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(8) Only the system using the adult lap and diagonal seat belt alone reduced the head excursion to below the most stringent limit of 500 mm as required in the New Zealand and Australian standards for "net" type devices. Three further systems (one frame seat with webbing lock, the 4-point seat and the adult belt and booster cushion) met the 540 mm limit which represent the centre rear seat of a typical car. If, on the other hand, a criterion of 810 mm (which represents the CRS installed on the non-struck side) were adopted, all the restraints would be satisfactory.

45° oblique impact

(9) All the CRS whether travelling towards (Series 2 tests) or away from (Series 3 tests) the C-pillar had 3 ms chest resultant accelerations less than 50 g, the lowest values being for the 4-point and 2-point seats and the frame seat without a webbing lock when tested towards the C-pillar.

(10) For all the systems the 3 ms head resultant accelerations were below 75 g.

(12) The values of maximum head excursion for all the CRS in oblique impacts was less than a limit of 777 mm (derived from the requirements for frontal impact). The lowest head excursion observed was for the 4-point seat. In general the performance of an adult lap and diagonal system compared well with that of the framed child seats with a webbing lock, and the 2- and 4-point systems.

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Comparison of Car-Bed and Rear-Facing Infant Restraint Systems

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Abstract

Comparisons are made between car-bed and rear-facing infant restraint systems in terms of design concepts, accident experience, use and misuse, and dynamic test criteria. Terminology from various jurisdictions is defined and the different regulation summarized as a starting point for enhancing communication and attempting to harmonize requirements for infant restraint systems. Suggestions are also made for improving the ways in which infant restraints are evaluated, so that these systems will better meet future needs.

Introduction

Parents in Europe and the United Kingdom have traditionally transported their infants in car-beds or carry-cots, some of which are crashworthy or are installed in crashworthy frames. Only in the last few years have rear-facing infant restraints been officially recognized and become available for use. In the United States, on the other hand, rear-facing restraints for infants have been available and used for about 20 years, whereas crashworthy car-beds have not been generally available, and these only as imports. There is currently, however, new interest in such systems for newborn infants, particularly those with positional apnea, Pierre Robin Syndrome, or other medical conditions that require infants to lie flat (1, 2).* Consequently, some U.S. restraint manufacturers are exploring car-bed restraint designs.

Although the two restraint systems are similar in many ways, there are significant differences between them in concept, performance, and use. One purpose of this paper is to highlight these differences, so that more informed choices can be made in selecting an infant restraint. Another purpose is to indicate the different ways in which the same types of infant restraints are evaluated for crashworthiness in different parts of the world as an initial step in arriving at more uniform requirements. Finally, the paper describes potential additions or changes to test dummies and procedures to better address current infant restraint needs.

Terminology

To avoid confusion, some terms should be defined. *Rear-facing infant restraint* is used in this paper to refer to a system that positions the infant in line with vehicle travel, with its hips somewhat flexed and its back toward the front of the car. The system may be designed only for rear-facing use, or it may be convertible to forward-facing use with an older child. The corresponding term used by the United Nations Economic Commission for Europe in ECE 44 is *infant carrier,* but the British standard BS AU 202 on *rearward-facing restraining devices for infants* defines *infant carrier* as only that part of the restraint system that holds the infant, excluding anchorage straps. *Infant restraint system* refers to the complete system within the context of the British standard, while the Australian standard AS 1754–1989 has adopted the phrase *rear-facing enclosing restraint.* The US FMVSS 213 uses *rear-facing child restraint system* for both infant-only and convertible restraints, but the Canadian CMVSS 213 defines the term *infant restraint system* as only rear-facing.

