EFFECTS OF SEAT BELT LOAD LIMITERS ON DRIVER FATALITIES IN FRONTAL CRASHES OF PASSENGER CARS

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ABSTRACT

In the mid-1990s, seat belt load-limiting devices were introduced on many new passenger vehicles equipped with front airbags. These devices are intended to reduce belt-induced injuries such as rib fractures by allowing forward movement of occupants' torsos when belt loads exceed some threshold. Load limiters have been shown to reduce thoracic injury risk in controlled experiments with cadavers and in full-width rigid barrier frontal crash tests.

The Insurance Institute for Highway Safety has evaluated many vehicles equipped with load limiters in 64.4 km/h (40 mi/h) frontal offset crash tests. Results indicate that in some crash circumstances the amount of forward movement allowed by load limiters could increase the risk of head injury from contacts with vehicle interior components. Thus, although load limiters perform well in rigid barrier tests with high deceleration, short duration, and low intrusion, the forward movement they allow in crashes with longer duration and higher intrusion may increase head injury risk.

To examine the effects of load limiters on driver fatality risk in real-world crashes, the present study compared rates of belted driver deaths per vehicle registration before and after load limiters were added to seat belts. Study vehicles were restricted to models and years with no other significant design changes. Fatality rate comparisons for passenger cars with and without load limiters suggest these devices have not reduced fatality risk and even may have increased risk.

Also presented in this study is a review of a small number of cases from the National Automotive Sampling System that illustrate how increased occupant forward movement can contribute to head injury risk even in vehicles with front airbags.

INTRODUCTION

Seat belts are the single most important safety feature of any passenger motor vehicle. They have been estimated to have saved more lives since 1960 than all other crashworthiness design features combined (National Highway Traffic Safety Administration (NHTSA) 2005). However, many studies have shown that seat belts can contribute to thoracic injuries under certain loading conditions, especially among older occupants (Augenstein et al., 1999; Dalmotas, 1980; Hill et al., 1992; Niederer et al. 1977; Patrick and Andersson, 1974). Several patents filed as early as the 1950s and 1960s described methods of limiting the magnitude of belt loads to reduce the risk of these injuries (Viano, 2003). The major drawback of these technologies is that they must sacrifice occupant coupling to the vehicle by allowing forward movement of the occupant's torso, increasing the risk of head or chest contact with the steering wheel or other vehicle interior components. As a result, it was not until front airbags were installed as standard safety equipment that automobile manufacturers began to equip production vehicles with seat belt load limiters in large numbers. Although airbags provide additional occupant protection against contacts with the vehicle interior, they may not eliminate the risk associated with large amounts of increased forward movement in many serious frontal crashes.

Prior Research on Load Limiters

Cadaver tests – Cadaver testing has examined the potential of load-limiting seat belts in combination with airbags to mitigate thoracic injuries. Kent et al. (2001) conducted seven cadaver tests and found a 40 percent reduction in the average number of rib fractures for belts that limited loads to 3.5 kN compared with standard belts that did not limit loads. Cadaver subjects averaged older than 60 years and were positioned to avoid potential hard head contacts. Crandall et al. (1997) conducted six cadaver tests and found a 58 percent reduction in the average number of rib fractures for belts that limited loads to 2 kN compared with standard belts. Cadaver subjects averaged 57 years old, and although no hard head contacts were observed in tests with either standard or load-limiting belts, forward head excursion averaged 42 percent greater in tests with load-limiting belts. Kallieris et al. (1995) conducted tests with five cadavers averaging 50 years old, two restrained with a standard belt and three restrained with a 4 kN load-limiting belt. Fewer thoracic injuries per subject were observed in tests with load-limiting belts (three total rib fractures among three subjects) compared with standard belts (three rib fractures among two subjects). Differences in the amount of forward head excursion were not reported.

Field studies – Field studies also have examined the effects of load limiters on injury risk. An early field study in France examined load-limiting seat belts in Renault and Peugeot vehicles (Foret-Bruno et al., 1978). Belt stitching near the upper anchorage points in these vehicles was designed to tear under load to introduce additional webbing into the belt system. The study correlated the amount of belt load to the risk of occupant thoracic injury. Among the findings were that occupants younger than 30 could sustain belt loads of 7.4 kN without any thoracic injury, but occupants older than 50 were susceptible to injury at lower belt loads. Mertz et al. (1991) later used these data to establish risk curves for Hybrid III dummy chest compression associated with seat belt loading.

In 1995, Renault vehicles were equipped with a new type of limiter that mechanically deformed under load, limiting belt forces to 6 kN. Foret-Bruno et al. (1998) combined crash data for vehicles equipped with the new limiter with cases involving the vehicles manufactured in the 1970s. Only 6 percent of the 256 total cases involved vehicles with airbags, and head injury risk was not reported. Risk curves were established to correlate shoulder belt loads with thoracic injury risk. A very strong dependence on age was found; the risk of AIS 3+ thoracic injury reached 50 percent with shoulder belt loads of less than 4 kN for 80-year-old occupants but more than 9 kN for 20-year-old occupants. The injury risk curves also were compared with those developed from 209 cadaver sled tests conducted in the 1970s. Belt loads associated with a specific level of injury risk were 2 kN lower in the cadaver tests than in the field cases. The authors suggested that belt load thresholds developed from cadaver tests may be low, possibly due to below-average bone strength for the post-mortem human subjects. According to the injury risk curves developed from the field data, limiting shoulder belt loads to 2 kN (as suggested by Mertz et al. (1995) and used in the cadaver tests conducted by Crandall et al. (1997)) would produce less than a 10 percent risk of AIS 3+ thoracic injury for 80-year-old occupants and essentially zero risk for younger occupants.

