JOURNAL OF ENGINEERING RESEARCH AND TECHNOLOGY, VOLUME 10, ISSUE 1, MARCH 2023

Received on (04-04-2022) Accepted on (10-11-2022)

Analysis of the Effect of Infant Carrier's Webbing Tension on 18-month-old Child Occupant's Chest Accelerations in Frontal Crash Accidents Based on Experimental Validations

Zhe Wei

https://doi.org/10.33976/JERT.10.1/2023/1

Abstract—Infant carriers play an important role in protecting child occupants from severe injuries caused by collisions, but the tension of harness webbing cannot be controlled properly most of the time. Infant carrier's user manual or instruction generally contains little information about the extent to which the adjusting belt should be pulled to cause the necessary webbing tension, and it is often neglected that the infants should be restrained securely. In order to improve public awareness, it is important to ascertain the effect of infant carrier's webbing tension on the occupant's chest accelerations. A testing scheme including 12 dynamic tests was devised and conducted, and test conditions were controlled strictly to ensure the accuracy and objectivity of results. P1.5 dummy's resultant and vertical chest accelerations were collected and analyzed. Both ISOFIX installation and seat belt installation methods were taken into consideration without lack of generality. Sled's accelerations and velocities were set and acquired, which constituted the fundamental testing conditions of dynamic tests and ensured the repeatability and reliability of tests. Furthermore, dummy's chest acceleration pulses were monitored and recorded, and the data were evaluated in accordance with criteria defined in relevant technical standards. The dummy's chest accelerations were classified into 2 groups according to child restraint systems' installation methods, i.e., the ISOFIX group and the seat belt group. In each group, both resultant chest acceleration and vertical chest acceleration were involved. Universal phenomena were displayed in all the tests, and the larger the tensile forces were, the lower the chest accelerations were in tests. Based on experimental validations, the relation between webbing's tensions and chest accelerations in frontal crash accidents was verified. Furthermore, suggestions were made about adjusting the webbing tension and the proper use of infant carriers.

Index Terms—Infant carrier; Tensile force; Child occupant; Frontal crash; Dynamic tests

I INTRODUCTION

Child restraint system is capable of being anchored to a power-driven vehicle, and is so designed as to diminish the risk of injury to the wearer, in the event of a collision or of abrupt deceleration of the vehicle, by limiting the mobility of the wearer's body. Being an effective device to keep child occupants from harmful and fatal secondary collisions between children and the vehicle in traffic accidents, child restraint systems play an important role in reducing preventable injuries and fatalities of child occupants [1]. In many countries, child restraint systems are very popular with caregivers, and widely used in adults' driving with children in cars [2, 3]. Actually, child restraint system, as a special device for passive safety, has been used for many decades, and at present has evolved greatly, can be considered as a sophisticated system especially when it functions in real accidents [4]. In order to achieve the optimum state of child restraint systems in use, many matters in the field of passive safety should be taken into consideration [5, 6, 7].

Meanwhile, regulations and technical standards about child restraint systems have been developed and entered into force in many countries [8]. For example, UN Regulation No. 44 and No. 129 are widely adopted and used in Europe, while FMVSS 213 and CMVSS 213 are perceived as the norms and specifications in the design, manufacture and use supervision of child restraint systems in North America [9]. In addition, GB 27887-2011 and AIS-072 are effective standards used compulsorily in China and India respectively, with the aim of standardizing the product, ensuring the safety performance, and protecting child occupants ultimately. In Japan, Brazil, South Africa and many other countries, similar regulations or standards also exist. Hence, different governments have reached a common view in improving the safety performance of child restraint systems and providing a powerful safeguard for child occupants [10, 11, 12].

There are many kinds and types of child restraint systems, and infant carrier is a very common one. Infant carrier is oriented to child occupants with comparatively lower ages, e.g., children from newborn to those aged 1 year or so, and it is different from child-safety seat, carry-cot, and booster cushion, etc., no matter in structure, function and installation methods [13]. Nevertheless, dynamic test methods are basically the same in different regulations and technical standards, and the differences mainly lie in the requirements about magnitudes of physical quantities and dimensions. Since infants are more vulnerable to abrupt deceleration of vehicle than toddlers, more rigorous requirements should be set for infant carriers, as reflected in most regulations [14, 15, 16]. In accordance with Regulations such as UN Regulation No. 44 and No.129, infant carriers generally belong to Group 0+, which is defined as the mass group suitable for children of a mass less than 13 kg.

In the daily use of infant carriers, inappropriate installations and wrong use can result in severe injuries or fatalities to infant occupants [17]. Heavy lessons from traffic accidents have raised public awareness in the proper use of infant carriers, and various researches and studies have been conducted on product standardization, safety performance improvement, injury evaluation, standards amendment, etc [18, 19, 20]. Achievements have also been made in the fields related to passive safety [21, 22, 23]. However, some inadequacies of usages are being exposed gradually, including but not limited to the control of tension of webbing that constitutes the harness used to restrain the child occupant [24]. Especially, the webbing tensile force is usually ignored by child occupants' parents or caregivers when they use infant carriers, for instructions and user manuals do not indicate and define the factor at all. Results in dynamic tests conducted in laboratories accredited according ISO/IEC 17025:2017 have shown that webbing tensile force is an unavoidable factor influencing accelerations of child dummies. In order to avoid the undue effects of the factor on testing results, measures have been taken to minimize the uncertainty, such as means of standardization or normalization of the magnitude of webbing tensile force in a dynamic test [25]. On the basis of that, testing results become comparable, and then can be analyzed. Despite the fact that laboratories begin to realize the importance of standardizing testing conditions, infant occupants' caregivers' failure to know or understand the relation between harness' webbing tensile force and infants' accelerations which is directly related to potential injuries, nevertheless, still remain a non-negligible factor in causing preventable injuries and fatalities. Furthermore, emphasis of past researches have seldom been placed on the aspect, thus making people pay less attention to the issue [26]. Therefore, it is necessary to carry out relevant research and to draw enough attention to the danger and harm of neglect or ignorance of controlling the tension of harness' webbing properly [27, 28, 29].

