleet composition. The U.S. fleet is dominated by a growing light truck component, and has few of the sub-1000 kg cars that are prevalent in Australian and European fleets. This paper will examine the structure of the passenger vehicle fleets in the U.S., Europe, and Australia, the relationship between fleet composition and real world crash fatalities and the prospects for a single, globally accepted, crash compatibility test procedure.

INTRODUCTION

The current worldwide state of crash safety regulation is a patchwork of differing rules, test procedures, and test devices that vary widely from country-to-country and region-to-region. Automakers that seek to market passenger vehicles in these different regions are faced with the difficult problem of designing vehicles that can meet these varying and potentially conflicting safety regulations. Unfortunately, the solution has often been a costly one: automakers market different designs for different markets, and pass the costs of duplicate design efforts on to the consumer. The ideal solution would be a single set of vehicle safety regulations that are globally applicable. The goal of globally applicable vehicle safety standards is referred to as international harmonization.

Side impact protection is one of the more contentious examples of crash safety regulation that has not achieved international harmonization. In the U.S., FMVSS No. 214 regulates dynamic side impact protection. In Europe, ECE Regulation 95 describes the requirement for dynamic side impact protection. Despite the fact that both standards were developed at the same time and were founded on much of the same research, the two regulations differ in virtually every respect [1]. Differences include the type of dummy used (SID vs. Euro-SID), the injury criteria (TTI vs. VC and HIC), the impactor mass (1365 kg vs. 950 kg), the impact speed (54 km/hr vs. 50 km/hr), the impactor height, the impactor stiffness, and the impact point on the struck car. Recent crash tests in which a common set of cars was tested with both FMVSS No. 214 and ECE Regulation 95 indicate that the two procedures may provide conflicting assessments of side impact crashworthiness [2]. How these conflicting assessments affect vehicle design remains unanswered.

INTERNATIONAL HARMONIZATION ON CRASH COMPATIBILITY – Crash incompatibility between disparate classes of passenger vehicles is an issue of growing global concern. The compatibility of a vehicle is a combination of its crashworthiness and its aggressivity when involved in crashes with other members of the vehicle fleet. While crashworthiness focuses on the capability of a vehicle to protect its occupants in a collision, aggressivity is measured in terms of the causalities to occupants of the other vehicle involved in the collision. Crashworthiness is sometimes referred to as self-protection while reduction in aggressivity is sometimes referred to as partner-protection.

There is widespread consensus, both in the U.S. and internationally, that any regulation or test procedure focusing on crash compatibility should be a globally harmonized standard. International harmonization requires at least two steps: (1) harmonization on crash safety research followed by (2) harmonization on crash safety regulation. International agreement on harmonized regulations is likely to be difficult without first achieving an international consensus on research results and approaches.

Recognizing the need for harmonized research as a precursor to harmonized standards, several forums have been established internationally to coordinate research efforts. The International Research Harmonization Agenda (IHRA), established at the 15th International Technical Conference on Enhanced Safety of Vehicles in Melbourne, Australia, has initiated a committee on crash compatibility research with representatives from Asia, Australia, Europe, and North America. The U.S. National Highway Traffic Safety Administration (NHTSA) Motor Vehicle Safety Research Activities Committee has established a working group on compatibility that regularly brings together crash safety experts from both the U.S. and international regulatory and research organizations. EC Working Group 15 regularly meets to share compatibility research results in Europe with invited observers from outside the EC. Together, these groups and others are jointly developing impact test procedures, injury criteria, and anthropomorphic test devices for crash compatibility assessment.

Despite an unprecedented level of cooperation between researchers, however, international harmonization of car crash compatibility regulation may prove to be an elusive goal. Crash compatibility is controlled by fleet composition, and there are huge differences between the U.S. and international passenger vehicle fleets. The U.S. fleet, for example, is dominated by a growing light truck and van (LTV) component, and has few of the sub-1000 kg cars that are prevalent in Australian and European fleets. A vehicle, which is compatible with one fleet, may not be compatible with other fleets.