Foret-Bruno et al. (2001) recently conducted a study based on field cases of vehicles equipped with a new 4 kN load-limiting seat belt. Results confirmed the earlier injury risk curves, finding a further reduction in thoracic injuries associated with the lower belt load threshold. The vehicles with the new load limiters were equipped with airbags, but the risk of head injury associated with increased forward excursion was not discussed.

NCAP frontal tests – Load limiters have improved test scores for many vehicles in NHTSA's New Car Assessment Program (NCAP), and this may have increased the use of such devices as manufacturers tried to achieve better NCAP ratings. NHTSA (2003) published a technical report and request for comments on the improvements in frontal NCAP scores associated with load limiters and belt crash tensioners. The Insurance Institute for Highway Safety (IIHS) identified 14 vehicle models that were structurally unchanged, added load limiters without other seat belt changes, and were retested in NCAP (Appendix A). None of these vehicles received a lower driver star rating in the retest with load limiters, and only one vehicle received a lower passenger rating (one less star). Four vehicles had unchanged ratings for both occupants, whereas the other nine improved by at least one star for either the driver, passenger, or both.

The frontal NCAP test is a full-width crash into a rigid barrier at 56.4 km/h (35 mi/h). The resulting crash pulse is very short, limiting the amount of time the dummy occupant loads the seat belt and airbag. The faster loading rate increases the effective initial stiffness of the restraint system. Furthermore, loading a vehicle across its full width limits the amount of intrusion, maintaining larger clearances in the occupant compartment. This configuration also ensures that occupant loading and rebound phases occur with minimal vehicle rotation. Because of these factors, the risk of dummy head contact with the vehicle interior is lower than in longer pulse crashes and in crashes with greater vehicle rotation or intrusion.

IIHS frontal offset tests – Since 1995, IIHS has conducted frontal offset crash tests in which only 40 percent of a vehicle's front end overlaps a deformable barrier. This configuration has a longer crash pulse than the NCAP test and is likely more representative of real-world crashes. NHTSA studies have found that about 20-25 percent of frontal crashes in the field are full width (Saunders and Kuppa 2004; Stucki et al. 1998), and many of these impacts are with objects less rigid than the NCAP barrier. The performance of load limiters in the IIHS offset test could be an important indicator of their potential effectiveness in many real-world crashes.

IIHS generally does not retest vehicles when adjustments to restraint systems are unaccompanied by structural changes, so there are no paired vehicle tests that isolate the contribution of load limiters. However, general observations can be made between vehicles with and without load limiters while recognizing that other restraint system differences exist.

As of June 2006, IIHS has evaluated 123 passenger cars in the frontal offset test that received structural ratings of good or acceptable. Comparing similar vehicles with such high ratings limits the influence that large amounts of intrusion have on dummy kinematics and injury measures and avoids issues that may arise from comparing different vehicle types. Of the passenger cars tested, 103 were equipped with load-limiting seat belts and 20 were not. Evidence from test film and dummy instrumentation plots suggest that driver dummy head excursion into the airbag resulted in steering wheel contact in 52 percent of the vehicles with load limiters and in 20 percent of vehicles without. Although many of these head contacts would be unlikely to cause serious injury, the contacts in about two-thirds of the cases produced the maximum resultant head accelerations recorded during the tests. In real-world crashes with different loading conditions or occupants of other sizes, the forces involved in these hard head contacts could be greater.

For most of the tested vehicles with load-limiting belts, the amount of webbing that spooled from the retractor during the crash was measured. Figure 1 shows the total amount of belt spool-out for the passenger cars tested with load-limiting belts. If a vehicle was equipped with belt crash tensioners, then the spool-out measurement was the amount of webbing pulled from the retractor after the tensioner activated. The average total amount of belt spool-out has been increasing in recent model years, from about 10 cm for 1997-2000 models, to 17 cm for 2003 models, and to 23 cm for the 2004-05 models for which spool-out was measured (15 tests). During the same period, many airbags were depowered and advanced airbags were introduced. These newer airbag designs are intended to reduce airbag inflation risks for out-of-position occupants, but they may permit more occupant forward movement than earlier airbag designs.