A testing scheme was devised to verify the effect of webbing tensile force on P1.5 dummy's chest accelerations. P1.5 dummy weighs about 11kg, and is suitable for being a substitute for infant whose mass and size fit child restraint systems of group 0+. Harness is mainly used to restrain child occupant's thorax and laps, and limit the mobility of the occupant's body. Furthermore, serious chest injuries could bring about more hazards and even deaths because of the locations of most vital organs [30, 31]. So chest accelerations can be a good choice for the current research, and they are in more direct relation with harness' webbing tensile force. In view of the installation methods of infant carriers, both ISOFIX, which is a system that provides a method of connecting a child restraint system to a vehicle, and is based on two vehicle anchorages and two corresponding attachments on the child restraint system in conjunction with a means to limit the pitch rotation of the child restraint system, and 3-point seat belt are taken into consideration, with the aim of diminishing the effect of installation methods on testing results.

Being an effective way to simulate and reproduce real crash accidents, dynamic tests were conducted in a devised pattern to verify the effect [32, 33, 34]. In most regulations and technical standards, the resultant chest acceleration shall not exceed 55 g except during periods whose sum does not exceed 3 ms, and the vertical component of the acceleration from the abdomen towards the head shall not exceed 30 g except during periods whose sum does not exceed 3 ms. Since they are basic safety requirements, the resultant and vertical accelerations of P1.5 dummy's chest in dynamic tests are taken as the object for quantitative research. As to the issue, it is more scientific and objective to explore the current research based on experimental validations than pure computer simulation, for the quality of computer simulation depends on algorithms to a great extent [35, 36, 37]. Furthermore, simulation itself needs experimental validation to check its validity and correctness [38, 39]. Small variation in configuring initial conditions for computer simulations may lead to a large discrepancy in results, while it is more robust when it comes to a real dynamic test. Hence, the current research is solely based on experimental validations for obtaining more accurate results.

Similar researches have been conducted, but seldom ones have been oriented to ameliorating the balance between child occupant's comfort feeling and safety, and to what extent should child restraint system's adjusting belt be pulled has never been ascertained [2, 4]. On the one hand, there are many different types, kinds, or groups of child restraint systems, and each system does not necessarily have the same structure, rigidity, and even installation methods [14]. It is difficult to ascertain the proper tensile forces for different restraint systems. On the other hand, child occupants are different, e.g., some are fat and tall, while others are thin and short. Besides, their feelings about comfort may vary greatly. Therefore, it is meaningless and even impossible to ascertain or calculate each value of tensile force in using child restraint systems. Being one kind of child restraint system, infant carriers are mainly used for children under the age of 18 months, i.e., from newborn to 1.5 years old. Although it is not necessary to ascertain each proper tensile force of harness restraining child occupants, to some extent, it is important to ascertain the relation between tensile forces and child occupants' safety. As to each infant carrier, it is possible to obtain the relation curve between the webbing tension and dummy's chest accelerations by experimental methods, thus making the relation displayed visually. However, the emphases of other researches have more been put on the structure design, the simulation algorithm, safety improvement in design and manufacture, proper installation and appropriate use, etc., than on the tensile force control. Since tendency exists that ISOFIX becomes more and more adopted in child restraint systems' installations, and the seat belt installation method is also applicable to infant carriers, the two installation methods are both analyzed in the research, which is different from the prior researches. In addition, the harness' webbing tensile force is directly related to child occupant's safety, and the harness consists of shoulder belts and abdomen belts used to restrain child occupant, so varying the values of tensile forces will result in variations of chest accelerations inevitably. By experimental validations for each installation methods including ISOFIX and seat belt, the relation curves between webbing's tensile force and child occupant's chest acceleration can be obtained. It is more meaningful and applicable to use such a curve than to know a single force value in instructing caregivers to use restraint systems. Therefore, the research filled the gap in the field. The findings in the research will help make a compromise between safety and comfort easily, and help improve infant carrier's safety in applications.

II METHODOLOGY

A Test Instruments, Equipment and Samples

Generally, dynamic test is oriented to simulating the real crash and obtaining the necessary information about safety performance of passive safety devices, and is normally conducted by means of special equipment and instruments. Being the impact simulator, sled or trolley is employed to reproduce collision conditions, and cause the devices for passive safety to function as they do in real world collisions. Sled can be classified into 2 types, i.e., sled of acceleration type and the one of deceleration type. In the past, sled of deceleration type was widely used because of its convenience and low cost in conducting various dynamic tests. Even nowadays, sled of the type can be seen in many laboratories and factories, for deceleration pulses can be generated in different ways, such as using specific structures of energy-absorbing mechanisms, pressing steel or polyurethane tubes, and deforming steel bars, which are all successful cases in carrying out dynamic tests in different laboratories. However, the reproducibility and repeatability can not be so well ensured when sled of deceleration type is employed in most cases, although the sled ' s deceleration pulses may also fall into the specified range. Meanwhile, it is more complicated to operate than the sled of acceleration type, and therefore, the latter one is comparatively a time-saving device. Hence, sled of the acceleration type was employed in the current research so that the reliability, objectiveness, and precision of test results could be ensured to a great extent. In Figure.1, (a) displays a kind of sled of the deceleration type , and (b) shows the sled used in the research. The deceleration or acceleration data of the sleds are generally collected by the accelerometers mounted on the sleds. Exactly speaking, only when acceleration pulses fall into the range defined by standards or regulations, can the tests be perceived as qualified ones, if dynamic tests are conducted according to the requirements and methods of relevant standards or technical regulations. In many other cases, acceleration curves are specified before tests, and yet similarity and coincidence are essential between real pulses and the curves set as objects.