PURPOSE

The objective of this paper is to investigate the feasibility of one specific aspect of crash compatibility harmonization: a test procedure that equally reflects the crash environment in the U.S., Europe, and Australia. More specifically, this paper will examine what the characteristics of the impactor should be for such a test. Other test conditions, e.g., impact speed and impact configuration, are not addressed here.

POTENTIAL TEST PROCEDURES FOR CRASH COMPATIBILITY

Many types of crash compatibility tests are possible [3]. Before examining the possibilities for a harmonized compatibility test, it is useful to consider the characteristics of the ideal compatibility test procedure.

1. Vehicle-to-Vehicle Test. Because compatibility encompasses both self-protection and partner-protection in a vehicle-to-vehicle crash, the ideal test would be a vehicle-to-vehicle impact that measures occupant responses in both of the colliding vehicles.
2. Evaluation of Compatibility with the Entire Fleet. Crash compatibility implies crash compatibility between a subject vehicle and the fleet of potential collision partners. In the ideal world, a compatibility test procedure would test the subject vehicle in a series of crash tests with all possible collision partners – an extremely expensive proposition. As a surrogate for testing against all collision partners, a less expensive approach would be to test the subject vehicle in a crash with a collision partner which is representative in some sense of the fleet.
3. Inexpensive and Repeatable. As with all crash tests, the test must be repeatable, reproducible, and cost-effective.

Two candidate test procedures are a car-to-car crash test, and a Moving Deformable Barrier (MDB) to-car test. A fixed full barrier or fixed half-barrier test can potentially test for some aspects of stiffness and geometric compatibility, but cannot capture the important interactions which occur as result of a mass mismatch between collision partners. Note that crashworthiness in single-vehicle collisions and rollovers, while important, is not in the domain of crash compatibility.

CAR-TO-CAR TEST PROCEDURE – Vehicle-to-vehicle testing with production cars, as shown in Figure 1, provides a superb simulation of crashes in the field. NHTSA has recently completed an example of this method of testing for crash compatibility [4,5]. In this test series, a single midsize car model was chosen as a common target vehicle. A series of frontal and side impacts were conducted in which three LTV models and one passenger car model were crashed into a midsize passenger car first in side impact and then in a frontal-frontal oblique configuration.

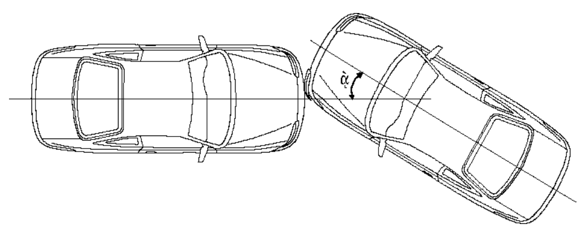

Figure 1. Car-to-Car Crash Test Configuration

Although vehicle-to-vehicle testing has proven to be a successful research approach, this procedure is not practical as a regulatory test for several reasons. First, vehicle-to-vehicle testing is expensive. Each vehicle-to-vehicle test demolishes, not one, but two new vehicles. Second, assuming that international agreement could be reached on a target car, the target car selection process would need to be repeated each time the chosen target car went out of production. Finally, unlike a fixed or moveable deformable barrier, the realities of manufacturing process make it extremely uncertain that the crash performance of a production car would be sufficiently repeatable to serve as a regulated test device.

MDB-TO-VEHICLE TEST PROCEDURE – A promising alternative to vehicle-to-vehicle testing with production cars is to replace the common target car with a moveable deformable barrier (MDB) oriented at the desired angle a and degree of overlap as shown in Figure 2. Moveable barriers are widely used in both side impact and fuel system integrity tests, are less expensive and more repeatable than full vehicle-to-vehicle tests.