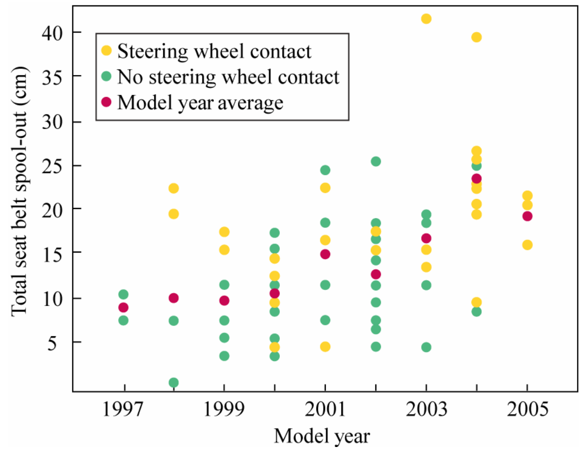

Figure 1. Total measured seat belt spool-out in passenger cars with load-limiting belt; IIHS frontal offset deformable barrier tests.

Thus, seat belt spool-out has been increasing while airbags may have been allowing more forward movement. Of 17 tests with more than 20 cm of total belt spool-out, 14 had hard contact between the dummy's head and steering wheel through the airbag.

The observations of load-limiting belts in frontal offset tests suggest that belt load thresholds that reduce measured injury risk in frontal NCAP tests could produce undesired results in longer pulse crashes. All three cadaver test series discussed earlier, as well as many of the mathematical models presented in the literature, employed crash pulses similar to those of full-width rigid barrier impacts. In addition to increasing driver head excursion through the airbag, too much belt spool-out also may increase injury risk during the rebound phase of a crash or in multiple-event crashes, including frontal impacts followed by a side impact or rollover. Front airbags provide occupant protection only during the initial loading phase of a crash, whereas seat belts have the potential to restrain occupants for the duration of a crash.

METHODS

To investigate the effectiveness of seat belt load limiters in real-world crashes, driver fatality rates for different vehicles were compared before and after load limiters were added to their designs. Vehicles with coincident changes to advanced airbags, electronic stability control, or front structure were not included. Due to these restrictions, only one vehicle model that also was equipped with belt crash tensioners could be included. Vehicle model years with unchanged front structure were identified using the same information collected by IIHS for its frontal crashworthiness evaluation program. Vehicles not tested by IIHS were not considered for study due to the limited amount of available structural and restraint system data. Only mechanical deformation-type load limiters were evaluated. Reliable model-specific information on belts with other energy management features, such as seat belt webbing with stitching that tears under load, was not widely available. The passenger cars that met the inclusion criteria are listed in Table B-1 of Appendix B.

Federal Motor Vehicle Safety Standard (FMVSS) 208 was amended in 1997 to allow compliance with frontal crash performance requirements to be demonstrated by using sled tests as an alternative to rigid barrier tests (NHTSA, 1997). In response, the airbags in many vehicles were depowered to inflate in a less aggressive manner. Because a depowered airbag could affect the performance of a seat belt load limiter, this variable also was considered in the analysis. All vehicles in the present study had depowered airbags installed at either the beginning or during the middle of the 1998 model year. To isolate the effects of load limiters, fatality rates were calculated separately for the years vehicles were equipped with depowered airbags. Any model that received depowered airbags in the middle of the 1998 model year was evaluated for 1997 and 1999 but not the year of the running change. It should be noted that the amount of airbag depowering may have varied considerably among these different makes and models.

Driver Fatality and Vehicle Registration Data

A query of the 1996-2003 Fatality Analysis Reporting System (FARS) provided the fatality counts of belted drivers in the study vehicles. FARS cases were restricted to crashes with a principal impact location of 12 o'clock. Direct frontal crashes were evaluated because load limiters are designed to have the greatest effect in this loading condition. Additionally, side impact airbags were introduced on some models as optional safety equipment during the model years that were compared, and this could confound the results for other impact locations.

Fatality rates were calculated by dividing the number of fatalities for a given model, model year, and calendar year by the number of registrations for that vehicle. Registration data were obtained from the National Vehicle Population Profile of R.L. Polk and Company. Because registration data are collected in the middle of each calendar year, the vehicles for each model year in the study were not evaluated until the following calendar year.

To test the null hypothesis that load limiters have no effect on driver fatality risk, expected fatalities were calculated for the vehicles with load limiters by multiplying the fatality rate for those vehicles before load limiters were added by the number of registered vehicle years after load limiters were installed. The number of expected fatalities then was adjusted for changes in environmental and behavioral factors using an adjustment procedure described below. Finally, rate ratios for each vehicle were obtained by dividing the observed fatalities in vehicles with load limiters by the adjusted expected fatalities. Rate ratios less than 1.00 indicate a reduction in fatal crash likelihood for vehicles with load limiters, whereas ratios greater than 1.00 suggest an increased likelihood.

Adjustment Procedure

Because driver belt use, average travel speed, vehicle fleet mix, and other factors change over time, fatality rates vary over time even for unchanged vehicle models. To control for these differences, a set of passenger car models that had no seat belt or structural changes across the same model and calendar years was identified for each study vehicle that received load limiting seat belts. The fatality rate ratios for these comparison models were used to normalize the rate ratios for the vehicles that received load limiters. Because airbag depowering also was tracked, this change was captured in the control group when the study vehicle also received depowered airbags.