Considering that the injury criteria of the dummy in frontal crashes were researched on, the definition of curves for frontal impact in most regulations including UN Regulation No.44, UN Regulation No.129, and GB 27887-2011, etc., was adopted in the current research, as shown in Figure.2. Acceleration pulses of the sled ' s falling into the specified zone being the prerequisite for sled tests, their closest approximation to the object curves has further beneficial effects on obtaining more exact test results.

The P1.5 dummy was chosen as a substitute for child occupant aged 18 months, and it was put into the infant carrier in accordance with user manual and installation instruction. Nevertheless, the manual or instruction generally indicates no information about the extent to which the adjusting belt should be pulled. Hence, tensions of the adjusting belt at 3 different levels were taken into consideration to verify the effects of harness webbing's tension on the chest accelerations of P1.5 dummy. Actually, the adjusting belt is connected to the harness straps, and is used to adjust the tension of the webbing constraining child occupant's torso, as for the structure and function of each infant carrier. In other words, the webbing's tension can be increased or decreased by changing the tensile force of adjusting belt during installation. The forces were applied to the adjusting belts of infant carriers by a force gauge at 3 different levels. The force gauge had been calibrated, and was used as the force-applying device, as displayed in Figure.3. In addition, the forces were applied with the same deflection angles to ensure comparable, objective and proper force transmissions and distributions.

The infant carrier samples involves 2 kinds of installation methods, i.e., using the ISOFIX and using 3-point seat belt respectively. Both were taken into consideration in the research so that test results could be comprehensive and representative. The samples can be classified into 2 kinds according to installation methods, but samples of the same kind are completely the same in the category, type, structure, and even the brand. The total quantity of infant carriers used in the testing scheme is 12, 6 sets for each kind of installation method respectively, as is tabulated in Table.1. Infant carriers are generally installed rearward-facing, since it is safer for a newborn baby or toddler to be kept rearward-facing in driving because of young child's physical structure. But even being kept rearward-facing and using the rearward-facing restraint system, cannot necessarily ensure child occupant's safety, if harness webbing's tensile forces cannot be controlled properly. Forward-facing child restraint systems are more used for children aged three or more, and will not be involved in the research.

.

(a) (b)

Figure.1 Sleds of the Deceleration Type and the Acceleration Type

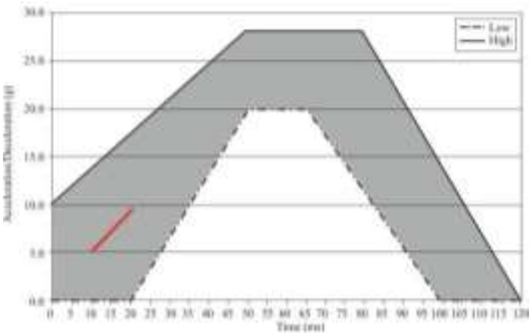

Figure.2 Definition of Curves for Frontal Impact

Figure.3 Force Gauge

Table.1 Testing Scheme

Test No.	Installation Method	Dummy	Sled Type	Tensile Force (N)	Parameters to Measure (g)
1, 2	ISOFIX	P1.5	Acceleration	360	Resultant chest acceleration & Vertical component of the acceleration from the abdomen towards the head
3, 4	ISOFIX	P1.5	Acceleration	260	
5, 6	ISOFIX	P1.5	Acceleration	160	
7, 8	Seat Belt	P1.5	Acceleration	360	
9, 10	Seat Belt	P1.5	Acceleration	260	
11, 12	Seat Belt	P1.5	Acceleration	160	

B Experimental Procedure

The infant carrier was firstly placed on the test seat. Then the P1.5 dummy was placed into the infant carrier, and gap existed between the rear of the dummy and the restraint. A hinged board 2.5 cm thick and 6 cm wide, and of length equal to the shoulder height less the hip centre height in the sitting position of P1.5 dummy, was put between the dummy and the back of the infant carrier. The board followed as closely as possible the curvature of the infant carrier and its lower end was at the height of the dummy's hip joint. Figure.4 displays the hinged board used to cause the slack which is unavoidable in the actual state when an infant carrier is used to protect the child occupant in a vehicle.

The adjusting belt was pulled by means of the force gauge in accordance with the testing scheme shown in Table.1. The tensions were applied at 3 different levels, with deflection angles of the belt at the adjuster of $45^{\circ} \pm 5^{\circ}$ for all the samples, as displayed in Figure.5.

During installation of the infant carrier with adult seat belt to the test seat, the 3-point seat belt incorporating a diagonal belt and a lap belt was used in the same way before each dynamic test. As for infant carriers with ISOFIX attachments, top tether and supporting leg can both be used as the anti-rotation device, and prevent infant carriers from rotating in frontal crashes effectively. In the current research, samples with ISOFIX attachments relied on the supporting legs to stay stable in dynamic tests. In the process of installation, ISOFIX attachments were connected and used uniformly to ensure that the installation would not influence the test results too much. Finally, the hinged board was removed just before the sled system was launched and the test started. Standardization of installation is of great importance, since non-standardization brings about more errors and makes test results not comparable.

Because the foam test cushion would compress after installation of the infant carrier, the dynamic test was conducted no more than 10 minutes after installation as possible. To allow the cushion to recover, the period between 2 dynamic tests using the same cushion was 20 minutes. Figure.6 shows the final state of the sled and the installed infant carrier with P1.5 dummy in it before the test start.

