THE EFFECT OF IMPACT ENVIRONMENT ON OCCUPANT RISK AND THE BELTED/UNBELTED DILEMMA

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ABSTRACT

The fleet-wide occupant risk for frontal impact is estimated using a previously developed, data-based model. The model is constructed using the National Automotive Sampling System (NASS), the Fatality Analysis Reporting System (FARS), and the New Car Assessment Program (NCAP) databases and evaluated against Insurance Institute of Highway Safety (IIHS) data. The occupant risk is obtained from the NASS and FARS databases. The accident velocity distribution is obtained from the NASS data base. The vehicle impact response characteristics that are incorporated into the model are derived from the NCAP test data. The parameters included in the investigation are "intrusion" and vehicle "stiffness", for both belted and unbelted conditions. The model is used to demonstrate that these are not independent in terms of overall occupant risk. The optimal level of vehicle stiffness is different for the belted and the unbelted conditions: Vehicle impact response optimized for the belted may be counter-indicated for the unbelted and vehicle impact response optimized for the unbelted may be counter-indicated for the belted. The model is used to study the effects of limiting intrusion, by stiffening the front structure in the current fleet. The results indicate that limiting the vehicle's intrusion in this manner may reduce fleet wide occupant risk at the high impact velocities; however, it is counter-productive at low impact velocities and, may have no value overall in the current fleet for the current accident velocity distribution.

INTRODUCTION

In an effort to increase occupant safety and reduce fatality rates, the governments of many countries have enacted vehicle safety regulations that automakers must comply to in order to sell their vehicles. NHTSA has been tracking the fatality rates and publishes detailed reports each year, showing trends in vehicle occupant injuries and fatalities. Based on the data shown in Figure 1, the trend appears to be that the fatality rate has been progressively decreasing per 100 million vehicle miles traveled (VMT) for passenger cars (PC) and light trucks and vans (LTV).

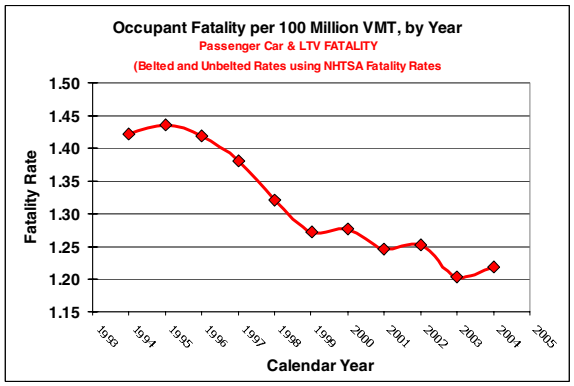


Figure 1. Fatality rate per 100 million miles traveled for PC & LTV.

What does this mean? Is it the result of regulations or ratings tests or something else. Many other factors have changed through the years and contributed to the trends shown above as well. One such change has been in seat belt usage, as reported by the National Occupant Protection Use Survey (NOPUS) which is shown in Figure 2. The reduction in fatality rate shown in Figure 1 could be attributed to the increase usage of belt.

Since there is considerable influence of safety belts on fatality risk, the effect of safety regulations and rating tests need to be ascertained for belted and unbelted cases separately. Using the data shown in Figures 1 and 2, along with the FARS fatality data for belted and unbelted occupants, the adjusted fatality

risk for unbelted and belted occupants are evaluated and are shown in Figures 3 and 4. Figure 3 shows that the fatality rate has been decreasing for belted occupants and Figure 4 shows that the fatality rate has actually been increasing for unbelted occupants.

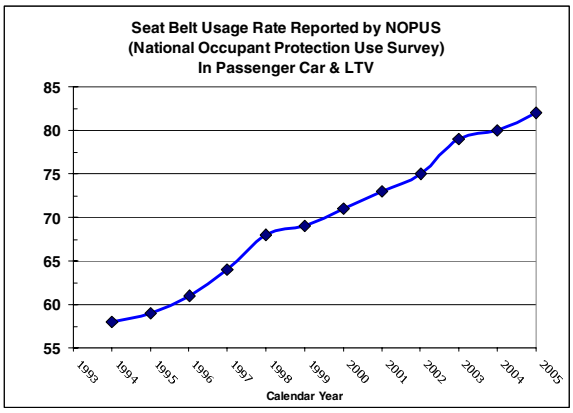


Figure 2. Seat belt usage rate reported by NOPUS for PC & LTV.