For example, the Dodge Stratus and its corporate twins were structurally identical for the 1995-2000 model years and had load-limiting seat belts and depowered airbags installed beginning with 1998 models. An expected number of belted driver fatalities for vehicles with the seat belt and airbag changes was calculated based on the fatality rate for vehicles with the unchanged restraint systems. This expected value then was multiplied by the fatality rate ratio for a control group of vehicle models that also had depowered airbags installed in 1998 but did not receive seat belt or structural changes during the same model years. Finally, the rate ratio for the Stratus was determined by dividing the observed fatalities by the adjusted expected value.

Two selection criteria were established for the control vehicles in this analysis. First, vehicles older than 4 years were excluded to reduce the effect of any model-specific trends related to changes in vehicle ownership. The second criterion resulted from the fact that differing numbers of control vehicles could be used based on the range of model years for which each study vehicle was being compared. To balance the requirements for multiple vehicles in the control group and sufficient exposure for the study vehicle, the model years in each comparison were chosen to produce the most registered vehicle years for the study vehicle, provided the control group contained at least four distinct models with a minimum of 400,000 total registered vehicle years. In the few cases where no comparison existed with at least four such models, the next highest number of control vehicles was selected. Table B-2 in Appendix B lists the models used for the control groups. Several control vehicles had side airbags introduced during this time period, giving further reason to consider only those crashes with a principal impact location of 12 o'clock.

Overall rate ratios were computed by grouping vehicle models that received the same restraint system change and comparing the total adjusted expected and observed fatalities. Because depowered airbags were distinguished from earlier generation airbags, four different technology combinations were possible for the vehicles without belt crash tensioners (all but one model in the study). In a given model year, a vehicle could have depowered airbags, load limiters, both, or neither.

Ninety-five percent confidence limits were calculated for the overall rate ratios corresponding to each change in restraint technology. The limits were computed using a formula developed by Silcocks (1994):

Lower:

$$\beta_{0.025}(O, E + 1) / \{1 - \beta_{0.025}(O, E + 1)\} \quad (1).$$

Upper:

$$\beta_{0.975}(O + 1, E) / \{1 - \beta_{0.975}(O + 1, E)\}, \quad (2).$$

where O is the sum of the observed fatality counts, E is the sum of the expected fatality counts, and $\beta p(x,y)$ is the pth percentile from the beta distribution with parameters x and y. The expected fatality counts were those adjusted with the control group rate ratios. This method does not capture the uncertainty in the rate ratio estimates of the control vehicles themselves, making the confidence intervals somewhat narrower than they would be otherwise. Rate ratios with associated confidence intervals that do not include 1.00 are considered statistically significant.

RESULTS

Results for the groups of vehicles with similar restraint system changes are reported in Table 1. The fatality rate ratios in the first and third rows of the table are relative to the ratio for other passenger cars that had unchanged restraint systems during the same model and calendar years, whereas the fatality rate ratios in the second and fourth rows are relative to the ratio for passenger cars that received only depowered airbags. In every case, the control group of vehicles had substantially more registered vehicle years than the study vehicle with which they were compared.

The number of vehicle models and their exposure varied for each technology change. The smallest group consisted of the Chevrolet Cavalier and Pontiac Sunfire, corporate twins, which were the only vehicles that received load-limiting belts before depowered airbags (first row of Table 1). There were 18 percent fewer fatalities than expected in these vehicles after load-limiting belts were installed. This result was not statistically significant at the selected confidence level.

Fifteen different model/body style combinations received both depowered airbags and load-limiting belts, making up the largest group with a total exposure of more than 17 million registered vehicle years (second row of Table 1). There were 36 percent more fatalities than expected for these vehicles after the airbag and seat belt changes, a statistically significant finding. This increase is relative to other models that received depowered airbags at the same time as the study vehicles but that had no seat belt changes. When analyzed individually (Table 2), six of the eight vehicle platforms in this group had adjusted fatality rate ratios ranging from 1.35 to 2.55. The other two vehicle models had fatality rate ratios near 1 (1.01 and 1.04).

Table 1
Passenger cars that received load-limiting seat belts; rate ratios for driver deaths in crashes with principal impact location of 12 o'clock among structurally unchanged vehicles, adjusted for change in fatality rates of other passenger cars without load-limiting seat belts in same model and calendar years

Belt load limiter and/or depowered airbag?		Pre-change		Post-change				
Pre-change	What added	Registered vehicle years	Driver deaths	Registered vehicle years	Driver deaths	Adjusted expected deaths	Rate ratio	95% confidence interval
Neither	Load limiter	765,309	12	1,644,406	29	36	0.82	(0.48, 1.37)
Neither	Both	8,825,779	126	8,632,257	148	109	1.36	(1.06, 1.76)
Depowered airbag	Load limiter	6,069,741	91	8,281,390	131	130	1.01	(0.79, 1.30)
Neither	Both (+ crash tensioners)	1,410,719	14	3,263,383	34	27	1.27	(0.74, 2.19)

Not all vehicles received depowered airbags and load limiters simultaneously. As mentioned previously, the Cavalier and Sunfire designs incorporated load-limiting belts before depowered airbags. Another subset of vehicles had depowered airbags for at least one model year before load limiters were introduced. Relative to other models that had no restraint system changes, these vehicles had 1 percent more fatalities than expected after seat belts were changed (third row of Table 1). At the model-specific level (Table 3),