Figure.4 The Hinged Board Used to Cause the Slack

Figure.5 The Way to Apply the Tension

(a) (b)

Figure.6 The Final State of the Sled and the Samples of 2 Kinds before Test Starts

C Evaluation Criteria

The dummy of 11 kg is required to use for the tests of Group 0+ device, and it is the biggest dummy for the group. That means the P1.5 dummy displayed in Figure.7 could cause more severe damages to the restraint system in frontal collisions than P0 dummy and P3/4 dummy do. Since child occupants' chest accelerations are directly relevant with the tension of infant carrier's harness straps, accelerations of the part of P1.5 dummy's body can be collected for analysis in the 12 tests. However, the lateral acceleration, i.e., the acceleration of Y axis are influenced less than the ones of the other 2 axes obviously by frontal collisions. Generally, resultant chest acceleration and the vertical component of the acceleration from the abdomen towards the head are required to measure in most regulations and technical standards concerned. To ensure the objectivity and generality, the 2 parameters are also taken into full consideration for the evaluation of potential injuries caused by arbitrariness in the extent to which the adjusting belt of a infant carrier is pulled. Especially, the acceleration of Z axis and the resultant acceleration of dummy's chest are obviously the most significant factors that can be influenced by a frontal collision, considering that the infant carrier accommodates the child occupant in a rearward-facing semi-recumbent position.

The resultant chest acceleration exceeding 55 g except during periods whose sum does not exceed 3 ms, or/and the vertical component of the acceleration from the abdomen towards the head exceeding 30 g except during periods whose sum does not exceed 3 ms, can be perceived as a failure to meet the requirements of relevant regulations and technical standards. In laboratories, safety performance of the infant carrier is also generally evaluated based on the criteria, when it comes to the injury potentials of child occupant's chest in traffic crashes.

Figure.7 P1.5 Dummy

III Experimental Results

A Sled's Accelerations and Velocities

After conducting the testing scheme, the accelerations and velocities of the sled were collected, as shown in Figure.8 and Figure.9. Acceleration pulses all fall into the specified zone, and are qualified and valid ones that meet the requirements.

Besides, they have the same trends as the object curves. As for the velocities, the maximum one is 51.6 km/h, and the minimum one is 50.5 km/h, i.e., all the velocities are valid and within the specified range. Detailed information is tabulated in Table.2, and the data about sled's velocities and accelerations are shown. Although discrepancies between data exist, test conditions of the 12 dynamic tests could be deemed to be the same because of high coincidence between pulses.

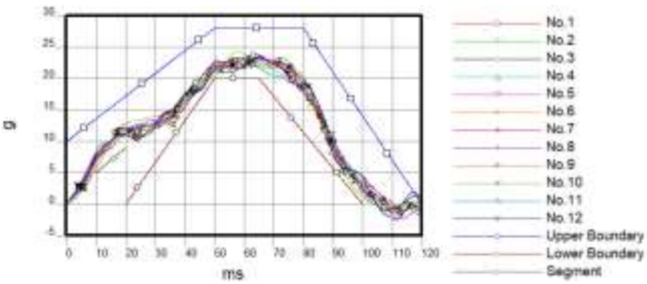

Figure.8 Sled Acceleration Pulses in 12 Dynamic Tests

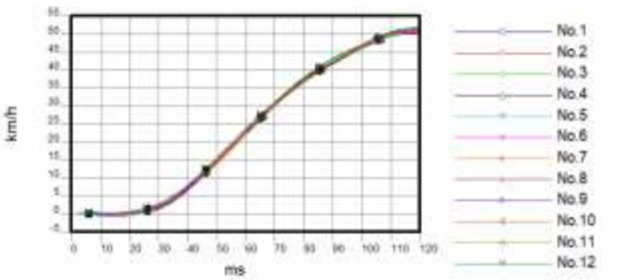

Figure.9 Sled Velocity Pulses in 12 Dynamic Tests

Table 2. Sled's Accelerations and Velocities in Tests

Test No.	Peak Acceleration	Velocity	Test No.	Peak Acceleration	Velocity
1	22.9 g	50.7 km/h	2	23.2 g	50.5 km/h
3	23.7 g	51.8 km/h	4	23.2 g	51.0 km/h
5	23.1 g	50.7 km/h	6	22.8 g	51.0 km/h
7	23.3 g	51.6 km/h	8	23.0 g	51.2 km/h
9	22.7 g	50.2 km/h	10	22.9 g	50.7 km/h
11	22.6 g	50.7 km/h	12	23.2 g	51.6 km/h

B Dummy's Chest Accelerations

According to the testing scheme, both resultant chest acceleration and vertical component of the acceleration from the abdomen towards the head were collected. Due to data acquisition achieved by the accelerometer and the follow-up data processing, pulses of resultant chest accelerations and vertical chest accelerations of P1.5 dummy were displayed, as shown in Figure.10, Figure.11, Figure.12, and Figure.13. The measuring procedures corresponded to those defined in ISO 6487: 2002, and the channel frequency class (CFC) was set as CFC 180 for signal filtration. Figure.10 and Figure.11 display how the resultant and vertical chest accelerations of P1.5 dummy change with the changes of sled's accelerations when infant carriers with ISOFIX attachments are tested. All the tests from No.1 to No.6 are relevant with safety performance of the infant carrier equipped with ISOFIX interface used to install the system to the vehicle. The tests from No.7 to No.12 involve the research on the infant carrier using seat belt for installation. Figure.12 and Figure.13 show that, being the functions of time, the resultant and vertical chest accelerations change in real time under the action of sled's motion.