Car-bed restraint is used throughout the paper to refer to a restraint system that positions the infant perpendicular to the direction of vehicle travel and in which the infant lies flat, either prone (chest down) or supine (on its back). *Carry-cot* is the corresponding term used in ECE 44, while *carry-cot restraint* refers to a frame or anchorage system when separate from the carry-cot. In British standard BS AU 186a, however, *carry cot* refers to any flat carrying device for an infant, whether crashworthy or not, and *carry cot restraint* refers to a separate device, not necessarily crashworthy, that is used to retain the carry cot in place on the seat. The US FMVSS 213 uses the term *car bed* as defined above, while the phrase *transversely installed enclosing restraint* was chosen for AS 1754–1989. The term *bassinet restraint* applies to both rear-facing and car-bed restraints in Australian literature, although it is synonymous with car-bed restraint in American usage. Canada does not recognize the car-bed as a restraint system.

*Numbers in parentheses designate references at end of paper.

Design Concepts

Rear-facing infant restraints

In the United States, the most common restraint system for infants under 9 kg (20 lb) is a semi-reclined seat that faces the rear of the car (figure 1). The back surface is typically at an angle of 25 to 45 degrees from vertical, depending on the slope of the vehicle seat on which the restraint is placed. In the U.S. and Canada, the restraint must be able to be anchored in place with only a lap belt, while internal harness straps are provided to secure the infant's shoulders. In an impact, the crash forces are transferred from the back of the restraint to the infant's back, which is its strongest body surface, while the restraint also supports the infant's head. Even in an oblique or lateral impact, the back of the rear-facing infant restraint turns toward the direction of impact, still providing its occupant with effective protection. In rear-end and rollover crashes, the shoulder straps provide containment as the restraint and the infant both rotate in the rearward direction, often completely enclosing the infant against the vehicle seatback. In jurisdictions where rear-facing restraints are allowed to have, and in some cases depend upon, additional belts or anchor straps, the crash dynamics of the restraints will be different.

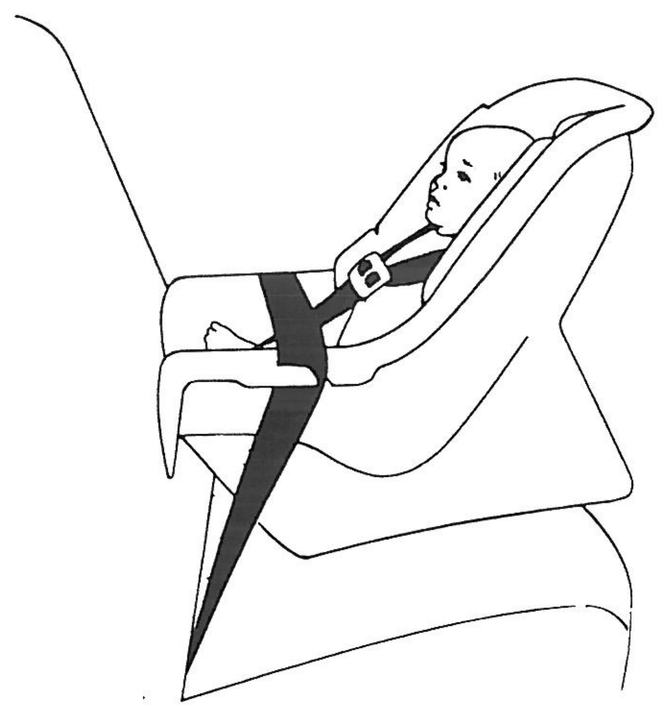

Figure 1. Rear-facing infant restraint secured with lap belt.

The first rear-facing infant restraint in the U.S. was introduced in April 1969 (3). It was the result of careful consideration of many factors, including load distribution, accident characteristics, infant comfort, and parental convenience. Foremost, of course, was the concern that localized loading on the infant's body be avoided, because of the cartilaginous make-up of the skeleton, and that the crash forces be distributed as widely as possible. Because the restraint was designed for infants up to 10 months, it was thought that visual contact with the environment would help make the infant more content. Thus, the designers arrived at a rear-facing, semi-reclined position, with the back slope low enough to keep the infant's head comfortably back during travel but high enough to keep the infant from ramping up the back of the restraint during frontal impact. Although a number of different configurations were considered for the containment straps, double shoulder straps were determined to be the most convenient, effective, and appropriate for the infant's anatomical structure. For further convenience, the restraint was designed to be installed using only the lap belt already available in each seating position.

