Abdominal and Thoracic Injury Risk Functions for the Large Omni-directional Child (LODC) ATD

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Abstract The objective of this study was to develop injury risk functions for the Large Omni-directional Child (LODC) ATD abdomen and thorax. Paediatric specimen biomechanical data were gathered from literature, and thorax deflection and abdomen pressure were collected when the LODC was tested in the same conditions. Using the assumption of biofidelity and the measured relationships between various LODC responses, abdomen pressure and thorax deflection, compression, and velocity were estimated for paediatric specimen tests and used with the paediatric injury outcomes to construct risk functions. The maximum abdomen pressure associated with 50% risk of AIS3+ injury was found to be 114.5 kPa. LODC sled test data in various restraint conditions associated with low (e.g. 5-point harness) and high (e.g. submarining in lap belt only) probability of abdominal injury aligned well with the injury risk function. For the thorax, V_{max}*C_{max} was found to be the strongest predictor of thoracic injury, with a 50% risk of AIS2+ injury of 0.45 m/s. The accuracy of the thorax risk function was evaluated using LODC data from several restraint conditions, real-world cases using LODC response relationships, and literature-reported V_{max}*C_{max} injury thresholds for adult specimens.

Keywords Abdomen, Injury Risk, Large Omni-Directional Child, Paediatric, Thorax

I. INTRODUCTION

The abdomen is the second most commonly injured body region, after the head, for children in motor vehicle crashes [1-2]. For older children restrained by a belt in both booster seat child restraint systems (CRS) as well as belt-only cases, these abdomen injuries usually occur through loading of the lap portion of the belt [1]. Three kinematic patterns that resulted in abdominal injury due to lap belt compression were identified from real-world crashes in a primarily frontal direction: pre-submarining, where the lap belt is improperly positioned too high above the pelvis on the abdomen; classic submarining, where the lap belt is properly positioned over the pelvis pre-crash but the pelvis slides under while the torso reclines during the crash; and submarining and jackknifing, where the pelvis slides under the belt while the torso flexes forward [2].

There have been several studies that have investigated abdominal injury risk in paediatric post-mortem human subjects (PMHSs) [3-4] and animal models [5-6] where belt penetration was the focus for the development of an injury risk function (IRF). The issue with using belt penetration is that this measurement is not easily made with a soft anthropomorphic test device (ATD) abdomen in a sled or crash environment. It is easier to measure pressure in such a component because pressure is a non-directional, full system measurement where two relative positions in the abdomen do not have to be accurately tracked in three-dimensional space. Internal pressures were collected in studies with adult PMHS, during either an impact or belt loading event, with resulting injuries documented [7-9]. A pressure-based IRF was developed from that work. However, it is uncertain how that risk function can (or should) be applied to a child occupant.

For children, the abdominal and thoracic organs are more closely related than in adults from a protection standpoint as the boney thorax is more superior in children, providing less protection to the solid organs underneath [10]. Although injuries to the thorax are less common than injuries to the abdomen in children, protection of the thorax is also important as it contains vital organs that are necessary for life. Thoracic injuries to children are different than those to adults due to different material properties; therefore, an age-based thoracic injury criterion might be more appropriate [11]. Children frequently sustain pulmonary injuries with the absence of rib fractures, which is different than adults, where internal organ injuries are rare without rib fractures

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[10-11]. When children sustain rib fractures, the injuries are usually severe [10]. It has been hypothesised that thoracic injury in children is dependent on the rate of loading, more so than in adults. The rib flexibility of younger occupants is greater than older occupants, resulting in less injury at lower speeds. At higher speeds, this increased flexibility permits deformation to the underlying viscoelastic tissue, where a high loading rate results in lung injuries such as pulmonary contusion, without rib fracture [10][12].

Current methods for developing thoracic injury criteria for children involve scaling adult-based criteria, which is often based on rib fracture severity in adult PMHS tests [10]. These criteria predict rib fracture risk with the occasional soft tissue injury. However, a thorax injury criterion for children should do the opposite – predict a soft tissue injury with the occasional rib fracture. It has been observed that due to a more compliant thorax, there is an increased occurrence of pulmonary contusion in children and that this occurrence increases with a higher delta V, or a higher loading rate [12]. In other studies, pulmonary contusions have been found to be rate dependent [13-15]. The rate sensitivity of soft tissue injury was reported and the viscous criterion has been proposed as the best predictor of soft tissue injury in the thorax [16]. However, it is uncertain how this criterion should be applied to children. There have been paediatric biomechanical studies [4, 17-18] aimed at characterising the thoracic response in varying loading conditions that reported thorax compression magnitudes, thorax loads, and thorax compression rates along with injuries.

The National Highway Traffic Safety Administration (NHTSA) is developing the Large Omni-directional Child (LODC) ATD, which contains a pressure-measuring abdomen and a deflection-measuring thorax component, with force-deflection responses matching paediatric biomechanical data with excellent biofidelity ranking system (BRS) scores of 0.79 and 0.78, respectively [19-20]. To measure pressure, the LODC abdomen is equipped with Abdominal Pressure Twin Sensors (APTS) (Transpolis, France). To measure thoracic compression, the LODC thorax is equipped with a laser displacement sensor (Althen Sensors & Controls) at the mid-thorax (6^{th} thoracic vertebra) level. Injury risk functions (IRFs) for the abdomen and thorax are needed so that the LODC can be used to design optimised restraint strategies that minimise the risk of both abdominal and thoracic trauma to children.

Due to the difficulty of measuring belt penetration in a soft ATD abdomen in vehicle tests, a pressure-based child abdomen IRF would be more practical. Additionally, a thorax IRF that includes a rate component would be more appropriate for characterising the soft tissue injuries seen in children. Therefore, the objective of this study is to use available data from biomechanical studies and corresponding injury outcomes, along with LODC responses and real-world case information, to develop pressure-based abdomen and rate dependent thorax IRFs for the LODC ATD.

II. METHODS

Biomechanical data from non-injurious and injurious tests conducted at various velocities on paediatric specimens subjected to abdominal and thoracic loading were gathered from literature. The abdominal pressures and thorax deflections for the LODC were obtained under similar loading conditions [19, 20]. Using the assumption of biofidelity and the measured relationships between various LODC responses (abdomen pressure vs. belt penetration, internal vs. external thorax deflection, deflection vs. deflection rate), LODC abdomen pressure and thorax deflection metrics associated with the paediatric specimen tests in those previous studies were estimated and used with the injury outcomes to construct abdomen and thorax IRFs. For the abdomen, an IRF using maximum pressure was constructed. For the thorax, compression, velocity, and several combinations of compression and velocity were compared statistically to determine the strongest predictor. The accuracy of the resulting IRFs were then verified by examining LODC data from several restraint conditions, test data from the literature, and real-world crash cases.

Abdomen Injury Risk Function

For the development of an abdomen IRF, the first step was to quantify the relationship between LODC abdominal pressure, as recorded by the APTS, and abdomen penetration measured externally using a string potentiometer attached to the belt in fixed back belt tests. The average pressure (average of left and right APTS) vs. belt penetration for each of five repeated tests in this configuration are shown in Fig. A1. These pressure and penetration responses were then averaged across the five tests at each time interval to find their means. A curve was fitted to the mean pressure vs. mean penetration curve (Fig. A2) resulting in Eq. A1.

Eq. A1 was then applied to porcine abdomen penetration data [5-6] and human PMHS data [3-4] in order to estimate LODC abdominal pressures in those tests. Estimated LODC abdominal pressures from the porcine penetration data are shown in Table AI and from the human PMHS penetration data are shown in Table AII.