As shown in Table.3, P1.5 dummy's maximum chest accelerations during periods whose sum exceeds 3 ms in dynamic tests from No.1 to No.12 are all obtained, and the results include 2 kinds, i.e., resultant chest acceleration and the vertical component of the acceleration from the abdomen towards the head. All the data are adequate to respond to the testing scheme, and the relation between the infant carrier's webbing tension and the chest accelerations of child occupants in frontal crash accidents could be revealed based on the analysis of the data.

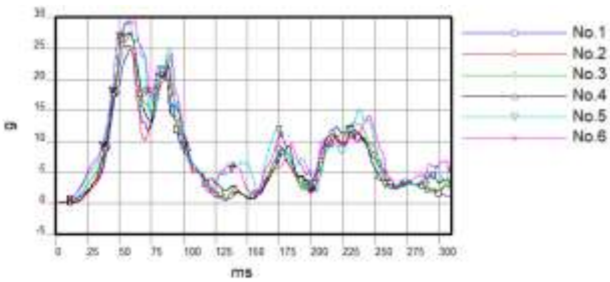

Figure.10 P1.5 Dummy's Resultant Chest Acceleration Pulses in Dynamic Tests from No.1 to No.6

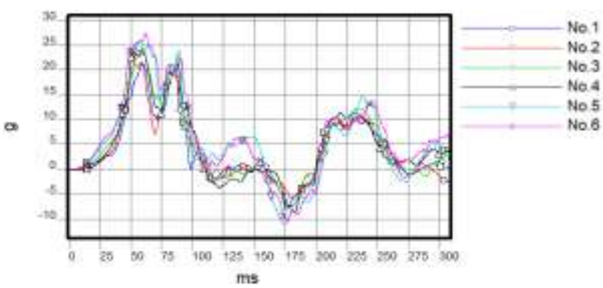

Figure.11 P1.5 Dummy's Vertical Chest Accelerations from the Abdomen towards the Head in Dynamic Tests from No.1 to No.6

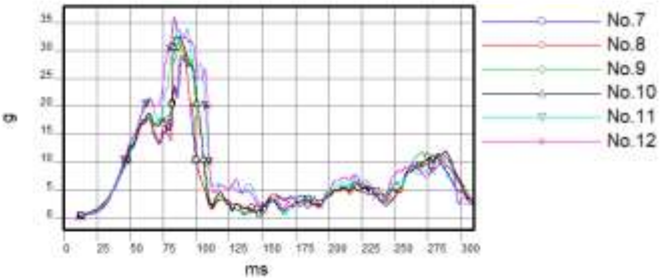

Figure.12 P1.5 Dummy's Resultant Chest Acceleration Pulses in Dynamic Tests from No.7 to No.12

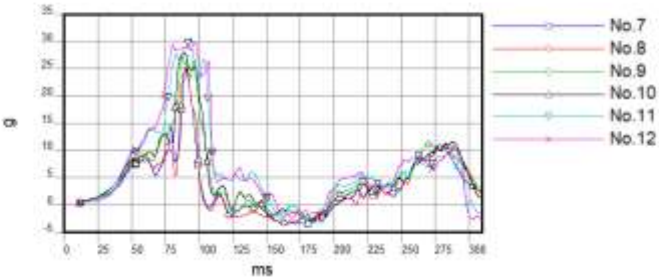

Figure.13 P1.5 Dummy's Vertical Chest Accelerations from the Abdomen towards the Head in Dynamic Tests from No.7 to No.12

Table.3 P1.5 Dummy's Maximum Chest Accelerations during Periods Whose Sum Exceeds 3 ms in Dynamic Tests from No.1 to No.12

Test No.	Resultant Chest Acceleration	Vertical Chest Acceleration	Test No.	Resultant Chest Acceleration	Vertical Chest Acceleration
1	24.8 g	21.1 g	2	25.5 g	21.6 g
3	27.6 g	23.8 g	4	27.4 g	24.2 g
5	29.3 g	25.9 g	6	29.5 g	27.4 g
7	28.7 g	25.0 g	8	29.1 g	25.4 g
9	32.2 g	27.3 g	10	32.5 g	27.9 g
11	35.4 g	30.7 g	12	36.1 g	29.9 g

IV Discussion

Sled test being the simulation of a real crash, it is an effective way to reproduce the crash conditions and validate the hypothesis about passive safety. In order to ensure the reliability, repeatability, objectivity, and accuracy of testing scheme and its output, test conditions including but not limited to sled's accelerations and velocities, must be set meticulously. Based on the testing results, it can be concluded that the sled ran in a stable state during the 12 tests, and the pulses of either acceleration or velocity were almost the same between different tests. In addition, the acceleration pulses meet the requirements of UN Regulation No.44, UN Regulation No.129, and other similar regulations. Therefore, the testing scheme can be conducted effectively and will not bring about avoidable errors, thus preventing results' deviations from happening.

As for the chest accelerations of P1.5 dummy, it indicates that the injury potentials could be influenced greatly by the harness' webbing tension. There is a negative correlation between the chest accelerations and the tensile force of infant carrier's webbing. No matter which method of installation is used in tests, it appears that the bigger the tensile force is, the lower the chest acceleration is. It is the same for both resultant chest acceleration and vertical chest acceleration, as shown in Figure.14 and Figure.15.

Although infant carrier equipped with ISOFIX attachment shows obvious advantages in safety performance, the relation between chest acceleration and webbing's tension seems not to be related to installation method. In other words, installation method influences infant carrier's safety performance mainly, yet it cannot change the trends of the effects of webbing Tension on child occupant's chest accelerations, and the effects are objective existences. Nevertheless, controlling the tensile force of an infant carrier is a paradox, because increasing the tension of webbing will inevitably affect the comfort, and make child occupants unwilling to wear the harness or to use the infant carrier. It is also meaningless to make the harness too loose, for the feeling of comfort cannot be made at the expense of safety.