Car-bed restraints

This type of infant restraint is a natural extension of the way infants are often transported in baby carriages or prams. Many crashworthy systems merely place the pram insert into a sturdy frame that is in turn anchored to the vehicle. One car-bed, currently available in several countries, was designed specifically as a restraint system (figure 2). Others, however, are expected to be available within the year, generated by the realization that some newborns as well as some older infants must lie flat.

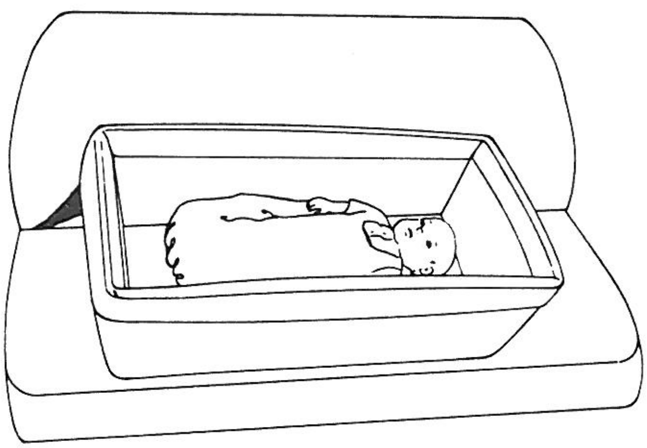

Figure 2. Car-bed infant restraint secured with belts at each end.

The car-bed restraint concept is similar to that of the rear-facing restraint, in that frontal impact loads are distributed over a large body area while the head/neck system is supported and contained. Car-beds also have internal straps, netting, or other fabric systems to keep the infant from ejecting, and they are also often designed to turn toward the seatback on rebound, protecting the infant from flying debris. The critical difference is in oblique and lateral impacts, when the infant's head and neck are theoretically more vulnerable in a car-bed than in a rear-facing restraint.

Although the car-bed may adequately contain the infant in a side impact, direct head loading as well as neck compressive and bending loads may be excessive, especially if the infant's head lies next to the point of impact. The larger the car-bed, the closer the infant's head is likely to be to an exterior panel. Smaller car-beds, which take up only one seating position or half of a bench seat, have the advantage of being installable with the infant's head near the center of the vehicle. When adequate space is available, the internal restraining system in combination with the end structure of the car-bed should be able to limit the infant's motion and absorb enough energy that compressive neck loading should not be a problem. If, however, the head is near the impacted side or there is sufficient intrusion that the end of the car-bed and then the head are stopped by the intruding surface, serious head and neck injury may result.

It is interesting to note that the problem of potential neck compression is recognized for rear-facing restraints by CMVSS 213 and ECE–44, which prohibit any loading to the crown of the head during impact.

Accident Experience

There has been a long history of positive experience with rear-facing infant restraints in the U.S. Properly used, and even sometimes when they are not, rear-facing restraints have proven to be extremely effective in actual crashes (4, 5). It has gotten to the point that no special effort is made any more to investigate their effectiveness in the field. Manufacturers of these systems receive letter after letter from thankful parents whose children have escaped injury in apparently severe crashes, while other members of the family have not been so fortunate.

In contrast, extensive documented evidence of car-bed effectiveness in serious crashes was not discovered either in the literature or from some informal inquiries. Perhaps this is because the use of crashworthy car-beds has not been widespread for a long enough time. Colleagues were able to report a few known cases, however, including one side impact. In all of these cases, the infants were not injured. The side impact involved a motorcycle ramming a subcompact car at approximately the left B pillar. The driver suffered a serious brain concussion, but the infant, whose head was on the impacted side, was not injured (6).