An LODC relationship between pressure rate and penetration rate was also constructed to investigate whether other metrics derived from pressure should be considered. However, this relationship did not encompass the penetration rates reported by Kent [5-6] and extrapolating the relationship to the desired rates could not be justified due to the nonuniformity of the curve. Additionally, Kent [6] found that penetration was a good predictor of injury outcomes while penetration rate was not. Therefore, in this study, since penetration is related to pressure, only maximum pressure was used as the predictor of abdomen injury.

For the porcine data [5-6], the presence of injury was defined as Abbreviated Injury Scale (AIS) 3+ since this information was available. For the PMHS data from [4], no gross abdominal injuries were observed during the tests. For the PMHS data from [3], all but one subject sustained an abdominal injury. Test numbers, estimated LODC abdominal pressures, and the presence of injury are listed in Table I.

TABLE I
ESTIMATED LODC ABDOMINAL PRESSURES AND PRESENCE OF INJURY FROM PORCINE AND PAEDIATRIC DATA

Data	Pressure kPa	Injury Y or N	Data	Pressure kPa	Injury Y or N
Porcine [5-6]			Porcine [5-6]		
PAC1.01	136	N	*PAC1.32*	120	N
PAC1.02	142	Y	*PAC1.33*	128	Y
PAC1.03	123	Y	*PAC1.34*	137	Y
PAC1.04	137	Y	*PAC1.35*	126	Y
PAC1.05	144	Y	*PAC1.36*	100	N
PAC1.06	174	Y	*PAC1.37*	98	N
PAC1.07	114	Y	*PAC1.38*	132	Y
PAC1.08	120	Y	*PAC1.39*	141	Y
PAC1.09	104	N	*PAC1.40*	120	Y
PAC1.10	162	N	*PAC1.41*	126	Y
PAC1.11	102	N	*PAC1.42*	133	Y
PAC1.12	88	N	*PAC1.43*	149	N
PAC1.13	102	N	*PAC1.44*	166	Y
PAC1.14	129	N	*PAC1.45*	191	Y
PAC1.15	116	Y	*PAC1.46*	162	Y
PAC1.16	125	N	*PAC1.47*	140	Y
PAC1.17	88	N	Paediatric PMHS [4]		
PAC1.18	78	Y	*PEDVE9*	68	N
PAC1.20	128	Y	*PEDVE10*	78	N
PAC1.21	128	Y	*PEDVE11*	83	N
PAC1.22	112	Y	*PEDVE24*	49	N
PAC1.23	125	N	*PEDVE25*	76	N
PAC1.24	145	N	*PEDVE26*	78	N
PAC1.25	132	Y	Paediatric PMHS [3]		
PAC1.26	128	Y	*Subject5*	151	Y
PAC1.27	88	N	*Subject6*	163	Y
PAC1.28	133	Y	*Subject7*	316	N
PAC1.29	143	Y	*Subject8*	243	Y
PAC1.30	78	N	*Subject9*	198	Y
PAC1.31	123	Y			

The presence of injury (yes = 1, no = 0) from the total of 57 tests listed in Table I are plotted against the estimated LODC abdominal pressures for each of the corresponding tests in Fig. A3. Using the software R version 3.6.0 (The R Foundation for Statistical Computing, 2019), a Weibull Survival function was fitted to the injury versus abdominal pressure data. Non-injury data was considered to be right censored. Injury data from the porcine studies [5-6] and human PMHS study [3] were considered to be left censored. Although multiple impact data from the human PMHS study [4] was used, no injuries occurred, so these were also considered non-injurious right censored data. Due to a high pressure without injury, the PMHS data point [3] for *Subject7* (316 kPa, no injury) was found by R using the difference in beta values (DFBETAS) statistic to be overly influential. The pressures were estimated using Eq. A1 and it is possible that the high penetration for *Subject7* resulted in an over-estimated pressure due to the use of a nonlinear curve to fit the LODC pressure vs. penetration data. This nonlinear curve predicts an abrupt increase in pressure at penetrations beyond the range of the LODC data.

Thorax Injury Risk Function

Low-speed thorax cardiopulmonary resuscitation (CPR) data [18], medium speed diagonal belt pull data [4], and high-speed pneumatic impact data [17] were utilised in the construction of a thorax injury risk curve. Compressions were calculated from the data as a percentage of chest depth. Velocities, or rates of thorax penetration, were differentiated from the thorax penetration-time histories. Maximum compression (C_{max}), maximum velocity (V_{max}), and several combinations of compression and velocity that have been proposed in previous studies [16] were used as predictors for the construction of the injury risk curve.

The presence of thorax injury was defined as AIS2+. For the CPR data, no injuries were observed. For the diagonal belt pull data, injuries were observed in three tests. For the high speed impact data, injuries were observed in all tests. Test numbers, compression and velocity predictors, and presence of injury are listed in Table BI (see Appendix B).

The presence of injury (yes = 1, no = 0) was then plotted versus the various LODC compression-velocity predictors for the development of an injury risk curve. Using the software R version 3.6.0 (The R Foundation for Statistical Computing, 2019), Weibull Survival functions were fitted to the data. Non-injury data was considered to be right censored. Injury data from the high speed impact [17] and CPR [18] studies were considered to be left censored. The diagonal belt pull study [4] consisted of multiple impact data and injury data from this study (*PEDVE19* and *PEDVE34*) were considered to be interval censored. The area under receiver operating characteristic (AUROC) was used as the primary indicator for the goodness of fit where a score closer to 1 indicates a better fit. Log Likelihood (LogLik), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC) were used as secondary indicators of goodness of fit where scores closer to zero indicate a better fit. The scores for the different statistical measures are summarised in Table II. An IRF based on the product of maximum penetration rate and maximum compression ($V_{max}*C_{max}$) was found to be the strongest predictor of thoracic injury.

TABLE II
STATISTICAL COMPARISON OF CANDIDATE INJURY METRICS
AUROC – SCORE CLOSER TO 1 IS BETTER
LOGLIK, AIC, BIC – SCORES CLOSER TO ZERO ARE BETTER

	$(V*C)_{max}$	$[V*C/(1-C)]_{max}$	$V_{max}*C_{max}$	V_{max}	C_{max}
AUROC	0.962	0.962	0.974	0.974	0.923
LogLik	-3.6	-3.61	-2.25	-3.25	-5.82
AIC	11.19	11.23	8.5	10.5	15.63
BIC	13.18	13.22	10.5	12.49	17.62
Rank	3	4	1	2	5

The paediatric biomechanical data consists of external measures, but internal measures are needed for the LODC thoracic IRF. With the assumption that the LODC thorax is biofidelic [19-20], the relationship between the external and internal compression and penetration rate was developed from LODC component tests (diagonal belt pull and probe impacts) where both external and internal measurements were recorded over a range of loading rates (Fig. B1 and Fig. B2). These relationships were then applied to the biomechanical data in order to convert external to LODC internal measures for the development of the injury risk curve shown in Table III.