Generally, there are some ways to solve the problem. Firstly, choosing a proper installation method is of importance, for ISOFIX attachments help reduce chest accelerations in frontal crashes. Once an infant carrier equipped with ISOFIX is used, the webbing tension can be decreased to some extent, so that the feeling of comfort can be ensured. Secondly, making some necessary slacks of webbing can also lead to a good user experience. But it depends on the sense and knowledge of caregivers, and needs some skills. Risk still exists that the child occupants may fail to be restrained in collisions. Thirdly, the product itself can be optimized and redesigned to improve the safety performance, and it involves a lot of work. Finally, based on the current research, it is better and easier to keep the webbing tightened to the extent that the wearer can endure and shows no obvious rejection of the use. Since the child occupants are too young to tell their feelings anytime, it is essential that caregivers or adult occupants have close observations and pay enough attention to the states of infants. Adjusting the webbing's Tension may be frequent, for safety and comfort are both important for infants in a vehicle.

Nevertheless, the tensile forces were chosen from a proper range, i.e., the forces or so that fall into the range are more likely to be applied by caregivers. So it is nearly impossible to bring about restraint failures or severe injuries if sled's accelerations are set according to technical standards, and if the infant carriers are qualified and have no inherent quality problems or defects. Undoubtedly, if the webbing's tensile force is zero, the chest acceleration will inevitably exceed the limit and appear greater than the permitted one, which has been proved in many laboratories. Similarly, if the force is too large, the occupant will feel very uncomfortable and will not cooperate in wearing the harness. In the respect, the tensile forces chosen in the research are typical. Moreover, the quality of products, public awareness, and many other relevant factors must be taken into consideration in actual applications. The tensile force remains one of risk sources in applications, is very likely to be neglected or ignored, and should be paid enough attention to.

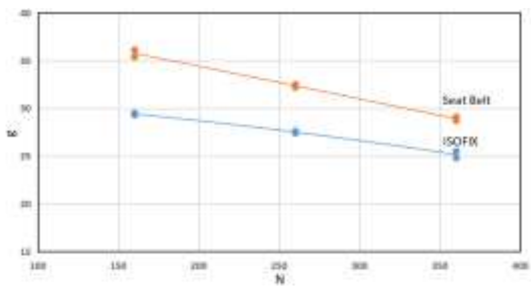

Figure.14 Relation between Resultant Chest Accelerations and Webbing's Tensions

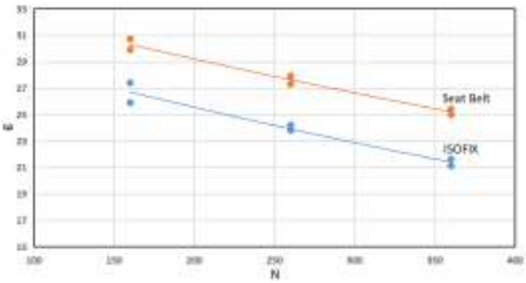

Figure.15 Relation between Vertical Chest Accelerations and Webbing's Tensions

V CONCLUSION

A testing scheme incorporating 12 dynamic tests was devised and conducted, and the data obtained were analyzed. The accelerations and velocities of the sled were controlled strictly to meet the relevant requirements, and the repeatability of crash conditions was ensured. The resultant chest accelerations and the vertical components of the accelerations from the abdomen towards the head of P1.5 dummy were collected for further analysis of the relation between the infant carrier's safety performance and webbing's tension. Based on the testing results, the analysis leads to the following conclusions:

There is a negative correlation between infant carrier's webbing tensile force and the chest acceleration of the child occupant in frontal crash accidents. It is necessary to tighten the harness' webbing enough during vehicle's driving, for bigger tensile force of webbing means lower accelerations of chest when a collision happens. Although occupant's feeling of comfort should be emphasized, the safety cannot be ignored especially. Equal emphasis should be placed on pulling the adjusting belt and tightening the harness when an infant carrier is used, even user manual or instruction indicates little information about the extent to which the adjusting belt should be pulled.

Besides, infant carrier equipped with ISOFIX attachment has the better safety performance than the one using seat belt for installation. ISOFIX and the anti-rotation device help reduce the impact that the child occupant suffers from, and it is superior to the installation method using seat belt, on the aspects of convenience, misuse prevention, and protection effect, etc.

No matter what installation method is adopted, relation exists between webbing's tensile forces and child occupant's resultant and vertical chest accelerations objectively. The accelerations can be influenced by harness webbing's tensile forces for both installation methods, even though the influence levels are different.

REFERENCES

[1] F. Muhammad Butt, M. A. Dalhat, K. Shahid Minhas, and A. Al-mojil, "Influence of seat belt use behavior and road traffic crash experience on the use of child restraint systems: A step further," J. King Saud Univ. - Eng. Sci., 2021, doi: https://doi.org/10.1016/j.jksues.2021.07.005.

[2] M. Cornelissen, M. Hermans, L. Tuijl, M. Versteeg, E. van Beeck, and E. Kemler, "Child safety in cars: An observational study on the use of child restraint systems in The Netherlands," Traffic Inj. Prev., vol. 22, no. 8, pp. 634–639, 2021, doi: https://doi.org/10.1080/15389588.2021.1980562.

[3] B. A. West, M. A. Yellman, and R. A. Rudd, "Use of child safety seats and booster seats in the United States: A comparison of parent/caregiver-reported and observed use estimates," J. Safety Res., vol. 79, pp. 110–116, 2021, doi: https://doi.org/10.1016/j.jsr.2021.08.011.

[4] C. Visvikis, C. Thurn, M. Kettner, and T. Müller, "The effect of chin-to-chest contact on upper neck axial force in UN Regulation No. 129 frontal impact tests of child restraint systems," Traffic Inj. Prev., vol. 21, pp. S173–S176, 2020, doi: https://doi.org/10.1080/15389588.2020.1829923.