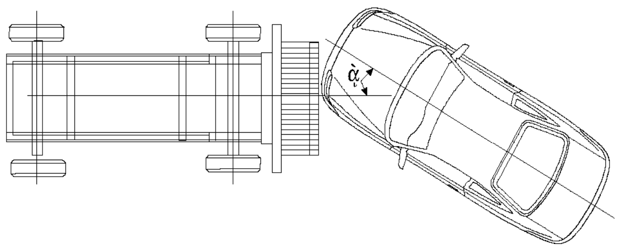

Figure 2. Offset Moveable Barrier Frontal Crash Test Configuration

The downside of MDB-to-vehicle tests is of course the absence of occupants on the MDB. To evaluate self-protection, subject vehicle occupant responses, e.g., HIC or chest deflection, would be measured and compared against limits on allowable injury. To measure partner-protection, other approaches, such as measuring and setting limits on the impact response of the MDB (e.g., peak deceleration or peak interface force) should be pursued as a surrogate for occupant response.

THE STRUCTURE OF PASSENGER VEHICLE FLEETS

Key to the success of the MDB-to-vehicle test procedure is the appropriate selection of an impactor mass which is representative of crash conditions in the field. To select the appropriate impactor mass, we must first examine the structure of the passenger vehicle fleet.

COMPOSITION BY VEHICLE MASS – Figure 3 shows the distribution of car masses in three different regions of the world: Australia, the United Kingdom, and the United States [6,7,8,9]. Clearly, U.S. cars (median mass = 1400 kg) are substantially heavier than their counterparts in Europe (median mass = 1140 kg). The Australian car fleet (median mass = 1240 kg) is situated between these two extremes. Figure 3 is based upon 1997 new car sales, and not registrations, which makes these figures more indicative of the future fleet composition to which any potential regulation would apply. Note that the U.S. median mass is for cars only, and does not include the light truck component of the U.S. fleet.

Distribution by Vehicle Type. The distribution of vehicle type also varies widely from country to country. For example, the U.S. fleet is divided into two distinct categories of passenger vehicles -- (1) passenger cars, and (2) light trucks and vans (LTVs). As shown in Figure 4, LTVs are significantly heavier than passenger cars. The median mass for the U.S. LTV fleet in 1997 was approximately 1830 kg – 430 kg heavier than the median mass car. This huge mass mismatch is reflected in a serious incompatibility between cars and LTVs in the U.S. [4,10,11,12].

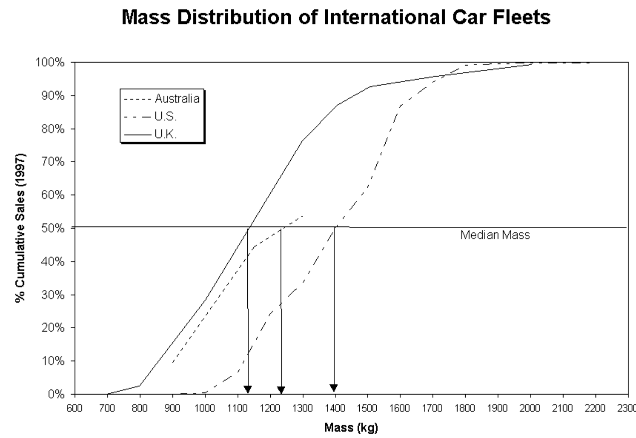

Figure 3. Mass Distribution of International Car Fleets – 1997 Sales

Table 1. International Fleet Composition by Vehicle Type – 1997 Sales

Country	Per Cent sub-1000 kg Cars	Per Cent Light Trucks and Vans
United Kingdom	28	0
Australia	23	1 – 2
U.S.	5	45

