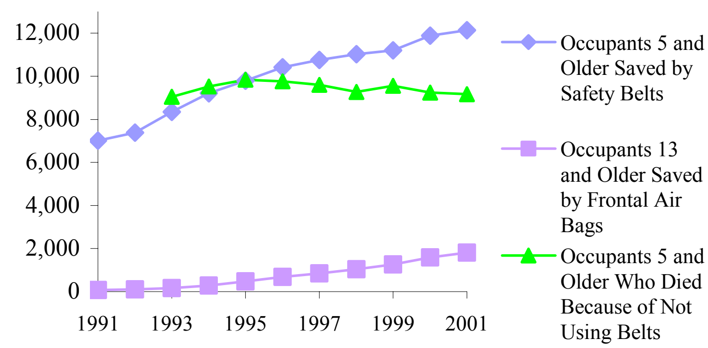
Estimating the Lives Saved by Safety Belts and Air Bags

Donna Glassbrenner, Ph. D.
National Highway Traffic Safety Administration, 400 Seventh St SW, Washington DC 20590
donna.glassbrenner@nhtsa.dot.gov

0. Introduction

Safety belts and air bags are among the most important safety devices in society today, together saving thousands of lives each year. The National Highway Traffic Safety Administration (NHTSA) estimates the number saved each year, as well as the number that would have been saved if more occupants had buckled up. These estimates are not determined by examining crashes on a case by case basis, but rather are estimated from the number of occupants who died, the restraints they used, and the effectiveness of the restraints in preventing fatality.

Chart 1: Passenger Vehicle Occupants Saved by Safety Belts and Air Bags, and Lost from not Using Belts



Source: National Center for Statistics and Analysis, NHTSA, FARS 1991-2001

Specifically, NHTSA estimates on an annual basis:

- the passenger vehicle occupants over 4 years old saved by safety belts,
- the passenger vehicle occupants over 12 years old saved by frontal air bags, and
- the passenger vehicle occupants over 4 years old that would have been saved by safety belts if more of them had buckled up.

Note that these do not include the relatively small numbers of occupants of large trucks saved by belts, children under five saved by belts, children under 13 saved by frontal air bags, and occupants saved by side air bags. Side air bags have not yet been rated for effectiveness, and so the lives that they save cannot currently be estimated. The current data do not support reliable air bag effectiveness ratings for children under 13. NHTSA recommends that these children not be in front of an air bag, unless no other seating position is available.

Lives saved and savable are used in calculating the economic impact of belt use and nonuse. (Blincoe, Seay, et al, 2002) This paper presents improvements made the calculations of lives saved and savable. More detailed information can be found in (Glassbrenner, 2003). In the rest of this paper, "air bag" will mean "frontal air bag", although we occasionally write "frontal air bag" for emphasis. "Lives saved by belts" will mean "passenger vehicle occupants over 4 years old saved by belts", and "lives saved by bags" will mean "passenger vehicle occupants over 12 years old saved by (frontal) air bags".

1. Input to the Lives Saved Calculations: Effectiveness Ratings, Restraint Configurations, and Fatality Counts

1.1 Effectiveness Ratings

NHTSA rates the effectiveness of belts and bags in preventing fatality, finding for instance the following ratings for the driver's seat of passenger cars:

1. Three-point belts are 48% effective for occupants over 4 years old.
2. Air bags are 14% effective for occupants over 12 years old.
3. Air bags are 11% effective for belted occupants over 12 years old who are not saved by their belt.
4. Three-point belts in conjunction with air bags are 53.72% effective for occupants over 12 years old.

The first rating means that 48% of the drivers (over 4 years old) of passenger cars in crashes severe enough that they would die if they were unbuckled and any air bag in their position were removed, would live if they buckled up. The second means that 14% of the passenger car drivers over 12 who would die without a belt and bag would live with the bag. The third means that 11% of the passenger car drivers over 12 who would die with a belt but no bag, would live with a belt and bag. The fourth means that 53.72% of the drivers over 12 years old who would die without a belt and bag would live if they buckled and had an airbag. This rating and can be derived from 1 and 3. (Report to Congress, 2001; Glassbrenner, 2003) Note that the belt and bag ratings are specified for different age ranges. Of course, there will be few drivers under 12 years old.