[5] B. S. Acar, "Passive Prevention Systems in Automobile Safety," R. B. T.-I. E. of T. Vickerman, Ed. Oxford: Elsevier, 2021, pp. 406–414.

[6] A. V. Ngo, J. Becker, D. Thirunavukkarasu, P. Urban, S. Koetniyom, and J. Carmai, "Investigation of occupant kinematics and injury risk in a reclined and rearward-facing seat under various frontal crash velocities," J. Safety Res., vol. 79, pp. 26–37, 2021, doi: https://doi.org/10.1016/j.jsr.2021.08.001.

[7] Y. Liu, X. Wan, W. Xu, L. Shi, G. Deng, and Z. Bai, "An intelligent method for accident reconstruction involving car and e-bike coupling automatic simulation and multi-objective optimizations," Accid. Anal. Prev., vol. 164, p. 106476, 2022, doi: https://doi.org/10.1016/j.aap.2021.106476.

[8] S. Levi, H. Lee, W. Ren, S. McCloskey, and A. Polson, "Reducing child restraint misuse: national survey of awareness and use of inspection stations," Traffic Inj. Prev., vol. 21, no. 7, pp. 453–458, 2020, doi: https://doi.org/10.1080/15389588.2020.1782896.

[9] P. Baranowski, K. Damaziak, L. Mazurkiewicz, J. Malachowski, A. Muszynski, and D. Vangi, "Analysis of mechanics of side impact test defined in UN/ECE Regulation 129," Traffic Inj. Prev., vol. 19, no. 3, pp. 256–263, 2018, doi: https://doi.org/10.1080/15389588.2017.1378813.

[10] D. S. Usami, L. Persia, and V. Sgarra, "Determinants Of The Use Of Safety Restraint Systems In Italy," Transp. Res. Procedia, vol. 45, pp. 143–152, 2020, doi: https://doi.org/10.1016/j.trpro.2020.03.001.

[11] B. Benzaman, N. J. Ward, and W. J. Schell, "The influence of inferred traffic safety culture on traffic safety performance in U.S. States (1994–2014)," J. Safety Res., 2021, doi: https://doi.org/10.1016/j.jsr.2021.12.014.

[12] M. Haghani, A. Behnood, O. Oviedo-Trespalacios, and M. C. J. Bliemer, "Structural anatomy and temporal trends of road accident research: Full-scope analyses of the field," J. Safety Res., vol. 79, pp. 173–198, 2021, doi: https://doi.org/10.1016/j.jsr.2021.09.002.

[13] B. Albanese et al., "Influence of child restraint system design features on comfort, belt fit and posture," Saf. Sci., vol. 128, p. 104707, 2020, doi: https://doi.org/10.1016/j.ssci.2020.104707.

[14] G. Lee, C. N. Pope, A. Nwosu, L. B. McKenzie, and M. Zhu, "Child passenger fatality: Child restraint system usage and contributing factors among the youngest passengers from 2011 to 2015," J. Safety Res., vol. 70, pp. 33–38, 2019, doi: https://doi.org/10.1016/j.jsr.2019.04.001.

[15] L. Williams, T. Standifird, and M. Madsen, "Effects of infant transportation on lower extremity joint moments: Baby carrier versus carrying in-arms," Gait Posture, vol. 70, pp. 168–174, 2019, doi: https://doi.org/10.1016/j.gaitpost.2019.02.004.

[16] A. Raj, C. W. Christian, J. E. Reid, and G. Binenbaum, "A baby carrier fall leading to intracranial bleeding and multilayered retinal hemorrhages," J. Am. Assoc. Pediatr. Ophthalmol. Strabismus, 2022, doi: https://doi.org/10.1016/j.jaapos.2021.10.008.

[17] J. B. Cicchino and J. S. Jermakian, "Vehicle characteristics associated with LATCH use and correct use in real-world child restraint installations," J. Safety Res., vol. 53, pp. 77–85, 2015, doi: https://doi.org/10.1016/j.jsr.2015.03.009.

[18] A. Alrejjal, A. Farid, and K. Ksaibati, "Investigating factors influencing rollover crash risk on mountainous

interstates," J. Safety Res., 2021, doi: https://doi.org/10.1016/j.jsr.2021.12.020.

[19] R. Schindler, C. Flannagan, A. Bálint, and G. Bianchi Piccinini, "Making a few talk for the many – Modeling driver behavior using synthetic populations generated from experimental data," Accid. Anal. Prev., vol. 162, p. 106331, 2021, doi: https://doi.org/10.1016/j.aap.2021.106331.

[20] G. Deng et al., "Assessment of standing passenger traumatic brain injury caused by ground impact in subway collisions," Accid. Anal. Prev., vol. 166, p. 106547, 2022, doi: https://doi.org/10.1016/j.aap.2021.106547.

[21] L. Lalika, A. E. Kitali, H. J. Haule, E. Kidando, T. Sando, and P. Alluri, "What are the leading causes of fatal and severe injury crashes involving older pedestrian? Evidence from Bayesian network model," J. Safety Res., 2021, doi: https://doi.org/10.1016/j.jsr.2021.12.011.

[22] B. Wali, N. Ahmad, and A. J. Khattak, "Toward better measurement of traffic injuries – Comparison of anatomical injury measures in predicting the clinical outcomes in motorcycle crashes," J. Safety Res., 2021, doi: https://doi.org/10.1016/j.jsr.2021.11.013.

[23] D. V McGehee, C. A. Roe, P. Kasarla, and C. Wang, "Quantifying and recommending seat belt reminder timing using naturalistic driving video data," J. Safety Res., 2022, doi: https://doi.org/10.1016/j.jsr.2021.12.022.