TABLE III
PAEDIATRIC BIOMECHANICAL TEST EXTERNAL AND INTERNAL MEASUREMENTS AND INJURY OUTCOMES

Test ID	Ref	External Measurements			Internal Measurements			Injury
		V_{max}	C_{max}	V_{max}*C_{max}	V_{max}	C_{max}	V_{max}*C_{max}	
		m/s	%	m/s	m/s	%	m/s	Y or N
Subj6	[17]	5.9	58.0	3.42	5.2	47.2	2.47	Y
Subj7		6.7	50.8	3.41	5.9	41.4	2.46	Y
Subj8		6.3	51.3	3.23	5.6	41.8	2.33	Y
Sub9		7.0	38.1	2.67	6.2	31.1	1.93	Y
PEDVE16	[4]	2.5	22.5	0.56	2.2	18.3	0.40	N
PEDVE18		2.4	24.5	0.59	2.1	20.0	0.42	Y
PEDVE32		2.0	29.6	0.59	1.8	24.1	0.43	N
PEDVE33		2.0	30.1	0.60	1.8	24.5	0.43	N
PEDVE34		2.2	40.9	0.90	1.9	33.3	0.65	Y
PEDVE43		1.8	24.9	0.45	1.6	20.3	0.32	N
CPR1	[18]	0.3	20.2	0.05	0.2	16.5	0.04	N
CPR3		0.5	36.8	0.17	0.4	30.0	0.12	N
CPR4		0.4	21.0	0.07	0.3	17.1	0.05	N
CPR6		0.4	22.8	0.10	0.4	18.5	0.07	N
CPR7		0.3	25.1	0.08	0.3	20.4	0.05	N
CPR8		0.4	30.4	0.12	0.4	24.7	0.09	N
CPR9		0.3	18.0	0.05	0.3	14.7	0.04	N
CPR10		0.5	19.7	0.10	0.4	16.1	0.07	N
CPR11		0.4	24.2	0.09	0.3	19.7	0.07	N

III. RESULTS

IRFs for both the LODC abdomen and thorax were constructed by estimating LODC abdomen pressures and thorax V_{max}*C_{max} for paediatric biomechanical tests. The IRFs are shown below.

Abdomen Injury Risk Function

The Weibull injury risk curve for LODC abdominal pressure is shown in Fig. 1 with an AUROC score of 0.82, indicating a good fit.

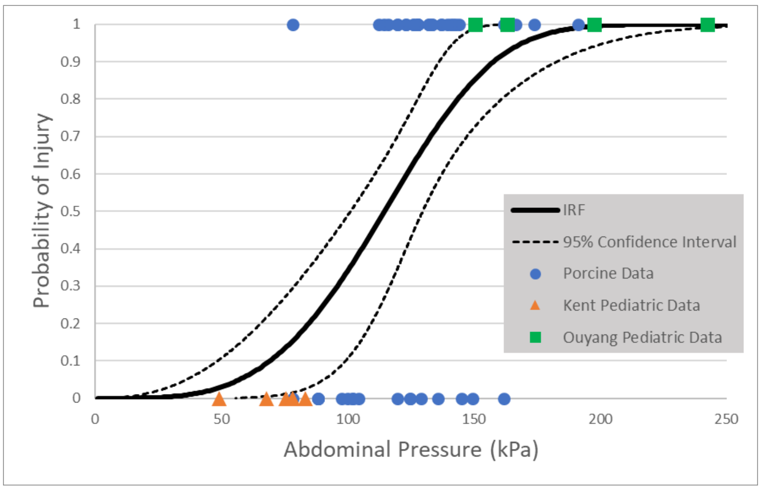

Fig. 1. Weibull survival injury risk function for LODC abdominal pressure.

The pressure-based abdomen IRF shown in Fig. 1 is described by the following equation with shape and scale parameters of 3.74879 and 126.2844, respectively:

$$F(x) = 1 - e^{-(x/126.2844)^{3.74879}} \quad (1)$$

Pressures corresponding to different risk levels typically used as injury criteria in ATD testing are in Table IV.

TABLE IV
PRESSURES CORRESPONDING TO VARIOUS RISK LEVELS TYPICALLY USED FOR ATD INJURY CRITERIA

Abdomen Injury Risk	Pressure (kPa)
5%	57.2
10%	69.3
25%	84.7
50%	114.5
75%	137.8

Thorax Injury Risk Function

The Weibull injury risk curve for LODC thorax $V_{max}*C_{max}$ is shown in Fig. 2 with an AUROC score of 0.97, indicating a good fit.

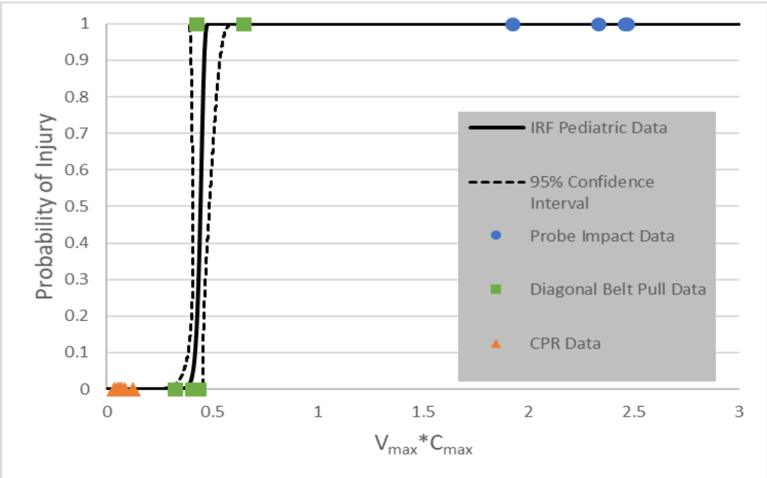

Fig. 2. Weibull survival injury risk function for LODC thorax $V_{max}*C_{max}$.

The thorax IRF using paediatric biomechanical data shown in Fig. 2 is described by the following equation with shape and scale parameters of 11.7919 and 0.4719295, respectively:

$$F(x) = 1 - e^{-(x/0.4719295)^{11.7919}} \quad (2)$$

Table V lists the $V_{max}*C_{max}$ values corresponding to different risk levels typically used as injury criteria in ATD testing.

TABLE V
$V_{MAX}*C_{MAX}$ VALUES CORRESPONDING TO VARIOUS RISK LEVELS TYPICALLY USED FOR ATD INJURY CRITERIA

Thorax Injury Risk	$V_{max}*C_{max}$ (m/s)
5%	0.41
10%	0.42
25%	0.43
50%	0.45
75%	0.46

IV. DISCUSSION

Abdomen Injury Risk Function

From the abdomen IRF shown in Eq. 1, an average LODC abdominal pressure (peak of the average of left and right pressures) of 114.5 kPa will result in a 50% risk of AIS3+ injury, which agrees with previous LODC sled testing where submarining was observed [19]. Fig. 3 shows the LODC abdomen pressures in various CRS conditions. In the belt positioning booster (BPB) seat cases, there was slight engagement of the shoulder portion of the belt with the upper portion of the abdomen, but above where the pressure sensors are located. In the "No CRS" cases, there is minimal shoulder belt engagement with the abdomen as the shoulder belt rests high on the thorax. Therefore, a majority of the pressures in these sled tests were from the lap portion of the belt, which matches the belt pull tests used for the IRF. In tests where the LODC was properly seated and no submarining was observed ("Backless BPB," "5-pt Harness," "Highback BPB"), abdomen pressures were all 69 kPa or lower, which corresponds to a risk level below 10%. On the other hand, tests where submarining and excessive lap belt intrusion into the abdomen was observed - lap/shoulder belted LODC in a slouched posture seated without a child restraint system ("No CRS - Slouch") and LODC seated upright without a child restraint system with only a lap belt ("No CRS - Lap Belt Only") - resulted in abdomen pressures of 223 kPa or more (100% risk of abdominal injury). In the case where no CRS was used and the LODC was positioned upright ("No CRS – Upright"), the average pressure was 92 kPa, which gives a 26.3% risk of abdominal injury according to the risk function. This agrees with previous research [2], which found that belt compression directly to the abdomen due to improper lap belt placement, poor posture, or shoulder belt misuse resulted in abdominal injury.