Use and Misuse

Rear-facing infant restraints designed only for such use are relatively light in weight and portable compared to convertible child restraints. Some have handles for carrying, and some have additional positions for in-home use. Although designed to be installed rearward, there is often not enough space between the front and rear seats to accommodate even the smaller infant-only type. Even when there is enough space, parents want to be able to see their babies, particularly when the driver is the only adult in the car. The parent is then left with two choices: put the restraint in the front seat or face it forward in the back. Although the former is really the *only* choice, a third of parents in a recent observation survey did the latter, but more often with convertible than with infant-only restraints (7). Another frequent misuse was to leave the internal harness straps off the infant. This was particularly a problem when the vehicle lap belt was routed over the restraint (41% no harness used), rather than through a slot or frame structure underneath (6% no harness used). Nearly a quarter of the restraints were either belted incorrectly (9%) or not secured at all (14%).

Other than the gross misuse associated with failure to secure the restraint or infant in any way, incorrect usage of these restraints will have varying consequences depending on the particular design. Facing an infant-only restraint forward, with or without the harness straps on, is probably the most serious (figure 3) (8, 9). In the first case, the infant may slide under the vehicle belt until stopped at the neck. In the other case, the infant may flex at the waist around the vehicle belt and suffer spinal and upper abdominal injuries. There are, however, many ways to degrade the performance of rear-facing restraints. Amazingly, most misuse of infant restraints was found to be intentional, with 71% of those facing infant restraints forward knowing it was wrong (7).

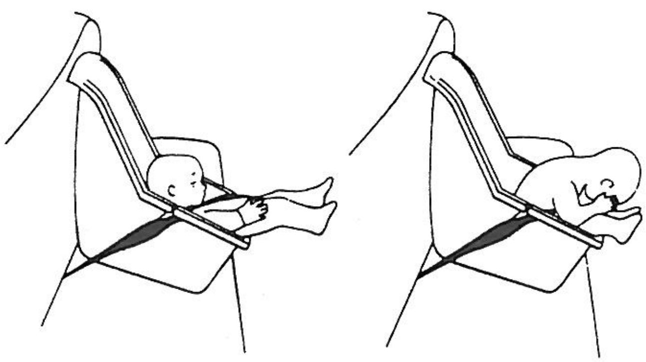

Figure 3. Infant and restraint incorrectly installed facing forward during frontal impact: (A) with shoulder straps in place, (B) without shoulder straps.

Car-beds offer similar opportunities for misuse relative to installation and internal restraint. A survey in Victoria, which reported combined observations of rear-facing and car-bed restraints for children under 6 months, found 22% incorrectly installed and 10% incorrectly worn (10). Although car-beds can only be installed laterally, thus eliminating the forward-facing misuse, those that take up less than the full rear seat can be incorrectly installed with potential serious consequences if the infant's head is placed outboard.

A design complaint often heard by child restraint manufacturers in the U.S. is that rear-facing restraints are too upright for newborns, and thus the head flops uncomfortably forward. Car-beds, of course, solve this problem. Although parents are told that they can prop up the front edge of a rear-facing restraint with a rolled towel until the infant's head lies back, many are reluctant to do this. One reason that rear-facing restraints may be more upright in cars than they were designed to be is that the Standard Bench Seat cushion of FMVSS 213 and CMVSS 213.1 is about 6 degrees more horizontal than the average rear seat (11). Because the primary performance criterion of these standards is a limitation on the maximum back angle during the impact, a back angle that is appropriate for the crash test may be unnecessarily upright for actual use. To improve the crash performance of a rear-facing restraint while increasing the initial back angle, some manufacturers have followed the lead of those in the UK and Europe by adding a slot in back for the vehicle shoulder belt, when it is available (figure 4). This configuration is not allowable, however, when determining compliance with the U.S. or Canadian standards.