Three–point belts are the manual lap/shoulder belts in today's vehicles and the automatic lap/shoulder belts that appeared primarily in vehicles made by General Motors. Two-point belts consist of either a) an automatic shoulder belt combined with a manual lap belt, a configuration that appeared in some passenger cars in the 1980's and into the 1990's, or b) an automatic or manual shoulder belt together with a knee bolster under the dashboard, a less common configuration.

Defining ratings this way follows standard practice for two devices, A and B, that act in conjunction. In general, defining *potential fatalities* as those who would die with neither A nor B, the effectiveness of A is the percent of potential fatalities who would live if they used A but not B, the effectiveness of B is the percent who would live if they used B but not A, and the residual effectiveness of B is the percent who would live if they used A and B but A did not save them.

We will call the effectiveness in 2 the *effectiveness of bags* and that in 3 the *residual effectiveness of bags*, since it is the remaining effectiveness after belts are applied. These are the only two ratings of air bags. Belts are rated for their performance as they are used, so the rates reflect both proper and improper use (such as not buckling the manual lap belt if the shoulder belt is automatic). Also note that the air bags are rated for the life-saving capability of their presence, not their deployment. However the deployment ratings would be the same as those for presence.

Vehicle technology is constantly improving and the types of potentially fatal crashes may change over time. For instance the increasing popularity of SUVs has been accompanied by an increase in rollover crashes. Consequently NHTSA periodically updates its ratings to reflect changing conditions. The most recent belt effectiveness ratings are in (Kahane, 2000) and (Morgan, 1999), and the most recent bag ratings in (Report to Congress, 2001). Kahane and Morgan were computed using data from 1986 – 1999 and 1988-1997 respectively, and the Report to Congress used 1986-2000.

1.2 Restraint Configurations and Fatality Counts

We define a *restraint configuration* to be a 6-tuple consisting of the coordinates in Table 1. Note that this includes information on the vehicle and occupant as well as the restraint. The coordinate "air bag?" is to take the value "yes" if the occupant is the driver or right front passenger and there is an air bag in their seating position, and "no" otherwise. The effectiveness of belts and bags in (Kahane, 2000), (Morgan, 1999), and (Report to Congress, 2001) are specified in terms of the restraint configurations.

Table 1: Restraint Configurations

Coordinate	Values
vehicle type	passenger car; light truck or van
seating position	driver, right front passenger, front center, rear outboard, rear center
belt type	3-point, 2-point, lap
belt used?	yes, no
air bag?	yes, no
age	5-12, 13 or older

NHTSA compiles a census of all motor vehicle fatalities in the U.S. from police reports, hospital records and other state documents called the Fatality Analysis Reporting System (FARS). Fatal crashes are defined as police-reported crashes involving a motor vehicle in transport on a public road, street, or highway in which at least one person, called a *fatality*, died within 30 days of the crash. From FARS, we produce counts of occupant fatalities in passenger vehicles, called the *fatality counts*, who are ages 5 or older and had access to a belt, for the various restraint configurations.

For instance, the fatality counts for drivers of passenger cars with 3-point belts in 2001 are given in Table 2. We will refer to this as *Example 1*. Note that belted children under 13 have the same effectiveness rating, whether or not they had an air bag.

Table 2: 2001 Fatality Counts Ratings for Drivers of Passenger Cars with 3-Point Belts

Age 5-12?	Belt Used?	Air Bag in Seating Position?	Effectiveness of Restraint Used	Fatality Count
No	Yes	Yes	53.72%	3,555
No	No	Yes	14%	3,354
No	Yes	No	48%	1,989
No	No	No	0%	2,873
Yes	Yes	NA	48%	0
Yes	No	NA	0%	2

Source: National Center for Statistics and Analysis, NHTSA, FARS, 2001

1.3 Notation

Table 3 defines the notation used in the remainder of this paper. For instance, the second restraint configuration in Table 2 is i=(passenger car, driver, 3-point belt, no, yes, 13 or older), F_i= 3,354, belt(i)=0, bag(i)=1, e_i(belt)= 48%, e_i(used) = e(bag) = 14%, e_i(system)=53.72%, and e_i(belt | bag)=46.19%, which is the residual effectiveness of these belts.

2. The Total Lives that Were Saved by a Belt or a Bag

It is a relatively straightforward matter to estimate the lives saved by both restraints combined. If *x* people die using a safety device that has an effectiveness *e* (i.e. that reduces fatalities in settings in which people would otherwise die by $e \times 100\%$), then one can infer that a total of $x/(1-e)$ used the device in a setting in which they would otherwise die (the potential fatalities), $ex/(1-e)$ of which were saved by the device.