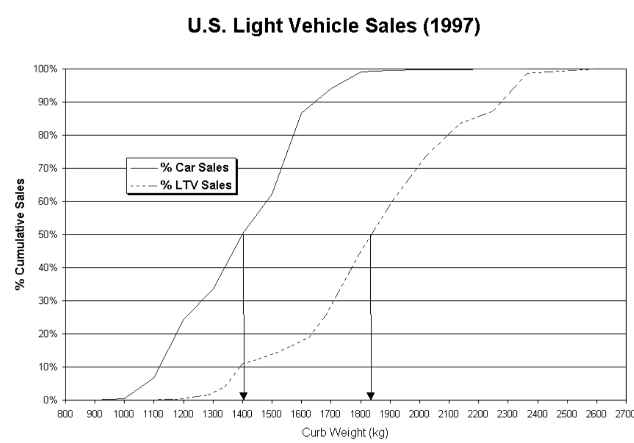

Figure 4. U.S. Light Vehicle Sales in 1997 (estimated from 1997 NHTSA Cafe database).

The fleets of Europe and Australia have large numbers of very small (sub-1000 kg) cars that are not present in significant numbers in the U.S.. Table 1 presents international 1997 sales of these two extremes of the passenger vehicle fleet: (1) very small cars (< 1000 kg) and (2) LTVs.

DISTRIBUTION BY VEHICLE ENGINE SIZE – Table 2 compares the fleet composition of the United Kingdom, Australia, and Japan by categorizing vehicle size based upon the engine size of motor vehicles licensed in these countries [6]. This analysis illustrates the different proportion of mini and small cars between the UK, Japan, and Australia from recent registry data files. Most notably, the proportion of very small (mini) cars (<1000 engine capacity) is appreciably greater in Japan than either the UK or Australia and small cars (1000-1500cc) were most popular in both the UK and Japan. Interestingly, medium to large cars were more prevalent in Australia probably reflecting differences in roads, spaciousness, and lower operating costs in this country.

FLEET VARIATION ACROSS A REGION – The preceding analysis suggests that fleet composition varies dramatically from one region of the world to the next. A closer look at Western Europe reveals that these fleet composition disparities are present even within a single region. Data provided by the European Automobile Manufacturers Association [6] enabled a comprehensive comparison to be undertaken of new car registrations in 1997 in European and nearby countries in Table 3.

Fleet composition varies widely from European country to country. For example, on average, small cars (< 900 kg) comprised 28% of all new car sales in Europe in 1997. However, there were considerable individual differences across the continent varying from a low of 7% for Sweden to a maximum of 54% in Portugal. Clearly, selection of an impactor to represent the fleet within Europe will be as equally difficult as picking a single impactor to represent the worldwide fleet.

SELECTION OF AN IMPACTOR MASS

The preceding analysis has demonstrated that the median mass of passenger vehicles varies widely from country to country – from 1140 kg for cars in the United Kingdom to 1830 kg for LTVs in the U.S. This huge variation in mass makes the prospects for an internationally harmonized impactor weight very unlikely – unless it can be shown that crash outcomes are relatively insensitive to impactor weight.

The following analysis investigates the outcome of vehicle-to-vehicle frontal impact testing as a function of impactor mass. Based upon the FARS database, Joksch [12] has estimated the relationship between the mass ratio of collision partners, and the fatality ratio of collision partners to be:

$$\frac{F_2}{F_1} = \left(\frac{M_1}{M_2}\right)^4$$

where M_1 = the mass of vehicle 1, M_2 = the mass of vehicle 2, F_1 = fatalities in vehicle 1, and F_2 = fatalities in vehicle 2. This formula predicts that a mass ratio of 2:1 results in a fatality ratio of 16:1—i.e., for vehicle-to-vehicle collisions in which one vehicle weighed twice that of its collision partner, for every fatality in the heavier car there were sixteen in the lighter car.

In the field, there are some crash events that are so catastrophic that only extremely expensive countermeasures are likely to make the crash surviveable. For this analysis, a crash producing a fatality ratio of 10:1 will be referred to as catastrophic. Note that a fatality ratio of 10:1 results from a mass mismatch of 1:1.78.