Table 2
Breakdown of fatality rate ratios by make and model for vehicles that received load-limiting seat belts in combination with depowered airbags, adjusted for change in fatality rates of other passenger cars that received depowered airbags only

	Without depowered airbags or belt load limiters			With depowered airbags and belt load limiters				Adjusted using control group	
Vehicle	**Model years**	**Registered vehicle years**	**Driver deaths**	**Model years**	**Registered vehicle years**	**Driver deaths**	**Expected driver deaths**	**Expected driver deaths**	**Rate ratio**
Chevrolet Cavalier	1995	765,309	12	1998	1,320,263	24	21	24	1.01
Control group		3,697,812	56		2,431,750	40	35		
Dodge Stratus	1996-	1,455,193	15	1998	786,383	14	8	8	1.78
Control group	1997	11,669,667	171		4,916,952	70	72		
Ford Contour	1997	392,015	5	1999	674,760	13	9	8	1.54
Control group		2,896,644	56		2,574,133	46	47		
Ford Escort	1997	1,472,942	36	2000	274,852	11	7	4	2.55
Control group		1,567,249	30		843,361	10	16		
Ford Taurus	1997	1,952,174	23	1999	2,087,706	25	25	24	1.04
Control group		2,896,644	56		2,574,133	46	47		
Honda Civic	1997	1,179,115	12	1999	1,002,126	16	10	10	1.60
Control group		2,896,644	56		2,574,133	46	47		
Pontiac Grand Prix	1997	845,252	8	1999	1,752,665	26	17	16	1.60
Control group		2,896,644	56		2,574,133	46	47		
Saturn SL	1997	763,779	15	1999	733,502	19	14	14	1.35
Control group		2,896,644	56		2,574,133	46	47		
Study vehicle total		**8,825,779**	**126**		**8,632,257**	**148**	**110**	**109**	**1.36**

Table 3
Breakdown of fatality rate ratios by make and model for vehicles that received load-limiting seat belts after receiving depowered airbags, adjusted for change in fatality rates of other passenger cars that already had depowered airbags

	With depowered airbags and without belt load limiters			With depowered airbags and belt load limiters				Adjusted using control group	
Vehicle	**Model years**	**Registered vehicle years**	**Driver deaths**	**Model years**	**Registered vehicle years**	**Driver deaths**	**Expected driver deaths**	**Expected driver deaths**	**Rate ratio**
Ford Escort	1998	1,422,214	32	2000	274,852	11	6	7	1.55
Control Group		7,132,151	96		4,541,640	69	60		
Ford Taurus	1998	1,624,862	20	1999	2,087,706	25	26	34	0.74
Control Group		10,401,097	135		9,580,961	156	118		
Honda Civic (4 door)	1998	805,132	10	1999-	1,192,502	20	15	18	1.12
Control Group		7,132,151	99	2000	11,446,869	180	149		
Pontiac Grand Prix	1998	1,647,648	18	1999-	3,402,439	47	37	42	1.12
Control Group		5,159,890	73	2001	11,127,943	168	149		
Saturn SL	1998	569,885	11	1999 -	1,323,891	28	26	29	0.97
Control Group		5,159,890	73	2001	11,127,943	168	149		
Study vehicle total		**6,069,741**	**91**		**8,281,390**	**131**	**109**	**130**	**1.01**

the fatality rate decreased for one of the five models after load limiters were installed, was essentially unchanged for a second, and increased for the other three models.

Finally, the Toyota Camry was the only vehicle in the study to receive load-limiting belts, crash tensioners, and depowered airbags, all for the 1998 model year. Relative to models that received only depowered airbags in 1998, Camrys with the new restraint systems had 27 percent more fatalities than expected. The small exposure associated with studying only one model meant this finding was not statistically significant at the 95 percent confidence level. The observed increase was roughly in line with the study vehicles that received load limiters and depowered airbags without crash tensioners.

DISCUSSION

The present study attempted to evaluate the effectiveness of seat belt load limiters in reducing driver fatalities in real-world crashes. These devices now are widespread, but because they usually were integrated into vehicle designs at the same time as other crashworthiness changes, it is difficult to isolate the effects of their performance. The number of vehicle models available for study was fewer than desired, and their total exposure was too low to produce narrow confidence intervals. Although essentially all modern vehicle designs use load limiters in tandem with crash tensioners, this study could evaluate only one vehicle model with the combination of these technologies. This is due to the fact that manufacturers usually waited for substantial structural or airbag redesigns to introduce crash tensioners. Load limiters require only a new belt retractor, but pyrotechnic crash tensioners must receive a signal from the restraint system's sensing and diagnostic module based on the vehicle accelerometers. These additional structural and airbag changes confound comparisons of the belt technology.

Despite these limitations, there is unlikely to be a better opportunity to evaluate load limiters in real-world crashes. No current mainstream vehicle designs are known to be manufactured without load-limiting belts, so any changes in driver fatality rates associated with their introduction cannot be tracked in the future. Existing thresholds for belt loads will continue to be adjusted, but these modifications will be difficult to evaluate because of the proprietary nature of the information and the shorter design life of today's vehicles. For these reasons, the limited results available from the present study warrant serious consideration.