Table 3: Notation	
Notation	**Definition**
e(bag)	the effectiveness of air bags, i.e. 14%
e(bag | belt)	the residual effectiveness of air bags, i.e. 11%
R	the set of all restraint configurations
In the remaining definitions, i denotes a restraint configuration.	
F_i	the fatality count for i
belt(i)	1 if a belt is used in i, and 0 otherwise
bag(i)	1 if a bag is present and the occupant is over 12 in i, 0 otherwise
e_i(belt)	the effectiveness of the belt in I
e_i(system)	e_i(belt) if bag(i)=0, otherwise the effectiveness of the belt-bag system in i
e_i(used)	the effectiveness of the restraint (belt, bag, or belt-bag) used in i
e_i(belt | bag)	$\frac{e_i\,(\text{system}) - e(\text{bag})}{1 - e(\text{bag})}$ when bag(i)=1, otherwise undefined

Applying this to Example 1 gives that 6,508 drivers in passenger cars equipped with 3-point belts were saved in 2001. (See Table 4.) Formulaically, $\sum_{i \in R} \frac{e_i\,(\text{used})\,F_i}{1 - e_i\,(\text{used})}$ people were saved. Of course Example 1 only comprises drivers of passenger cars with three-point belts while the national calculation uses all passenger vehicles and all seating positions.

Table 4: Lives Saved in 2001 Among Drivers of Passenger Cars with 3-Point Belts						
Age 5-12?	**Belt Used ?**	**Vehicle Has Driver's Side Air Bag?**	**Effective-ness of Restraint Used**	**Fatal-ities**	**Potential Fatalities**	**Lives Saved**
No	Yes	Yes	53.72%	3,555	7,682	4,127
No	No	Yes	14%	3,354	3,900	546
No	Yes	No	48%	1,989	3,824	1,836
No	No	No	0%	2,873	2,873	0
Yes	Yes	NA	48%	0	0	0
Yes	No	NA	0%	2	2	0
Totals*				11,774	18,282	6,508
*Row entries may not sum to totals due to rounding. Source: National Center for Statistics and Analysis, NHTSA, FARS, 2001						

3. Attributing the Lives Saved to Belts and Bags

To quantify the benefits of belts and bags separately, NHTSA wishes to partition the total lives saved from the previous section into those that were saved by belts and those that were saved by bags. Unfortunately, there is no clear way to determine such a partition. One can determine the maximum number that could have been saved by either restraint, but this only places limits on the attribution, without determining it. (Logically there should also be occupants for whom both restraints were necessary for their survival, but there is no clear way to calculate this number.)

We illustrate on Example 1. Obviously the 1,836 drivers that were saved but did not have an air bag must have been saved by the belt. Had any children under 13 been saved, they would have also been saved by the belt, since we do not have a bag effectiveness rating in this age range. Similarly the 546 people who were unbelted were saved by the air bag. The only issue is how to attribute the 4,127 that were saved while being protected by both restraints.

Since their belts are 48% effective, belts could only have saved at most 3,687 of the 4,127 occupants ($0.48 \times 3{,}555/(1-0.5372) = 3{,}687$), leaving 439 saved by bags. Similarly, bags could have saved at most 1,075 of these occupants, leaving 3,051 for belts. We call these two attribution methods the *belt-maximizing* and *bag-maximizing methods*, respectively. Note that we do not mean to suggest by these names that the methods were contrived to favor belts or bags. There are simply the bounds set by logic.

NHTSA considered these attributions and a middle ground that attributes the 4,127 lives saved using both restraints to belts and bags in proportion to the effectiveness of belts and bags separately. This method, which we call *restraint-neutral*, attributes 3,195 of the 4,127 occupants to belts (i.e. $4{,}127 \times .48/(.48+.14) = 3{,}195$), and the remaining 932 to bags. Combining these calculations with the 1,836 occupants who were saved using only a belt and the 546 saved using only a bag yields the three attributions for Example 1 in Table 5. Table 6 gives the formulas for the three attribution methods.