[24] C. Se, T. Champahom, S. Jomnonkwao, P. Chaimuang, and V. Ratanavaraha, "Empirical comparison of the effects of urban and rural crashes on motorcyclist injury severities: A correlated random parameters ordered probit approach with heterogeneity in means," Accid. Anal. Prev., vol. 161, p. 106352, 2021, doi: https://doi.org/10.1016/j.aap.2021.106352.

[25] P. D. Tremoulet, A. Belwadi, B. Corr, S. Sarfare, T. Seacrist, and S. Tushak, "How do novel seat positions impact usability of child restraints?," Transp. Res. Interdiscip. Perspect., vol. 10, p. 100372, 2021, doi: https://doi.org/10.1016/j.trip.2021.100372.

[26] S. Kendi, M. B. Howard, M. A. Mohamed, S. Eaddy, and J. M. Chamberlain, "So much nuance: A qualitative analysis of parental perspectives on child passenger safety," Traffic Inj. Prev., vol. 22, no. 3, pp. 224–229, 2021, doi: https://doi.org/10.1080/15389588.2021.1877276.

[27] C. Buderer et al., "Effects of Multisystemic Therapy for Child Abuse and Neglect on severity of neglect, behavioral and emotional problems, and attachment disorder symptoms in children," Child. Youth Serv. Rev., vol. 119, p. 105626, 2020, doi: https://doi.org/10.1016/j.childyouth.2020.105626.

[28] A. Li, S. Shen, A. Nwosu, K. L. Ratnapradipa, J. Cooper, and M. Zhu, "Investigating traffic fatality trends and restraint use among rear-seat passengers in the United States, 2000–2016," J. Safety Res., vol. 73, pp. 9–16, 2020, doi: https://doi.org/10.1016/j.jsr.2020.02.005.

[29] C. Missikpode, C. J. Hamann, and C. Peek-Asa, "Association between driver and child passenger restraint: Analysis of community-based observational survey data from 2005 to 2019," J. Safety Res., vol. 79, pp. 168–172, 2021, doi: https://doi.org/10.1016/j.jsr.2021.08.016.

[30] T. Whyte, N. Kent, L. Keay, K. Coxon, and J. Brown, "Frontal crash seat belt restraint effectiveness and comfort accessories used by older occupants," Traffic Inj. Prev., vol. 21, no. 1, pp. 60–65, Jan. 2020, doi: 10.1080/15389588.2019.1690648.

[31] H. Fagerlind, L. Harvey, P. Humburg, J. Davidsson, and J. Brown, "Identifying individual-based injury patterns in multi-trauma road users by using an association rule mining method," Accid. Anal. Prev., vol. 164, p. 106479, 2022, doi: https://doi.org/10.1016/j.aap.2021.106479.

[32] C. S. Parenteau, D. C. Viano, and R. Burnett, "Second-row occupant responses with and without intrusion in rear sled and crash tests," Traffic Inj. Prev., vol. 22, no. 1, pp. 43–50, 2021, doi: https://doi.org/10.1080/15389588.2020.1842380.

[33] D. C. Viano, R. A. Burnett, G. A. Miller, and C. S. Parenteau, "Influence of retractor and anchor pretensioning on dummy responses in 40 km/h rear sled tests," Traffic Inj. Prev., vol. 22, no. 5, pp. 396–400, 2021, doi: https://doi.org/10.1080/15389588.2021.1910243.

[34] Z. Wei, "Effects of Deceleration on Secondary Collisions between Adult Occupants and the Vehicle in Frontal Crash Accidents," Int. J. Eng., vol. 34, no. 12, pp. 2658–2664, 2021, doi: 10.5829/ije.2021.34.12c.11.

[35] F. F. Florena, F. Faizal, and S. Viridi, "Experimental and simulation study of solid flows in beads mill," Adv. Powder Technol., vol. 32, no. 8, pp. 2703–2711, 2021, doi: https://doi.org/10.1016/j.apt.2021.05.029.

[36] A. Das and M. M. Ahmed, "Adjustment of key lane change parameters to develop microsimulation models for representative assessment of safety and operational

impacts of adverse weather using SHRP2 naturalistic driving data," J. Safety Res., 2022, doi: https://doi.org/10.1016/j.jsr.2022.01.002.

[37] H. Bin Tahir, M. M. Haque, S. Yasmin, and M. King, "A simulation-based empirical bayes approach: Incorporating unobserved heterogeneity in the before-after evaluation of engineering treatments," Accid. Anal. Prev., vol. 165, p. 106527, 2022, doi: https://doi.org/10.1016/j.aap.2021.106527.

[38] A. I. Dmitriev, L. B. Voll, and V. L. Popov, "The final NO-WEAR state due to dual-mode fretting: Numerical prediction and experimental validation," Wear, vol. 458–459, p. 203402, 2020, doi: https://doi.org/10.1016/j.wear.2020.203402.

[39] Y. Cheng, K. Liu, Y. Li, Z. Wang, and J. Wang, "Experimental and numerical simulation of dynamic response of U-type corrugated sandwich panels under low-velocity impact," Ocean Eng., vol. 245, p. 110492, 2022, doi: https://doi.org/10.1016/j.oceaneng.2021.110492.

Zhe Wei is a senior engineer in National Quality Supervision and Inspection Centre for Engineering Machinery affiliated to China Academy of Machinery Science and Technology. He obtained the B. Sc and M. Sc in 2007 and in 2010 respectively. His research field is related with vehicle's passive safety now. As the first author and the first inventor, he has more than 30 publications and 5 authorized patents. Meanwhile, he owns the premium membership of Chinese Society of Agricultural Machinery and is the committee member of SAC/TC 240.