Another check on the validity of the LODC risk function was made by comparing the risk function to what is currently being used for the Q child dummies. Abdomen pressures from simulating 19 case reconstructions were used to construct an injury risk curve for the Q3 and Q6 child ATDs [21]. It was determined that a pressure of slightly above 1 bar (100 kPa) corresponded to a *separation between inappropriate and appropriate loading conditions observed in Q6 sled testing* [21]. Such a limit is likely to relate to a 20% to 50% risk of AIS3+ injury for the Q6 child ATD, and for the Q10, *the same separation may occur at slightly higher pressure levels* [1]. In another study, maximum pressures between 1.4 and 1.7 bar (140 – 170 kPa) were suggested for the transition between no AIS2- and AIS3+ abdominal injury [22]. These assessments are very consistent with what has been determined for the LODC pressure-based abdomen IRF.

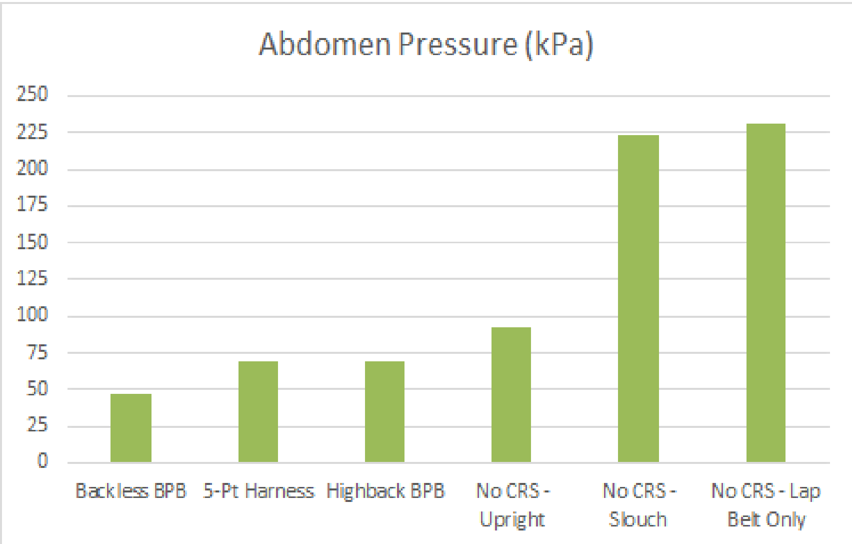

Fig. 3. LODC pressures measured in sled tests with different restraint conditions [19]
(BPB – belt positioning booster)

Both peak rate of pressure change ($\dot{P}_{max}$) multiplied by the peak pressure, $P_{max}*\dot{P}_{max}$, (50% risk = 710 kPa^2/ms) and peak rate of pressure change, $\dot{P}_{max}$, (50% risk = 10.2 kPa/ms) were better correlated with injury than peak pressure alone in PMHS testing [7, 8, 9]. A similar set of rate-dependent pressure variables were derived from the LODC sled tests shown in Figure 3 (Table VI). Based on these calculations, the rate-dependent pressure variables provide very similar demarcations between restraint conditions as peak pressure (child restraint cases are non-injurious, No CRS – Upright is marginal, No CRS – Slouch/Lap Belt Only are injurious). Given this similar discrimination between restraint conditions, it is possible that a rate-dependent pressure metric may be a more accurate injury indicator than pressure alone.

TABLE VI
COMPARISON OF PRESSURE-RELATED VARIABLES IN LODC SLED TESTS

Restraint Condition	P_{max} kPa	$\dot{P}_{max}$ kPa/ms	$P_{max}*\dot{P}_{max}$ kPa^2/ms
Backless BPB	47	4.2	197.4
5-Pt Harness	70	3.8	264.1
Highback BPB	70	3.9	271.1
No CRS - Upright	92	6.9	634.8
No CRS - Slouch	223	14.7	3278.1
No CRS - Lap Belt Only	232	16.2	3750.3

Thorax Injury Risk Function

From the thorax IRF shown in Eq. 2, an LODC thorax $V_{max}*C_{max}$ of 0.45 m/s corresponds to a 50% risk of AIS2+ injury. A $V_{max}*C_{max}$ of 0.46 m/s correlates with 75% risk of injury. This agrees with LODC thorax component testing that was performed under similar conditions as the diagonal belt [4] and high-speed impact testing [17]. In the diagonal belt pull tests, the LODC sustained an average $V_{max}*C_{max}$ of 0.17 m/s (V_{max} = 1.1 m/s, C_{max} = 0.15), which seems reasonable as the belt velocity or penetration rate was lower in the LODC tests than in the biomechanical tests. In the high-speed impact tests, the LODC sustained an average $V_{max}*C_{max}$ of 1.5 m/s (V_{max} = 5.5 m/s, C_{max} = 0.27). The biomechanical tests had slightly higher $V_{max}*C_{max}$ at the same impact speed, but the compressions in those tests were slightly higher, which may be due to the average age of the subjects tested (8 years old) being younger than the average occupant size represented by the LODC. The paediatric biomechanical tests were not exactly replicated and the differences in results could also be due to experimental setup inconsistencies such as subject posture, impact location, and probe size.

Real-world frontal crash cases with and without thorax injury were also gathered from the National Automotive Sampling System Crashworthiness Data System (NASS CDS), the Crash Investigation Sampling System (CISS), and the Crash Injury Research and Engineering Network (CIREN) to determine the validity of the risk function. Table BII lists the pertinent information from the real-world cases. However, the occupant information needed (thorax compressions and penetration rate) for checking the reasonableness of the IRF are unknown and need to be estimated.

With the case-reported vehicle delta V's, thorax compressions and penetration rates were estimated using LODC Federal Motor Vehicle Safety Standard (FMVSS) No. 213 (48 km/h) sled data. First, the maximum thorax penetration rate (V_{max}) was calculated for each of the LODC sled tests and averaged. A ratio between average LODC thorax V_{max} and sled delta V was then calculated (average LODC thorax V_{max} / sled delta V = 0.1946) and applied to the real-world case delta V's to estimate a thorax V_{max} for each of the cases (Table BIII). These estimated thorax V_{max} values can then be used with the relationship of compression versus V_{max} from paediatric biomechanical data of varying loading rates (Fig. B3) to estimate a thorax compression for each of the cases. An estimated $V_{max}*C_{max}$ value can then be calculated for each of the real-world cases for use in the construction of the injury risk curve (Table BIV). These real-world cases were used to check the effectiveness of the IRF constructed from the paediatric biomechanical data as shown in Fig. 4 (red triangles).

Given that the case occupants were not exactly the same anthropometry as the LODC and that there are uncertainties for how the occupant was restrained at the time of the crash impact, a perfect alignment between the real-world cases and the IRF was not expected. One theory for the discrepancy between the risk function and case estimates is that in the LODC sled test data utilized to estimate these relationships, the belt systems used in those sled tests did not adequately represent vehicle belt restraint behavior in the real-world cases. Specifically, vehicle belt technologies (e.g. pretensioners, load limiters) in the real-world cases would have reduced the chest velocity of the occupants and thus shifted the $V_{max}*C_{max}$ values to be lower, which would then be in closer alignment with the injury risk function.