Each method has merits. The belt-maximizing method is used in classical benefits analysis. Classically, the safety device that is instituted first (in this case, belts) is attributed the maximal benefits possible, and subsequent safety devices (in this case, bags) are attributed only the residual benefits. Also one can view air bags as restraints that supplement belts, and from this view, bags should only be attributed the residual benefits. In comparison, the restraint-neutral attribution does not give preference to either restraint. Finally, since bags activate automatically, belts can be viewed as restraints that supplement air bags. From this point of view, belts should only receive the residual savings, supporting the bag-maximizing attribution.

Table 5: Attributions Considered for the Lives Saved in 2001 Among Drivers of Passenger Cars with 3-Point Belts

Attribution Method	Lives Saved	
	Belts	Bags
Belt-maximizing	5,523	985
Restraint-neutral	5,030	1,478
Bag-maximizing	4,887	1,621

Source: National Center for Statistics and Analysis, NHTSA, FARS, 2001

Since each method, and in fact any method that falls within the limits set by the belt-maximizing and bag-maximizing attributions, is scientifically valid, choosing among them is a policy decision. NHTSA chose to use the belt-maximizing attribution, which is the method it has used in the past. The formulas for this attribution in Table 6 are improvements over the formulas previously used that better reflect the contributions of air bags.

Table 6: Formulas for the Attribution Methods

Method	Restraint	Lives Saved
Belt-maximizing	Belt	$\sum_{belt(i)=1} \frac{e_i(belt)\, F_i}{1 - e_i(used)}$
	Bag	$\frac{e(bag \mid belt)}{1 - e(bag \mid belt)} \sum_{\substack{belt(i)=1,\\ bag(i)=1}} F_i + \frac{e(bag)}{1 - e(bag)} \sum_{\substack{belt(i)=0,\\ bag(i)=1}} F_i$
Restraint-neutral	Belt	$\sum_{\substack{belt(i)=1,\\ bag(i)=0}} \frac{e_i(belt)\, F_i}{1 - e_i(belt)} + \sum_{\substack{belt(i)=1,\\ bag(i)=1}} \frac{e_i(belt)}{e_i(belt) + e(bag)} \frac{e_i(system)\, F_i}{1 - e_i(system)}$
	Bag	$\frac{e(bag)}{1 - e(bag)} \sum_{\substack{belt(i)=0,\\ bag(i)=1}} F_i + \sum_{\substack{belt(i)=1,\\ bag(i)=1}} \frac{e(bag)}{e_i(belt) + e(bag)} \frac{e_i(system)\, F_i}{1 - e_i(system)}$
Bag-maximizing	Belt	$\sum_{\substack{belt(i)=1,\\ bag(i)=1}} \frac{e_i(belt \mid bag)\, F_i}{1 - e_i(belt \mid bag)} + \sum_{\substack{belt(i)=1,\\ bag(i)=0}} \frac{e_i(belt)\, F_i}{1 - e_i(belt)}$
	Bag	$e(bag) \sum_{bag(i)=1} \frac{F_i}{1 - e_i(used)}$

4. The Lives that Would Have Been Saved if Belt Use Had Been Higher

NHTSA estimates the number of lives that would have been saved in a given year if front seat daytime belt use had been at various higher rates, such as one percentage point higher, 90%, or 100%. "Front seat daytime" is used because our best measurements of belt use arise from an observational survey that employs this restriction for practical reasons. (Glassbrenner, 2002) However, the resulting estimates are frequently referred to as the lives saved if belt use had been, e.g. 90% or 100%, instead of front seat daytime use being 90% or 100%, as will we.

The calculations utilize a belt use model developed by NHTSA. The most recent version of this model is UPF(x) = 0.47249 x^2 + 0.43751 x, where x denotes belt use in the front seat during daytime and UPF(x) denotes the belt use among potential fatalities when daytime front seat use is x. (Wang and Blincoe, 2003) We will refer to belt use among potential fatalities as *UPF*.

As with the total lives saved, it is a relatively straightforward matter to estimate the number of lives that would have been saved if belt use had been higher. We illustrate with Example 1, calculating the additional lives that would have been saved if (daytime front seat) belt use had been 90% in 2001. The UPF model from (Wang and Blincoe, 2002) estimates that UPF would have been 21 percentage points higher in 2001, when front seat occupants buckled up during 73% of their daylight driving time (i.e. 0.2053 = UPF(0.9) – UPF(0.73)). That is, the model predicts that 21% more of the potential fatalities would have buckled up. Applying this to the 18,282 potential fatalities gives 3,753 additional potential fatalities that would have buckled up. We would expect 2,160 of them to be over 12 and have an air bag, since 3,900 of the 6,776 original unbelted potential fatalities fit this description (i.e. 2,160=3,753 × 3,900 / 6,776).