With few exceptions, the addition of load-limiting seat belts appeared to have no effect on driver fatality rates in some cases and some association with increased fatality rates in others. When the largest group of vehicles received load limiters and depowered airbags, a statistically significant 36 percent increase in fatalities was observed compared with other vehicles that received only depowered airbags. The one model that received similar technology in combination with crash tensioners had a similar increase, though not statistically significant.

In total, fifteen fatality rate ratios were calculated for different restraint combinations on nine vehicle platforms to estimate the effect of load-limiting seat belts in fatal crashes. Of these combinations, two resulted in substantially fewer fatalities than expected: the 18 percent initial reduction for the Cavalier platform (Table 1) and the 26 percent reduction for the Taurus platform (Table 3). Three results were within 4 percent of the expected number of fatalities. The remaining ten rate ratios, including one for the model with crash tensioners, ranged from 1.12 to 2.55, with an average of 1.55.

Variation in Seat Belt and Airbag Load Sharing from Frontal NCAP

The varying fatality rate changes among the different vehicle models that received load-limiting seat belts highlights an important issue. Although some variation would be expected due to the limited exposure of several models, the reduction in fatality rates observed when load-limiting belts were installed on the Cavalier and Taurus platforms is in sharp contrast to the majority of the other models with large fatality rate increases. A significant explanation for these discrepancies may be the differences in the load-limiting mechanisms and airbags themselves. Load-limiter activation thresholds vary throughout the vehicle fleet and, potentially, even in the same vehicle across different model years. The same is true of airbag designs; the amount of depowering varied among vehicles, and subsequent designs may have been modified when load limiters were installed. A more detailed understanding of how certain restraint systems were changed would supplement the observed fatality rates associated with these changes.

One source of data that can be used to quantify restraint system changes is the frontal NCAP. In most of these tests, the belt is instrumented with a transducer to measure the force generated on each occupant's shoulder belt. Table 4 lists the study vehicles with belt load data available from frontal NCAP tests for the model years tested.

Table 4
Maximum driver shoulder belt forces (kN) during tests of study vehicles in frontal NCAP; maximum forces listed by presence of depowered airbags and/or load-limiting seat belts in model year tested

	Shoulder belt loads by presence of depowered airbags and belt load limiters			
Vehicle	**Neither**	**Depowered airbags only**	**Load limiters only**	**Both**
Chevrolet Cavalier (four-door)	6.7	N/A	9.5	6.9
Dodge Stratus	8.2	N/A	N/A	5.1
Honda Civic (four-door)	8.1	12.5	N/A	7.2
Pontiac Grand Prix / Oldsmobile Intrigue	8.6	7.0	N/A	4.8
Saturn SL	5.4	5.4	N/A	3.5
Toyota Camry	6.3	N/A	N/A	5.7*

*In addition to depowered airbags and load limiters, crash tensioners were also added to the Camry restraint system.

A decrease in shoulder belt load for a vehicle tested in NCAP suggests that an increased amount of the occupant's kinetic energy is being transferred through the airbag than in the previous restraint system design. This can be accomplished by allowing more belt webbing to spool out from the retractor during the crash (as with a seat belt load-limiting mechanism), changing properties of the airbag (such as size, venting, or inflation speed), or a combination of both. As discussed previously, it is unknown what airbag modifications, if any, accompanied the installation of load-limiting belts in the study vehicles. So although a change in belt load is not necessarily a direct estimate of the effects of a load limiter, it is likely a reasonable indicator of change in the restraint system's overall balance of loads between the airbag and seat belt.

Installation of a load limiter would be expected to produce a decrease in belt loads, and this was true for all vehicles listed in Table 4 except the Cavalier. The installation of load limiters on the Cavalier platform corresponded to an increased shoulder belt load measured in NCAP and a fatality rate ratio of 0.82 in real-world crashes. When depowered airbags subsequently were installed on the Cavalier platform, the measured belt load decreased to a value similar to the original measurement. The overall change in load was only 3 percent and corresponded to a fatality rate ratio of 1.01. A reason for the atypical belt loads in the Cavalier cannot be determined from the present study, but possibilities include adjustments to the driver airbag or load limiter or the previous installation of a load-limiting device other than the type initiated by mechanical deformation. In any case, the decrease in fatality risk for the Cavalier appears associated with increased occupant loading of the belt, not a reduction. This leaves the fatality rate ratio associated with the Taurus platform as the only decrease potentially resulting from reduced belt forces among the study vehicles.