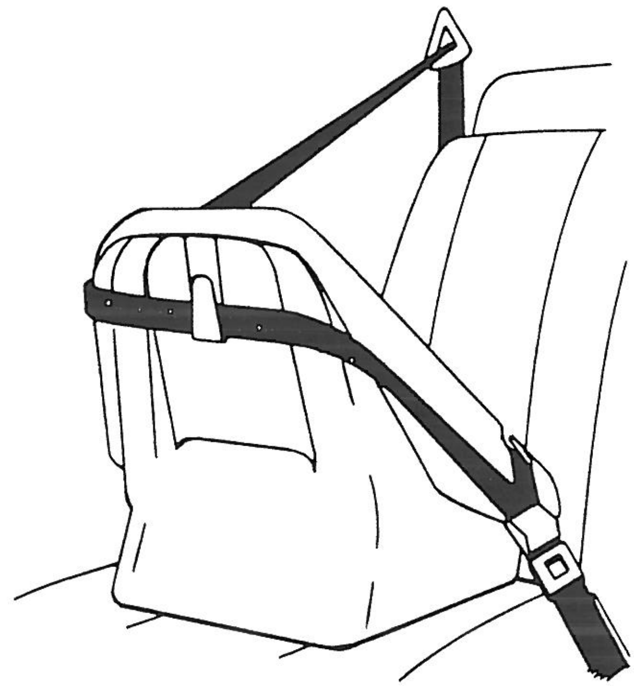

Figure 4. Rear-facing infant restraint secured with lap/shoulder belt.

An infant restraint loan program that has operated in Victoria since May 1985 offers a choice between a rear-facing and a car-bed restraint, both of which are fairly expensive and require special anchorage installation. Over three years time, less than 10% of the participants chose the car-bed. A few of the car-beds were later returned by parents, who said they took up too much space in the back seat (12). The length of time a child can use a car-bed and the space it consumes are obviously related. Perhaps a reduction in size, with an associated reduction in cost, would make car-beds more appealing.

Dynamic Test Criteria

Current standards

It is beyond the scope of this paper to present a comprehensive international review of the different regulations for car-bed and rear-facing infant restraints, but the major elements of dynamic test criteria can be summarized. The U.S. has different requirements for the two restraint types, but ECE–44 evaluates both in the same way. Australia has issued new standards for rear-facing restraints (AS 1754.2–1989), but the corresponding revision for car-beds is still being developed. The UK has dynamic test criteria for rear-facing infant restraints (BS AU 202) but only static test criteria for its carry cots (BS AU 186a). Canada has requirements only for rear-facing restraints. Japanese requirements were not surveyed.

The U.S. and Canada use the CAMI 6-month size dummy (8 kg, 17.4 lb), which has no instrumentation. The UK, ECE, and Australia use the TNO P–3/4 9-month size (9 kg, 20 lb), which can be instrumented in the head and chest. The UK and ECE also use a "new-born" manikin (3.4 kg, 7.5 lb), developed by Ogle and available from TNO, which has no provision for instrumentation. Each standard has a different test bench, although the U.S. and Canadian configurations are nearly identical, as are the ECE and UK test seats. Each standard also has different specifications for belt and harness tensions prior to impact. All require frontal impacts, but only Australia requires lateral and rear impacts.

For rear-facing restraints, the U.S., Canada, and the UK limit the maximum back angle during the impact to 70 degrees from vertical and require that the head targets (center of gravity) remain below the top of the shell, but they do not require any acceleration measurements. The UK and ECE limit forward excursion of the head and torso to 550 mm (21.6 in) from the cushion intersection, but the excursion limit formerly in the Australian standard appears to have been dropped. Australia limits head acceleration to 75 G, while ECE limits the chest acceleration to 55 G for the resultant and 30 G in the inferior-to-superior direction. As noted above, Canada and ECE prohibit any loading to the top of the head.

ECE 44 requires car-beds to meet the same dummy forward excursion and chest acceleration limits as rear-facing infant restraints, while the U.S. standard merely requires containment within the confines of the car-bed. BS AU 186a includes only a static pull test for carry cots and their restraints, and Canada has no test for car-beds, as they are not considered to be restraint systems.