Table 7 computes that a total of 1,925 of the 3,753 newly belted would be saved. However not all of the newly belted died when they were unbelted. One would expect that 302 of them were saved by their air bags when they were unbelted since 302 = 0.14 × 2,160. Subtracting these from the 1,925 that would have been saved if belted, we find that 1,623 additional occupants would have been saved if belt use had been 90%.

Table 7: The Newly Buckled Potential Fatalities Among Drivers of Passenger Cars with 3-Point Belts if Belt Use Had Been 90% in 2001

Age 5-12?	Belt Used?	Airbag Present?	Effective-ness	Potential Fatalities	Lives Saved	Lives Previously Saved by Bags	Net Lives Saved
No	Yes	Yes	54%	2,160	1,160	302	858
No	Yes	No	48%	1,592	764	0	764
Yes	Yes	NA	48%	2	1	0	1
Totals*				3,753	1,925	302	1,623

*Row entries do not necessarily sum to totals due to rounding.
Source: National Center for Statistics and Analysis, NHTSA, FARS, 2001

That is, the additional lives that would have been saved in a given time period (e.g. a given year) had belt use been x_{hypoth} is

$$(\mathrm{UPF}(x_{hypoth}) - \mathrm{UPF}(x_{current}))\sum_{i\in R} \frac{F_i}{1 - e_i(\text{used})}\left(e(\text{system}\,|\,\text{unbelted}) - e(\text{bag}) \sum_{\substack{bag(i)=1,\\ belt(i)=0}} \frac{F_i}{1 - e_i(\text{used})} \Bigg/ \sum_{belt(i)=0} \frac{F_i}{1 - e_i(\text{used})} \right),$$

where $x_{current}$ is the belt use in the time period considered, and e(system | unbelted) is average value of e_i(system) among the unbelted potential fatalities, which is $\sum_{belt(i)=0} \frac{e_i(\text{system})F_i}{1 - e_i(\text{used})} \Big/ \sum_{belt(i)=0} \frac{F_i}{1 - e_i(\text{used})}$ and was 53% in 2001. If one imagines choosing a random subset from the potential fatalities equal to the number you wish to additionally buckle, the formula takes the number saved if you buckle all of them and subtracts the number that were already saved by their bag. Note that we are **not** computing the additional lives saved by estimating the total lives saved in the natural way from the UPF model and subtracting the current lives saved. This would have resulted in a discontinuity, since the UPF model does not precisely predict the use rate that actually occurred among the potential fatalities when inputted the actual daytime front seat use.

The additional lives saved were previously calculated using a variety of formulas for various hypothesized use rates, which produced inconsistent estimates. For instance, the estimated lives saved at 100% use had been precisely this, which resulted in a large gap between the estimate at 99% use, which hypothesized 99% ***daytime front seat use***, and the 100% estimate, which hypothesized 100% ***use***. In addition to producing consistent estimates, the new calculation also uses an updated belt use model from (Wang and Blincoe, 2002). This model is better than that previously used, which predicted ***daytime front seat use*** among potential fatalities.

4. Attributing to the Total Lives Savable at Higher Belt Use to Belts and Bags

Table 8 applies the three attribution methods to the 1,925 people that would have been saved among the newly belted in Example 1 if belt use had been 90%. Recall that 302 of these occupants were saved by their air bags when they were unbelted. The bag-maximizing attribution continues to attribute all 302 to bags, while the belt-maximizing and restraint-neutral attributions revise the attribution for some of them to belts. Namely under the belt-maximizing attribution, 178 unbelted occupants saved by bags would have been saved by belts if they had buckled up, while the restraint neutral method would have reattributed 40 occupants. Table 9 contains the formulas for these attribution methods. Note that all methods attribute the **<u>additional</u>** lives saved (e.g. the 1,623 people in Example 1) to belts.