Figure 2 plots the adjusted model-specific fatality rate ratios by the changes in shoulder belt loads

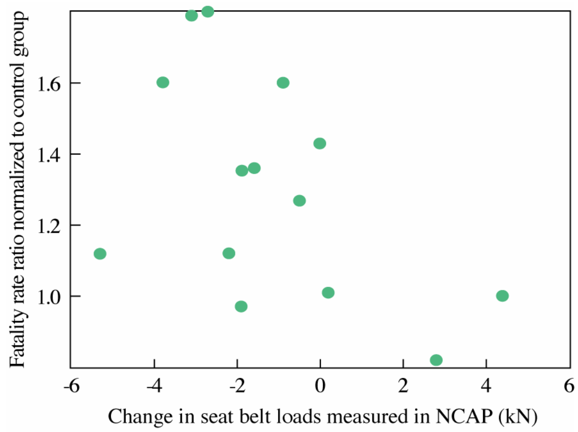

Figure 2. Belted driver fatality rate ratios in frontal crashes for passenger cars that received restraint changes, plotted by the change in belt loads in frontal NCAP tests.

measured in frontal NCAP. Restraint system changes that occurred in multiple steps are plotted for each individual step as well as the overall change. Increases in belt load suggest a greater emphasis on the seat belt in the overall function of the restraint system, whereas decreases suggest the airbag is providing more restraining force than before. The figure shows that the shifts toward lower belt loads were correlated with increased driver fatality rates; of the ten restraint system changes producing decreased belt loads, nine corresponded to increased fatality rate ratios. The three restraint system changes that produced increased belt loads were associated with fatality rate ratios less than or approximately equal to 1.

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The increased fatality rates for most vehicles challenges the assumption that for models with airbags, "the increased risk of significant head injury due to the greater upper torso motion allowed by the shoulder belt load limiter…only occurs for non-deploy accidents where the risk of significant head injury is low even for the unbelted occupant" (Mertz et al., 1995). Although a complete analysis of the overall effectiveness of load-limiting belts would include a comparison of injury risk to different body regions before and after installation, reliable injury data by body region are not available at the make-model level. However, review of a small number of cases from the Crashworthiness Data System (CDS), a part of the National Automotive Sampling System (NASS), reveals that airbag deployment does not prevent injurious excursion-related contacts with interior vehicle components in many crashes. Table 5 summarizes some of the relevant data from the reviewed cases.

In certain cases, occupants also may have sustained injuries from the seat belts. It often was difficult to discern the direct source of injury; some of the injuries coded as coming from excursion contacts may have been belt induced, whereas others coded as being caused by belt loading may have been excursion related. Due to the lack of photographic evidence, it also was impossible to determine precisely the amount of belt spool-out that occurred in most cases. However, the larger point is that these cases provide evidence that excursion contacts continue to occur in vehicles with airbags. In each of the NASS/CDS cases, either there was physical evidence of excursion contact in the vehicle or an investigator's best explanation for the observed injuries was hard contact through the airbag or with other interior surfaces. All vehicles appeared to have adequate postcrash survival space such that intrusion was not likely a source of upper body injuries.

Factors such as offset loading and multiple impacts may have contributed to increased forward excursion in the NASS/CDS cases. However, the greatest insight provided by review of the cases is the reminder that numerous and complex factors are involved in each real-world crash. Laboratory tests of individual restraint system components such as load limiters may produce desirable results and be generally repeatable. Crash tests add a level of complexity because the entire system of components is evaluated in a specific configuration that may be encountered in the field. However, real-world crashes are substantially more intricate. They involve occupants of all sizes and in different positions, differing numbers of impacts with objects of various shapes and strengths, vehicle loading from any direction and for a range of durations, and potential contacts with intruding vehicle components. Although it remains impossible to design restraint systems for every potential real-world crash scenario, the present study suggests that optimizing the performance of airbags and load-limiting belts for 56.4 km/h (35 mi/h) rigid barrier tests may compromise occupant protection in many serious real-world frontal crashes.

Results of the present study in no way diminish the importance of managing belt-induced thoracic loads during crashes. However, they do imply that continued development of alternative belt technologies could have unexpected benefits. Inflatable restraints or four-point belt systems that can mitigate localized thoracic loads without substantially increasing the risk of excursion contact may prove more beneficial than the continued downward trend of belt load thresholds. Alternatively, advanced systems capable of adjusting belt restraint forces based on occupant size, position, and other crash conditions could be required (Miller, 1996).

Table 5
Sample of cases from NASS-CDS with possible excursion contacts and injuries

Case number	Vehicle	Restraint system	Possible excursion contacts	Possible excursion injuries	Contributing factors
2002-042-025	2002 Jaguar X-Type	Airbag, tensioner, load limiter	Windshield, header, front dash (passenger)	Aorta laceration, cerebral hemorrhage	Multiple impacts, possible seat movement
2003-048-228	2002 Honda CR-V	Airbag, tensioner, load limiter	Steering wheel	Cerebral hemorrhage	Front undercarriage loading
2003-049-010	2002 Mitsubishi Galant	Airbag, load limiter	Steering wheel	Loss of consciousness, facial contusions	Multiple impacts
2003-050-101	2001 Ford F-150	Airbag, tensioner, load limiter	Steering wheel	Rib and sternum fractures	Occupant mass, offset loading
2004-050-041	2002 Ford Escape	Airbag, tensioner, load limiter	Steering wheel	Loss of consciousness, facial contusions	Multiple impacts, offset loading
2004-081-007	2002 Toyota MR-2	Airbag, tensioner, load limiter	Left A-pillar	Facial fracture and lacerations	Vehicle rotating at impact
2004-082-123	2002 Toyota Camry	Airbag, tensioner, load limiter	Steering wheel	Facial fractures, loss of consciousness, pneumothorax	Offset loading