Several studies [24-30] have quantified chest loading reduction through the use of seat belt technologies. One study [24] used mathematical modeling to demonstrate that force-limiting devices reduced chest accelerations of a 50th percentile adult male occupant by up to 14% in 48 km/h frontal impacts. Another [25] showed that when a Hybrid III 50th percentile adult male ATD was tested in a 33 g pulse, inclusion of a pretensioner reduced V*C from 0.95 to 0.55 (42.1%) and chest deflection from 61.0 to 49.8 mm (18.4%). A fully optimized belt design (pretensioner + force limiter) reduced V*C further to 0.28 (70.5%) and deflection to 36.9 mm (39.5%). It was demonstrated through 48 km/h simulations [26] that an optimized combination of pretensioner, force limiter arrangement, and pretensioner stroke resulted in a decrease in chest compression of roughly 50% for a 50th percentile adult male and 25% for a 5th percentile adult female. It was reported [27] that a 29% decrease in chest deflection in a booster-seated Hybrid III 6-year-old ATD in a 48 km/h frontal test was found when using a belt system that included a force limiter and pretensioner. The Hybrid III 50th male exhibited a 30% reduction while the 5th female showed a 38% reduction in chest deflection. The influence of an optimized belt system was further examined [28] by testing three adult PMHS approximating a 50th male anthropometry in 48 km/h sled tests. They found a 23% reduction in mid-spine acceleration from the baseline belt system. In an analysis of cases [29], it was found that a belted driver or passenger in the front row has a 12.8% lower fatality risk if the belt is equipped with a pretensioner and force limiter. This reduction is undoubtedly due to these systems distributing belt forces more efficiently to reduce chest loading. The combined effects of seat belt and airbag designs on rear seated occupants including children were also analyzed [30]. Using the Hybrid III 6-year-old ATD in an NCAP-level pulse, they were able to demonstrate that, when an optimized belt system (load limiter + pretensioner) was used without an airbag or any other countermeasures, chest deflection was reduced by approximately 32% from the baseline belt system. The reductions are summarized in Table BV. Based on this assessment, it is estimated that modern vehicle optimized belt systems reduce chest loading by approximately 34.3% ± 15% on average. The 15% standard deviation accounts for variability in belt systems, occupant size, chest metric, and test speed. This average reduction is slightly higher than the HIII 6-year old ATD reductions (29% and 32%), which may be a reasonable reduction for a 10-year old occupant represented by the LODC since belt technologies were found to be more effective as occupant size increased. Therefore, this 34.3% reduction was applied to the $V_{max}*C_{max}$ values in Table BIV and shown in Fig. 4 (green squares).

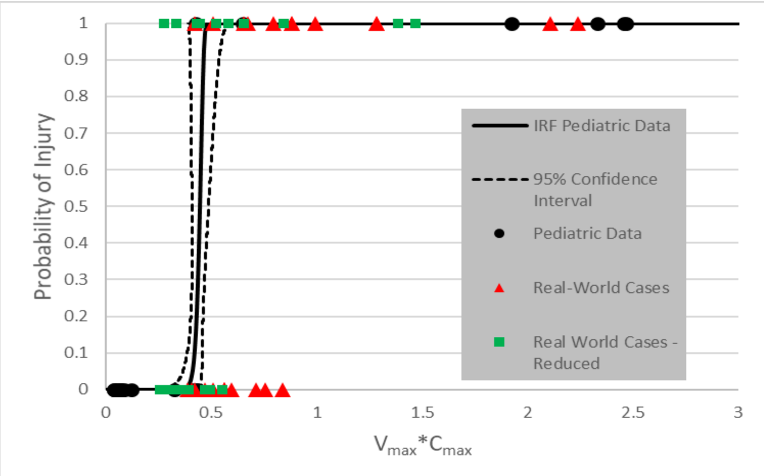

Fig. 4. Validation of the LODC thorax IRF using real-world cases.

To supplement the estimates of $V_{max}*C_{max}$ gathered from real-world cases, real-world crash scenarios were reconstructed using the LODC in sled tests with the FMVSS No. 213 bench. Three cases were reconstructed: 40 km/h non-injurious (NASS CDS #45-232), 50 km/h non-injurious (NASS CDS #73-25), and 56 km/h injurious (CISS #14737). In all three cases, the child occupants were seated in the second row without a CRS. Information for the three cases that were reconstructed are shown in Table VII. Only three cases were found in which the occupant was similar in size to the LODC, belted and seated in the rear seat, with or without thorax injury, and involved in a crash at a speed we could simulate on the FMVSS No. 213 bench. The LODC was seated directly on the FMVSS No. 213 bench in an upright position for the case reconstructions. The 50 km/h case was run at 48 km/h instead since it closely resembled the FMVSS No. 213 pulse. For the 40 km/h case, the sled velocity was matched to the FMVSS No. 208 pulse from a similar vehicle as the case vehicle (NHTSA component database TSTREF C70306). For the 56 km/h case, the velocity was matched using the pulse from a NHTSA New Car Assessment Program (NCAP) crash test using a similar vehicle as the case vehicle (NHTSA vehicle database TSTREF V10149). In the 56 km/h reconstruction, the LODC was rotated inboard 11 degrees since the case was not purely frontal and the LODC was also translated inboard in order to achieve the shoulder belt engagement of the thorax that was believed to better reproduce the actual observed injuries from the case. According to the thorax IRFs, the V_{max}*C_{max} outcomes for the 40 km/h and 50 km/h reconstructions (0.01 m/s and 0.04 m/s, respectively) are below a risk level of 1% of AIS2+ injury, which agrees with the actual injuries observed in the cases – surface area skin contusions and abrasions. For the 56 km/h case, a V_{max}*C_{max} of 0.36 m/s corresponds to a risk of injury below the 10% threshold. Since the loading to the LODC was slightly oblique and because there was submarining involved given the abdomen injuries attributed to the belt, the chest compression and rate of compression are likely underestimated since the LODC currently only measures thoracic deflection in the frontal direction. Although the shoulder belt was positioned so as to better reproduce the actual injuries, the belt was still high on the thorax and above the thorax displacement transducer. The height of the occupant is also unknown and it is possible that she or he could be taller than the LODC such that the shoulder belt was more centrally positioned over the thorax. Additionally, there were thorax injuries to the case occupant attributed to contact with the vehicle in addition to the shoulder belt. A vehicle interior was not included in this case reconstruction, which is another reason why the thorax V_{max}*C_{max} might seem low.

TABLE VII
REAL WORLD CASE INFORMATION FOR LODC SLED RECONSTRUCTIONS

Case ID	Case Year	Case Source	Height (cm)	Weight (kg)	Age (yr)	Speed (km/h)	Injuries / Source
45-232	2009	NASS CDS	157	39	11	40	Thorax skin contusion – shoulder belt
73-25	2013	NASS CDS	N/A	45	8	50	Neck abrasion – belt Thorax abrasion – belt Abdomen abrasion – belt
14737	2019	CISS	N/A	39	10	56	Thorax contusion – shoulder belt Lung contusion – shoulder belt Pneumothorax – shoulder belt Liver laceration – shoulder belt Rib fractures – arm rest Pneumothorax – arm rest Abdomen laceration – lap belt Small intestine laceration – lap belt Hip abrasions – lap belt

Limitations

The paediatric abdomen pressures used in the development of the injury risk function were estimated using a pressure-penetration relationship from LODC abdomen belt pull testing (Figs. A1-A2 and Eq. A1). It is possible that this relationship could overestimate the pressures for those penetrations beyond those which the LODC belt pull tests encompassed.