Potential improvements

There is clearly a need to arrive at a more common set of test criteria, considering the fact that the infant occupants and the vehicles they ride in are fairly similar across jurisdictional lines. The differences among rear-facing test configurations and criteria do reflect, however, the differences in installation methods prevalent in the various markets. For instance, all U.S. infant restraints can be installed using only a lap belt, while all rear-facing restraints in Australia have additional anchor straps.

The development of a uniform test seat that reflects current rear seat design should be a high priority. It should also be recognized that forward excursion by itself is less important for rear-facing restraints than for forward-facing ones, because, as long as the infant is retained and the restraint remains relatively upright, the infant's head is shielded from the instrument panel or other surface it may contact. Such a surface can in fact be used to advantage in actual vehicles if the restraint initially rests against it. Likewise, it may not be useful to restrict the forward motion of a dummy in a car-bed to the same extent as one in a forward-facing restraint, because the dummy leads with its torso rather than its head, and the head is relatively low.

Some measure of acceleration, even if based on adult tolerance data, would be useful for both types of infant restraints but is particularly so for car-beds. It is also useful to test all infant restraints with a newborn size dummy to ensure that the internal harness or other restraining system will not release a small, limp body. The "new-born" manikin used by ECE and the UK was developed for this purpose, but it may be somewhat stiff. The incorporation of accelerometers into this or another small dummy would also be helpful in testing the flexibility and energy absorption capabilities of car-beds designed for limited usage and not able to accommodate the larger P–3/4 dummy.

Although frontal impact tests have seemed to be adequate for evaluating rear- and forward-facing restraints in the past, the special problem of car-beds may make lateral testing desirable. In preliminary studies to develop additional test criteria for car-beds, a TNO P–3/4 dummy was modified in an attempt to measure neck compression. A GSE–FT–375–AL load cell, in the shape of a small doughnut, was inserted near the base of the neck column in place of one of the polyamide elements. In impact tests of both rear-facing and car-bed restraints, measured loads varied widely and in the expected directions for different designs, materials, and impact directions. The primary difficulty was that the load cell was sensitive to off-axis loading, so the results were invalid whenever the neck flexed. Further modification to the neck would be necessary if this concept were to be pursued. Such a test device could be applicable both to lateral car-bed testing and to evaluation of a rear-facing restraint that provided an enclosure for the head. If the test device were to respond to compressive loading in the same manner as the Hybrid III head/neck (13), a conservative limit would be 220 lb (1 kN) for short duration loads with no more than 60 lb (0.27 kN) for durations over 30 ms. These values are based on scaling using body weight. If neck dimensions are used, the calculated limits would be 33% higher.

Conclusion

When restraining infants in automobiles, there are two approaches that provide comfort, containment, energy absorption, and load distribution. The semi-reclined rear-facing restraint has been shown to be very effective over many years of use. However, not all infants can tolerate being on their back with their head and shoulders elevated. There is thus a need for a car-bed restraint that protects an infant while lying flat. Many parents and pediatricians may consider the car-bed restraint to be preferable for the small infant even when there is no medical need to use one. Those who do should be advised that there may be an elevated risk of head/neck injury in a lateral impact. At the same time, efforts should be made to reexamine the car-bed restraint concept and to design car-beds that will minimize the risk to further data on the performance of car-beds in crashes need to be gathered, design goals determined, and suitable criteria for laboratory evaluation established.

Although all infant restraint systems have the same purpose, there is a wide variety of methods across various jurisdictions to determine if these restraints will accomplish that purpose. The long-standing lack of biomechanical data for infants makes the task of establishing performance criteria all the more difficult. However, current test devices and procedures, when taken together, do seem to guarantee some threshold of acceptable performance. To increase the choice and availability of effective systems for all parents, however, some uniformity of requirements is needed. In this regard, we hope that the new ISO working group on child restraint systems will be successful.

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