Using the Joksch relationship between mass ratio, and fatality ratio, the fleetwide outcomes of four different impactor selections were examined for the UK fleet, the Australian fleet, the U.S. car fleet, and the U.S. LTV fleet. To explore the influence of impactor size, this analysis uses the impactor weights corresponding to the median fleet weight in each of these regions. For each impactor, the analysis first examines what fraction of the fleet would fail to provide self-protection in a frontal collision with the impactor. The analysis then examines, for a given impactor, what fraction of the fleet would be overly aggressive, or fail to provide partner-protection in a frontal-frontal collision. For these analyses, failure is defined to be those collisions which are catastrophic (F2/F1 > 10) either for occupants of the subject car or for occupants of the partner.

Note that a vehicle can fail the compatibility test in two ways: (1) if the vehicle cannot provide self-protection in a collision with the impactor, or (2) if the vehicle is overly aggressive in a frontal collision with the impactor. Overly aggressive here implies that the car to be tested would not provide partner-protection if the impactor were a car with occupants.

Table 2. International Fleet Composition by Engine Size [13,14]

<table>
<tr><th>Category</th><th>Mini
(<1000 cc)</th><th>Small
(1000-1800cc)</th><th>Medium
(1800-2500cc)</th><th>Large
(>3000cc)</th></tr>
<tr><td>UK</td><td>8%</td><td>66%</td><td>22%</td><td>4%</td></tr>
<tr><td>Australia</td><td>10%</td><td>36%</td><td>12%</td><td>42%</td></tr>
<tr><td>Japan</td><td>21%</td><td>60%</td><td colspan="2">19%</td></tr>
</table>

Table 3. Passenger Car Sales in Western Europe in 1997 [6]

Country	Small (< 900kg)	Lower Med (900-1100kg)	Upper Med. (1100-1400kg)	Executive (>1400kg)
Austria	19	40%	25%	16
Belgium	24	34	24	17
Denmark	21	39	34	6
Finland	13	39	35	12
France	40	32	19	10
Germany	22	33	22	23
Greece	39	44	13	4
Ireland	36	39	20	5
Italy	57	26	11	6
Luxembourg	23	29	24	24
Netherlands	27	35	26	12
Portugal	54	30	11	4
Spain	36	37	20	6
Sweden	7	29	27	37
England	29	35	24	12
Norway	13	38	36	14
Switzerland	20	31	26	24
Europe Average	**28**	**35**	**23**	**14**

Table 4. Percentage of Passenger Vehicles which would fail to provide Self-Protection by Impactor Mass by Region

Impactor Mass (kg)	Min.Car Size which will pass	% Fail in UK Fleet	% Fail in Aust. Fleet	% Fail in U.S. Car Fleet
1140 kg	640 kg	-	-	-
1240 kg	700 kg	-	-	-
1400 kg	790 kg	< 3	-	-
1830 kg	1030 kg	33	28	7

Table 5. Percentage of Passenger Vehicles which would fail to provide Partner-Protection (Overly Aggressive) by Impactor Mass by Region

Impactor Mass (kg)	Max Vehicle Size which will pass	% Fail UK Fleet	% Fail in U.S. Car Fleet	% Fail in U.S. LTV Fleet
1140 kg	2030 kg	-	-	26
1240 kg	2200 kg	-	-	13
1400 kg	2490 kg	-	-	<1
1830 kg	3250 kg	-	-	-

For self-protection, catastrophic collisions are presumed to occur for subject cars whose weight was less than $M_{Impactor}$*1.78. For each proposed impactor, Table 4 tabulates the minimum weight car which would pass this test. As shown in Table 4, all cars in the UK, Australian, and U.S. fleets would pass a self-protection compatibility test with both the 1140-kg and 1240-kg impactors. For the 1400-kg impactor, the lightest 3% of the UK fleet would suffer catastropic collisions, but the Australian and U.S. fleets would suffer no catastropic collisions. However, for the 1830-kg impactor (representing the median U.S. LTV), approximately 1/3 of the UK and Australian fleets and 7% of the U.S. car fleet would suffer catastrophic collisions.