CONCLUSIONS

Laboratory tests and limited field studies have shown that load-limiting seat belts have the potential to decrease the risk of belt-induced thoracic injuries. In the past, the increased occupant forward excursion resulting from load limiters kept them from being widely installed. However, with a modern vehicle fleet equipped with standard front airbags, load-limiting belts have become an integral part of restraint systems in new vehicle designs. Low force thresholds have been proposed for these belts, with the assumption that driver airbags can provide the necessary restraining forces during the later stages of a frontal crash. This can reduce injury measures in full-width rigid barrier tests. However, tests with greater intrusion, longer crash pulses, and impact forces offset from the vehicle centerline indicate an increased risk of excursion contact, and undesirable occupant kinematics can result from excessive amounts of belt webbing spool-out. Changes in driver fatality rates associated with the installation of load-limiting belts in passenger cars suggest this restraint technology has not reduced and may have increased the risk of driver fatality in some crashes. Where corresponding model-specific changes in seat belt restraint forces are available, the data indicate reductions in belt forces usually correspond to increased fatality rates. Observations from NASS/CDS cases illustrate the possibility of excursion contacts and injuries in vehicles with airbags under certain crash conditions. The present study suggests that optimizing the performance of airbags and load-limiting belts for rigid barrier tests without regard to the dangers of increased occupant excursion does not produce the most effective restraint systems for many real-world crashes and that alternative methods for reducing localized loading of seat belts should be targeted.

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APPENDIX A

Table A-1
Vehicles tested in frontal NCAP before and after addition of load limiters; no significant structural changes were made and crash tensioners were not added between retests

Make/model	Model year	Driver stars	Passenger stars
Chevrolet Blazer	1997	3	1
	1998	4	4
Chevrolet Cavalier	1995	3	3
	1997	4	3
Chevrolet S-10	1997	3	2
(extended cab)	1998	4	4
Chevrolet S-10	1995	3	1
(regular cab)	2000	3	3
Dodge Durango	1998	2	3
	1999	2	4
Dodge Grand Caravan	1998	3	3
	1999	4	4
Ford Taurus	1998	4	4
	1999	5	5
Honda Civic (2 door)	1996	4	4
	1999	4	4
Honda Civic (4 door)	1998	4	4
	1999	4	4
Oldsmobile Intrigue	1998	4	3
	1999	4	2
Pontiac Grand Prix	1997	4	4
	2001	4	4
Saturn SL	1998	5	4
	1999	5	5
Toyota 4Runner	1996	3	3
	1998	3	3
Volvo 850/S70	1994	5	4
	1995	5	5

APPENDIX B

Table B-1
Passenger cars with load limiter introductions not associated with structural changes; actual model year spans with identical structural platforms may be larger; model years with advanced airbag features or electronic stability control are not included

	Model years with depowered airbags and/or load-limiting seat belts			
Make/model	**Neither**	**Depowered airbag**	**Belt load limiters**	**Both**
Buick Century/Regal	1997	1998		1999-2002
Chevrolet Cavalier	1995		1997	1998-2002
Chrysler Cirrus	1995-1997			1998-2000
Dodge Stratus	1995-1997			1998-2000
Ford Contour	1995-1997			1999-2000
Ford Escort	1997	1998		2000
Ford Taurus	1996-1997	1998		1999
Honda Civic (coupe)	1996-1997			1999-2000
Honda Civic (sedan)	1996-1997	1998		1999-2000
Mercury Mystique	1995-1997			1999-2000
Mercury Sable	1996-1997	1998		1999
Oldsmobile Intrigue		1998		1999
Plymouth Breeze	1996-1997			1998-2000
Pontiac Grand Prix	1997	1998		1999-2002
Pontiac Sunfire	1995		1997	1998-2002
Saturn SL	1995-1997	1998		1999-2002
Toyota Camry	1997			1998-1999*

*The Toyota Camry was the only vehicle that received crash tensioners in addition to load limiters and depowered airbags.

Table B-2.
Passenger cars without load limiters or that had load limiters added previously; these vehicles were used for control groups; actual model year spans with identical structural platforms may be larger

	Structurally identical model years before and after depowered airbags	
Make/model	**Before**	**After**
Acura RL	1996-1997	1998
Audi A6		1998-2001
Buick Park Avenue	1997	1998-2002
Cadillac Catera	1997	1999-2001
Chevrolet Lumina	1995-1997	1998-2000
Chevrolet Malibu	1997	1998-2002
Chevrolet Prizm		1998-2002
Dodge Neon	1995-1997	1998-1999
Honda Accord		1998-1999
Hyundai Sonata	1995-1997	1998
Lexus LS400		1998-2000
Lincoln Continental	1995-1997	1998-2002
Mercury Tracer	1997	1998
Mitsubishi Galant	1994-1997	1998
Mitsubishi Mirage	1997	1998
Nissan Sentra		1998-1999
Oldsmobile Cutlass	1997	1998-2002
Plymouth Neon	1995-1997	1998-1999
Subaru Legacy	1995-1997	1999
Toyota Avalon		1998-1999
Toyota Camry		1998-2001
Toyota Corolla		1998-2002
Volkswagen Passat		1998-2000
Volvo S70		1998-2000