The thorax IRF that was constructed is nearly vertical, indicating that there is very little difference between a non-injurious and injurious V_{max}*C_{max}. This is likely due to the markedly distinct velocities (Table III) in the three paediatric biomechanical test conditions that were included in the IRF development. There are three groups of data: low velocity, non-injurious data [18]; injurious, high velocity data [17]; and mixed injury data at an intermediate velocity [4]. With only a small portion of the data containing any overlap between no injury and injury data, it is not surprising that the IRF is almost perfectly vertical. The IRF would likely benefit from more data collected in this mid-velocity range where there is a better chance of overlap.

Using chest compressions measured by the LODC has its caveats as it is currently equipped with only a single transducer at the center of the thorax that measures displacement in the frontal direction. The thorax displacements are therefore sensitive to shoulder belt location and direction of loading. If the shoulder belt lies above the displacement transducer, which is common in a no CRS scenario, the thorax compression may not be fully captured by the sensor. Likewise, in an oblique loading scenario, compressions to the side of the thorax may not be fully captured by the front-facing sensor. Future updates to the LODC include multiple sensors that will be able to capture displacements at varying heights and at oblique directions.

Lastly, this study assumes that the LODC is biofidelic based on component-level testing, and that by extension, the full dummy kinematics are also biofidelic for the purposes of validating the component-level based IRFs.

V. CONCLUSIONS

The LODC pressure vs. penetration response along with paediatric biomechanical data were used to generate a pressure-based abdomen IRF for the LODC:

$$F(x) = 1 - e^{-(x/126.2844)^{3.74879}} \quad (1)$$

For the thorax, the product of maximum penetration rate and maximum compression (V_{max}*C_{max}) was found to be the strongest predictor of thoracic injury and was used to generate a thorax IRF for the LODC. The thorax IRF developed from paediatric biomechanical data alone is described by the following equation:

$$F(x) = 1 - e^{-(x/0.4719295)^{11.7919}} \quad (2)$$

The abdomen IRF was found to be reasonable by applying it to LODC sled data in various restraint conditions as well as through comparison with previous work to develop abdominal IRFs for Q series child ATDs. The thorax IRFs were also found to be reasonable by applying them to real-world case data and case reconstructions using the LODC. These risk functions will be evaluated in future tests with the LODC in various restraint conditions to determine their applicability toward accurate assessment of the risk of abdominal and thoracic trauma in realistic crash scenarios for child occupants. In addition, the risk functions will be evaluated to determine their feasibility in optimising child restraint designs to limit both abdomen and thorax risk in children.

VI. ACKNOWLEDGEMENT

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VIII. APPENDIX

Appendix A

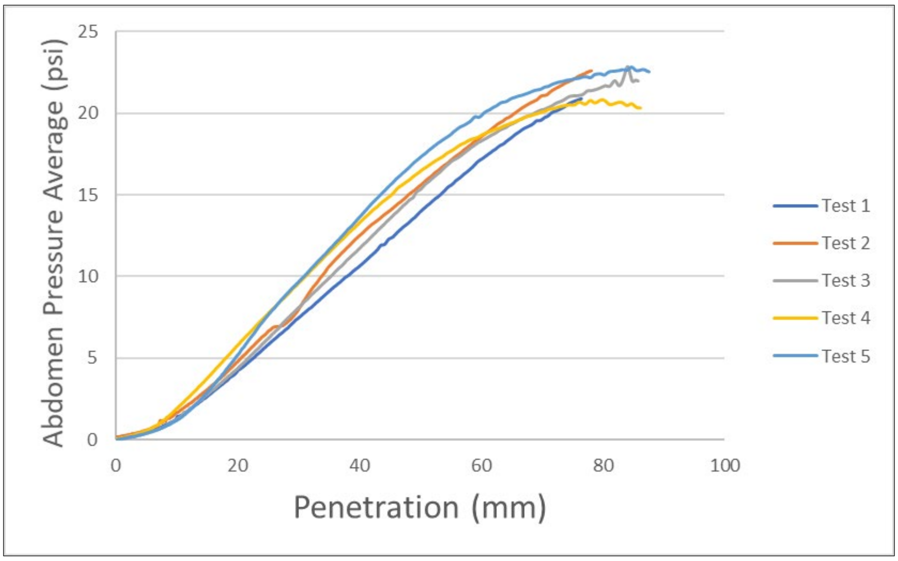

Fig. A1. Average of left and right LODC abdominal pressures versus abdomen belt penetration from fixed back belt testing of the LODC.

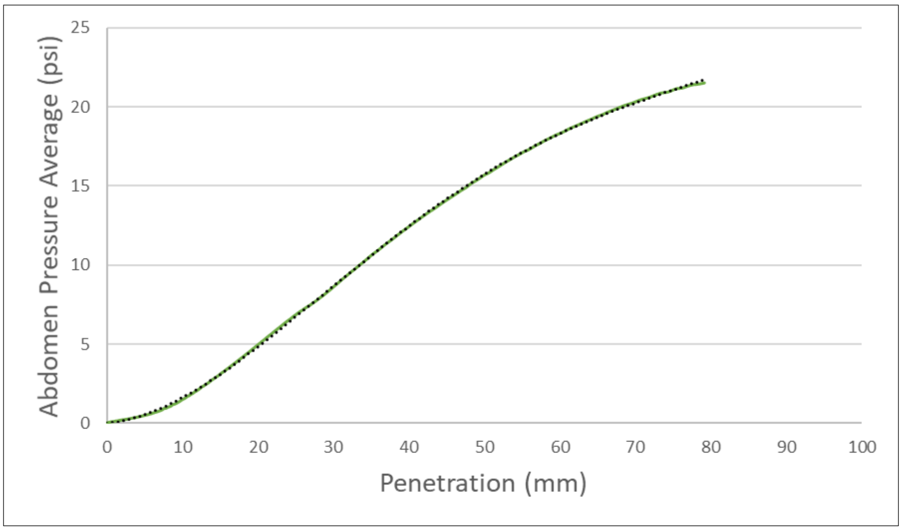

Fig. A2. The average of the five LODC fixed back pressure-penetration curves and the resulting curve fit (R^2 = 0.999).

The LODC abdominal pressure versus abdomen penetration relationship is quantified by the resulting curve fit (R^2 = 0.999), which is represented by the following equation:

$$y = 0.0000010459x^4 - 0.0002204404x^3 + 0.0137774696x^2 + 0.0462054262x - 0.0071453845, \quad \text{(A1)}$$

where y is abdomen pressure (psi), and x is abdomen penetration (mm).