For evaluation of aggressivity, a subject vehicle is presumed not to cause a catastrophic collision if its weight is less than $M_{Impactor}$/1.78. Table 5 tabulates this maximum weight limit for each proposed impactor. As shown in Table 5, no cars in either the UK or the U.S. car fleets would fail to pass the aggressivity test. Australian data was unavailable for this analysis. However, approximately 26% of LTVs in the U.S. fleet would be deemed catastrophically aggressive in collisions with an 1140-kg impactor. About 13% of the LTVs in the U.S. fleet would be deemed catastrophically aggressive in collisions with a 1240-kg impactor. All but the heaviest 1% of U.S. LTVs would pass an aggressivity test using a 1400-kg impactor as the struck vehicle.

The preceding analyses have been conducted to examine the practical limits on impactor weight. Assuming that a 10:1 fatality ratio is indeed unsurvivable, adoption of an 1830-kg impactor mass would essentially eliminate sub-1000 kg cars from the world's fleets for a failure to provide self-protection. Likewise, adoption of either the 1140-kg or 1240-kg impactor would eliminate a large fraction of the U.S. LTV fleet because of excessive mass-induced aggressivity. Clearly, neither these outcomes nor the impactors which lead to these outcomes are likely to be acceptable.

On the other hand, the 1400-kg impactor, which simulates the median U.S. car mass, does not produce these drastic outcomes and appears to have promise as the basis for a harmonized compatibility test. However, while 1400-kg vehicles are quite common in the U.S., 85-90% of the UK fleet is lighter than this impactor. As collisions with a 1400-kg vehicle are quite rare in the UK, designing for self-protection with this impactor may produce designs which are overly conservative and expensive for the UK accident environment.

The reader should keep in mind that this analysis has examined only one component of incompatibility – mass. A more complete analysis of potential candidate harmonized test procedures must also fully consider the distribution of geometric and stiffness mismatches among the world's fleets and factor these findings into any proposal for an internationally harmonized compatibility test procedure.

CONCLUSIONS

This paper has examined the structure of the passenger vehicle fleets in Australia, the United Kingdom, and the U.S., and, the relationship between fleet composition and real world crash fatalities and the prospects for a single, globally accepted, crash compatibility test procedure. The following conclusions were drawn:

- The structure of the Australian, U.K., and U.S. passenger car fleets are quite dissimilar. U.S. cars (median mass = 1400 kg) are substantially heavier than their counterparts in Europe (median mass = 1140 kg). The Australian car fleet (median mass = 1240 kg) is situated between these two extremes.
- A large component of the U.S. fleet is composed of light trucks and vans (over 45% of sales in 1997). This component is only a very minor component of the Australian fleet (1.5%), and is virtually non-existent in the U.K.
- Fleet composition varies widely from European country to country. For example, on average, small cars (< 900 kg) comprised 28% of all new car sales in Europe in 1997. However, there were considerable individual differences across the continent varying from a low of 7% for Sweden to a maximum of 54% in Portugal. Clearly, selection of an impactor to represent the fleet within Europe will be as equally difficult as picking a single impactor to represent the world-wide fleet
- It is not obvious that a single compatibility test procedure can be developed which is suitable for testing all the world's fleets. For example, an impactor based upon the mass of U.S. LTVs (median mass of 1830-kg) would be substantially heavier than the median mass of cars in any of the three fleets. In the U.K. and Australia, this test would produce results so severe that approximately the lightest 1/3 of these fleets would experience fatality ratios of 10:1 or greater. The severity of this test for lighter vehicles coupled with the fact that LTVs are virtually non-existent in the U.K. fleet and comprise only a small fraction of the Australian fleet would appear to make this test non-practical in these countries.

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