Table 8: Attributing the Lives Saved Among the Newly Buckled Potentially Fatal Drivers of Passenger Cars with 3-Point Belts if Belt Use Had Been 90% in 2001

Age 5-12?	Belt Used?	Airbag Present?	Lives Saved	Belt-Maximizing Attribution		Restraint-Neutral Attribution		Bag-Maximizing Attribution	
				Belt	Bag	Belt	Bag	Belt	Bag
No	Yes	Yes	1,160	1,037	124	898	262	858	302
No	Yes	No	764	764	0	764	0	764	0
Yes	Yes	NA	1	1	0	1	0	1	0
Totals			1,925	1,802	124	1,663	262	1,623	302

Source: National Center for Statistics and Analysis, NHTSA, FARS, 2001

Table 9: Reattribution Formulas When Belt Use is Hypothesized to Be x_{hypoth}	
Attribution	**Newly Belted Occupants Previously Saved by Bags Who Are Reattributed to Belts**
Belt-maximizing	$(UPF(x_{hypoth}) - UPF(x_{current})) \times \left[e(bag)\sum_{i \in R} \frac{F_i}{1 - e_i(used)} - \frac{e(bag \mid belt)}{1 - e(bag \mid belt)} \sum_{\substack{belt(i)=1,\\ bag(i)=1}} F_i - \sum_{\substack{belt(i)=0,\\ bag(i)=1}} \frac{e_i(used)\, F_i}{1 - e_i(used)} \right]$
Restraint-neutral	$(UPF(x_{hypoth}) - UPF(x_{current})) \times \left[e(bag)\sum_{i \in R} \frac{F_i}{1 - e_i(used)} - \frac{e(bag \mid belt)\, F_i}{1 - e(bag \mid belt)} \sum_{bag(i)=1} F_i - \sum_{\substack{belt(i)=1,\\ bag(i)=1}} \frac{e_i(belt)}{e_i(belt) + e(bag)} \frac{e_i(belt) + e(bag) - e_i(used)}{1 - e_i(used)} F_i \right]$
Bag-maximizing	0

Revising attributions for the 302 previously saved by bags makes perfect sense from the belt-maximizing and restraint-neutral points of view. Buckling the 302 previously unbelted occupants poses a new scenario, in which these occupants would now be restrained by both a bag and a belt. Either restraint might save them. The bag-maximizing perspective doesn't revise the attribution for these 302 occupants because they were saved by bags when they were unbelted. Again each method is justifiable. NHTSA had previously used the bag-maximizing approach for this computation. The other attributions would obviously cause much confusion among many of the people who use the estimates, many of whom are lay readers. Consequently it was decided to continue using the bag maximizing attribution.

5. Summary

In addition to the correction of oversights, we made three major improvements to the calculations of lives saved and savable by belts and bags. Formulas were improved to better reflect the contributions of air bags. The various calculations of savable lives were made consistent. In particular, the lives that would have been saved at 100% use was changed to be consistent with other estimates. Finally, updated effectiveness ratings and a better UPF model were incorporated.

The improvements have a substantial impact on the estimates. Under the new calculations, the lives saved by belts increases by about 10% and that for bags by 6%. The lives that would have been saved if belt use had been one percentage point higher drops by 10%, that for 90% belt use drops by 25%, and that for 100% drops by 19%.

References

1. Blincoe, L., Seay, A., Zaloshnja, E., Miller, T., Romano, E., Luchter, S., Spicer, R., *The Economic Impact of Motor Vehicle Crashes, 2000*, NHTSA Technical Report, DOT HS 809 446, May 2002
2. Fifth / Sixth Report to Congress, *Effectiveness of Occupant Protection Systems and Their Use*, DOT HS 809 442, November 2001
3. Glassbrenner, D., *Safety Belt and Helmet Use in 2002 – Overall Results*, NHTSA Technical Report, DOT HS 809 500, August 2002
4. Glassbrenner, D., *Improving the Calculations of the Lives Saved by Safety Belts and Air Bags*, NHTSA Technical Report, DOT HS 809, August 2003
5. Kahane, C., *Fatality Reduction by Safety Belts for Front-Seat Occupants of Cars and Light Trucks*, NHTSA Technical Report, DOT HS 809 199, December 2000
6. Morgan, C., *Effectiveness of Lap/Shoulder Belts in the Back Outboard Seating Positions*, NHTSA Technical Report, DOT HS 808 945, June 1999
7. Wang, J. and Blincoe, L., *Belt Regression Model - 2003 Update*, NHTSA Research Note, DOT HS 809, May 2003