TABLE AI

ESTIMATED LODC ABDOMINAL PRESSURES FROM PORCINE ABDOMEN PENETRATIONS [5-6]

Porcine Test ID	Penetration	Estimated LODC Pressure			Porcine Test ID	Penetration	Estimated LODC Pressure	
	mm	PSI	kPa			mm	PSI	kPa
PAC1.01	67	20	136		*PAC1.25*	64	19	132
PAC1.02	72	21	142		*PAC1.26*	61	19	128
PAC1.03	58	18	123		*PAC1.27*	41	13	88
PAC1.04	68	20	137		*PAC1.28*	65	19	133
PAC1.05	74	21	144		*PAC1.29*	73	21	143
PAC1.06	96	25	174		*PAC1.30*	37	11	78
PAC1.07	53	17	114		*PAC1.31*	58	18	123
PAC1.08	56	17	120		*PAC1.32*	56	17	120
PAC1.09	48	15	104		*PAC1.33*	61	19	128
PAC1.10	89	23	162		*PAC1.34*	68	20	137
PAC1.11	47	15	102		*PAC1.35*	60	18	126
PAC1.12	41	13	88		*PAC1.36*	46	14	100
PAC1.13	47	15	102		*PAC1.37*	45	14	98
PAC1.14	62	19	129		*PAC1.38*	64	19	132
PAC1.15	54	17	116		*PAC1.39*	71	20	141
PAC1.16	59	18	125		*PAC1.40*	56	17	120
PAC1.17	41	13	88		*PAC1.41*	60	18	126
PAC1.18	37	11	78		*PAC1.42*	65	19	133
PAC1.20	61	19	128		*PAC1.43*	79	22	149
PAC1.21	61	19	128		*PAC1.44*	92	24	166
PAC1.22	52	16	112		*PAC1.45*	103	28	191
PAC1.23	59	18	125		*PAC1.46*	89	23	162
PAC1.24	75	21	145		*PAC1.47*	70	20	140

TABLE AII

ESTIMATED LODC ABDOMINAL PRESSURES FROM PAEDIATRIC ABDOMEN PENETRATIONS [3-4]

[4]					[3]			
Test ID	Penetration	Estimated LODC Pressure			Test ID	Penetration	Estimated LODC Pressure	
	mm	PSI	kPa			mm	PSI	kPa
PEDVE9	33	10	68		*Subject5*	80	22	151
PEDVE10	37	11	78		*Subject6*	90	24	163
PEDVE11	39	12	83		*Subject7*	125	46	316
PEDVE24	26	7	49		*Subject8*	115	35	243
PEDVE25	36	11	76		*Subject9*	105	29	198
PEDVE26	37	11	78					

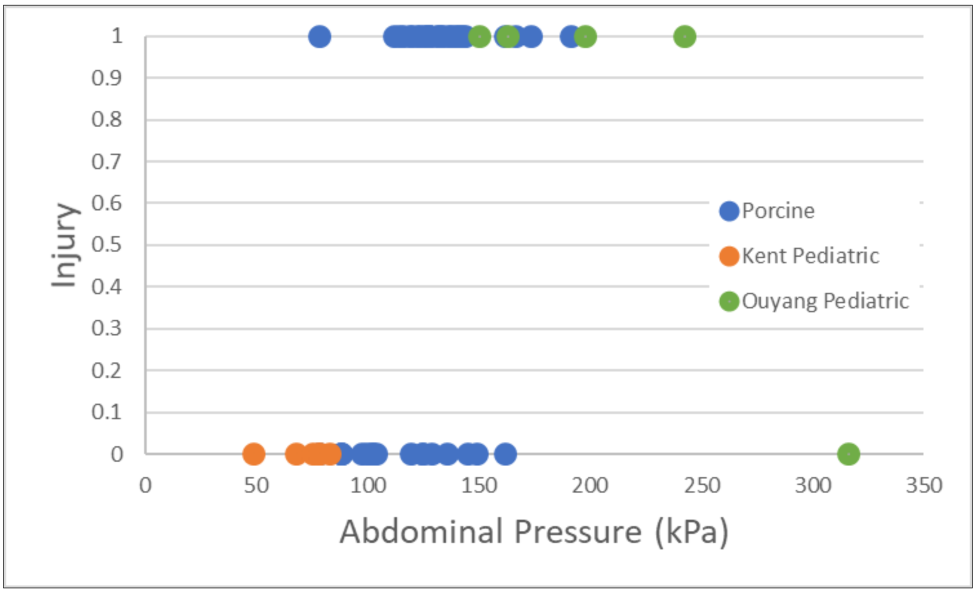

Fig. A3. Plot of injury versus abdominal pressure.

Appendix B

TABLE BI
INJURY OUTCOMES AND MEASUREMENTS IN PAEDIATRIC BIOMECHANICAL TESTS

Test ID	Ref	$(V*C)_{max}$ m/s	$[V*C/(1-C)]_{max}$ m/s	$V_{max}*C_{max}$ m/s	Velocity m/s	Compression %	Injury Y or N
Subj6	[17]	1.64	3.01	3.42	5.9	58.0	Y
Subj7		1.76	2.78	3.41	6.7	50.8	Y
Subj8		1.55	2.45	3.23	6.3	51.3	Y
Subj9		1.26	1.79	2.67	7.0	38.1	Y
PEDVE16	[4]	0.37	0.44	0.56	2.5	22.5	N
PEDVE18		0.33	0.43	0.59	2.4	24.5	Y
PEDVE32		0.39	0.52	0.59	2.0	29.6	N
PEDVE33		0.38	0.52	0.60	2.0	30.1	N
PEDVE34		0.44	0.59	0.90	2.2	40.9	Y
PEDVE43		0.29	0.34	0.45	1.8	24.9	N
CPR1	[18]	0.04	0.05	0.05	0.26	20.2	N
CPR3		0.12	0.16	0.17	0.46	36.8	N
CPR4		0.05	0.06	0.07	0.35	21.0	N
CPR6		0.07	0.08	0.10	0.44	22.8	N
CPR7		0.06	0.07	0.08	0.30	25.1	N
CPR8		0.09	0.12	0.12	0.40	30.4	N
CPR9		0.03	0.04	0.05	0.29	18.0	N
CPR10		0.06	0.07	0.10	0.49	19.7	N
CPR11		0.06	0.08	0.09	0.39	24.2	N

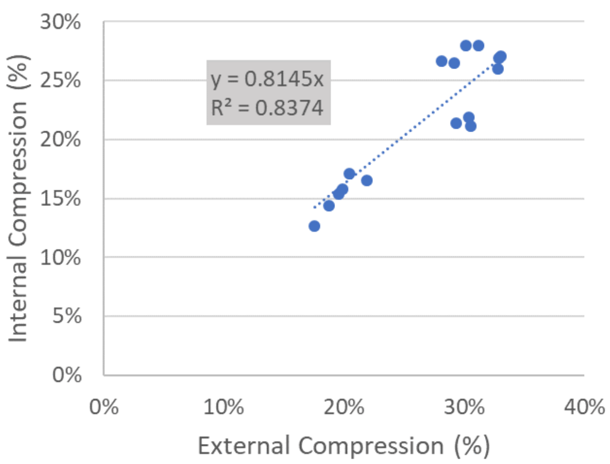

Fig. B1. LODC thorax internal versus external compression relationship from component testing.

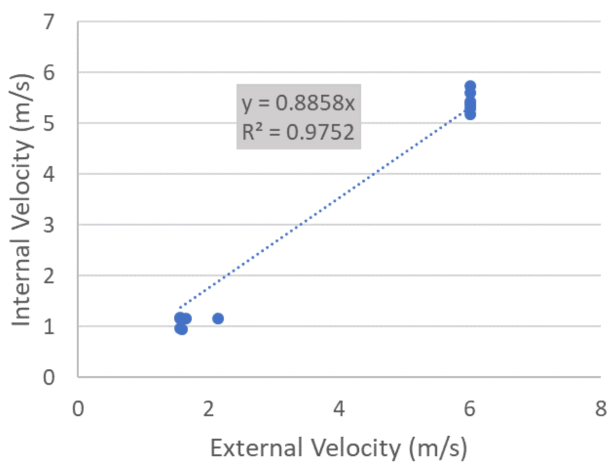

Fig. B2. LODC thorax internal versus external penetration rate from component testing.

TABLE BII

BELTED CHILD OCCUPANT REAL-WORLD CASES WITH/WITHOUT THORAX INJURY

Case Number	Case ID	Case Year	Source	Height (cm)	Weight (kg)	Age (yr)	Vehicle ΔV (km/h)	AIS2+ Thorax Injury (Y or N)
Case01	2-49	2007	NASS CDS	119	19	6	30	N
Case02	75-49	2006	NASS CDS	122	25	7	31	N
Case03	11307	2018	CIREN	170	59	16	32	Y
Case04	4-36	2006	NASS CDS	135	66	12	32	N
Case05	47-58	2007	NASS CDS	107	32	8	35	N
Case06	76-8	2007	NASS CDS	137	29	9	37	N
Case07	9692	2018	CISS	155	57	14	37	Y
Case08	81-110	2006	NASS CDS	152	34	8	40	N
Case09	45-232	2009	NASS CDS	157	39	11	40	N
Case10	47-94	2006	NASS CDS	163	50	15	40	N
Case11	75-39	2012	NASS CDS	Unk	Unk	12	42	N
Case12	16786	2020	CIREN	115	17	5	45	Y
Case13	11-194	2007	NASS CDS	157	59	15	46	Y
Case14	82-50	2008	NASS CDS	132	27	7	48	N
Case15	73-25	2013	NASS CDS	Unk	45	8	50	N
Case16	13-134	2008	NASS CDS	170	95	15	52	Y
Case17	12-47	2011	NASS CDS	163	50	14	54	N
Case18	14737	2019	CISS	Unk	39	10	56	Y
Case19	14737	2019	CISS	Unk	54	12	56	Y
Case20	6591	2017	CISS	150	43	10	61	Y
Case21	11024	2018	CISS	132	53	9	73	Y
Case22	11024	2018	CISS	Unk	58	11	73	Y
Case23	15326	2019	CISS	185	73	16	102	Y
Case24	14415	2019	CIREN	183	86	15	106	Y

TABLE BIII

FMVSS NO. 213 SLED TEST DATA USED TO CREATE A RATIO ESTIMATING THORAX V_{MAX} FROM SLED VELOCITY,

RATIO OF THORAX/SLED VELOCITY = 9.34/48 = 0.1946

	Test#	Internal V_{max} m/s	Internal V_{max} km/h
FMVSS No. 213 Sled Tests 48 km/h	1	2.14	7.71
	2	1.98	7.14
	3	2.11	7.60
	4	2.11	7.60
	5	2.13	7.68
	6	3.71	13.37
	7	3.19	11.50
	8	3.37	12.14
		Average =	9.34

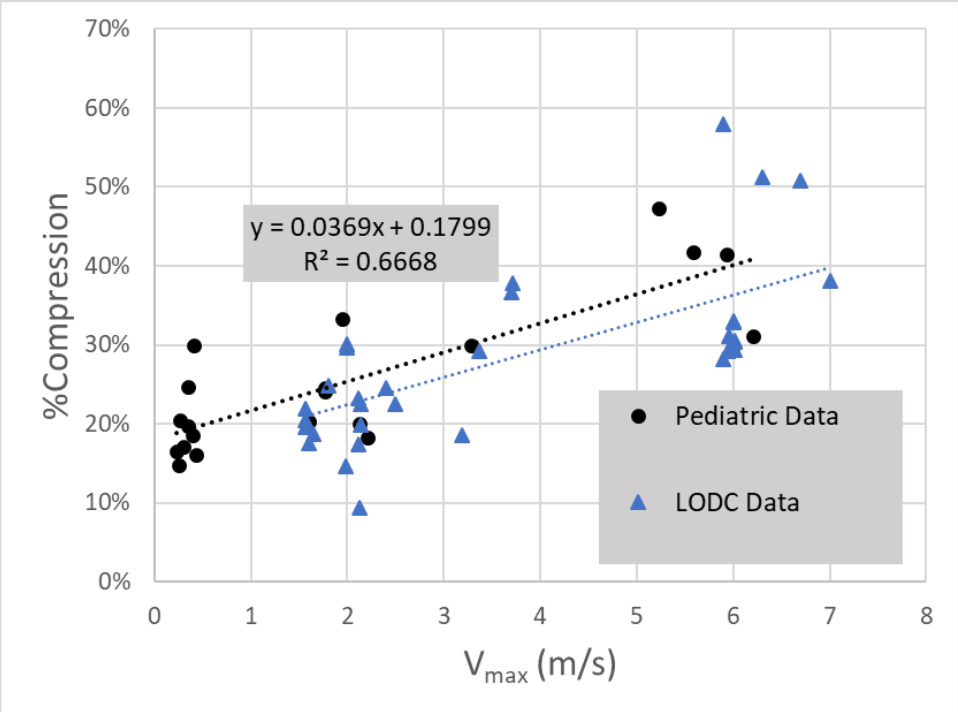

Fig. B3. The relationship between compression and V_{max} for paediatric biomechanical data and LODC sled tests.

TABLE BIV

ESTIMATED CASE OCCUPANT THORAX LOADING USING LODC SLED TEST DATA RELATIONSHIPS

Case Number	Case ID	Vehicle ΔV km/h	Vehicle ΔV m/s	Estimated Thorax V_{max} m/s	Estimated Max Compression %	Estimated $V_{max}*C_{max}$ m/s	AIS2+ Thorax Injury Y or N
Case01	2-49	30	8.3	1.6	24.0	0.39	N
Case02	75-49	31	8.6	1.7	24.2	0.40	N
Case03	11307	32	8.9	1.7	24.4	0.42	Y
Case04	4-36	32	8.9	1.7	24.4	0.42	N
Case05	47-58	35	9.7	1.9	25.0	0.47	N
Case06	76-8	37	10.3	2.0	25.4	0.51	N
Case07	9692	37	10.3	2.0	25.4	0.51	Y
Case08	81-110	40	11.1	2.2	26.0	0.56	N
Case09	45-232	40	11.1	2.2	26.0	0.56	N
Case10	47-94	40	11.1	2.2	26.0	0.56	N
Case11	75-39	42	11.7	2.3	26.4	0.60	N
Case12	16786	45	12.5	2.4	27.0	0.65	Y
Case13	11-194	46	12.8	2.5	27.2	0.67	Y
Case14	82-50	48	13.3	2.6	27.6	0.71	N
Case15	73-25	50	13.9	2.7	28.0	0.75	N
Case16	13-134	52	14.4	2.8	28.4	0.80	Y
Case17	12-47	54	15.0	2.9	28.7	0.84	N
Case18	14737	56	15.5	3.0	29.1	0.88	Y
Case19	14737	56	15.5	3.0	29.1	0.88	Y
Case20	6591	61	16.9	3.3	30.1	0.99	Y
Case21	11024	73	20.3	3.9	32.5	1.28	Y
Case22	11024	73	20.3	3.9	32.5	1.28	Y
Case23	15326	102	28.3	5.5	38.3	2.11	Y
Case24	14415	106	29.4	5.7	39.1	2.24	Y

TABLE BV
REDUCTION OF THORAX LOADING DUE TO VEHICLE SEAT BELT TECHNOLOGIES
PT – PRETENSIONER / FL – FORCE LIMITER

Source	Measurement	Reduction	Occupant Size
[24]	Chest Acceleration	14% (PT) 70.5% (PT +FL)	50th Male ATD
[25]	V*C	18.4% (PT) 39.5% (PT +FL)	50th Male ATD
[26]	Chest Deflection	25% 50%	5th Female ATD 50th Male ATD
[27]	Chest Compression	29% 30% 38%	6-Year Old ATD 5th Female ATD 50th Male ATD
[28]	Chest Deflection	23%	50th Male PMHS
[30]	Mid-Spine Acceleration	32%	6-Year Old ATD
	Average	34.3% ± 15.3	