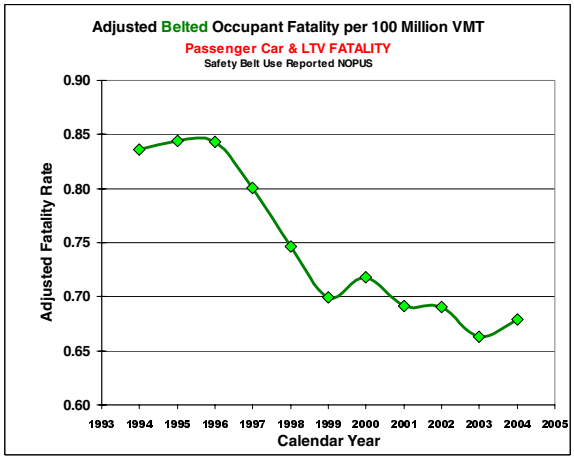


Figure 3. Adjusted belted occupant fatality rate per 100 million VMT.

Consequently, if it is assumed that these results are due to regulations or rating tests, then it appears that the regulations and ratings tests are providing a benefit for the belted and a dis-benefit for the unbelted. However, the foundational data shown in Figure 1, and the adjusted data shown in figures 3 and 4, are contaminated with driver behavior. Driver behavior is a very significant, possibly the most significant, contributing factor in accident and fatality rates. In particular, with the increase in seat belt usage, those who chose to remain unbelted tend to be higher risk takers than those who chose to wear seat belts. With a higher percentage of risk takers in the unbelted group, it is inevitable that they will experience a higher percentage of accidents, and consequently fatalities (exacerbated by the lack of seat belt usage), per 100 million vehicle miles

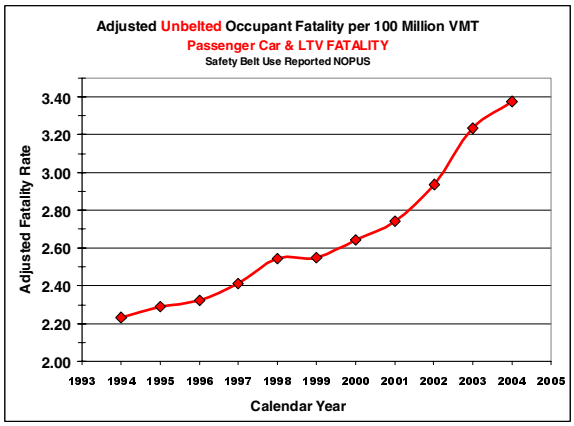


Figure 4. Adjusted unbelted occupant fatality rate per 100 million VMT.

traveled, than their belted counterparts do. Therefore, in this type of analysis, the fatality rates may be too dominated by driver behavior, Evans 2002. to allow the small effects of the regulations and ratings to be evident.

A double pair comparison method which is less sensitive to driver behavior was used by by Kahane [2000] to determine seat belt effectiveness.,Using the seat belt effectiveness reported in this study, the fatality risk is once gain estimated for the belted and occupants and these results are shown in Figure 5. This study indicates that there is little change in fatality risk over several years for both the belted and unbelted once seat belts are removed from consideration.

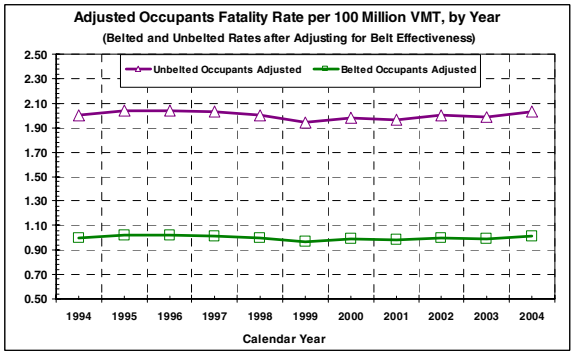


Figure 5. Adjusted occupant fatality rate based on restraint use per 100 million VMT.

Therefore, if we assume that the decrease in fatality rates for 100 million VMT is caused by regulations or ratings tests, then we can conclude that, at a

minimum, current regulations and/or ratings tests for the unbelted are unwarranted and may have negative benefits. However, most likely this assumption is not valid, and driver behavior dominates results to such a degree that the effects of the regulations and ratings tests can not be determined. This is an example of the complexity in trying to interpret the results of experimental tests, regulations, or ratings tests with the effect in the field.

We are going to try to address this complexity with one aspect of crashworthiness, which is the conflict between stiffness versus intrusion in vehicle crashes and the positive and negative effects they have on the belted and unbelted occupants, at slow and high speeds.

Frontal impact vehicle crash tests are conducted by various agencies worldwide to develop "safety" ratings for different vehicles. In The National Highway Traffic Safety Administration (NHTSA) New Car Assessment Procedure (NCAP), a vehicle is impacted against a flat, rigid barrier (RB) at 35 mph. In the Insurance Institute of Highway Safety (IIHS) and the European New Car Assessment Procedure (EuroNCAP) an offset deformable barrier (ODB) is used and the vehicle is tested at 40 mph. In the ODB test, the impact velocity is higher and the entire impact is concentrated on about 40% of the vehicle. As a result, the intrusion into the passenger compartment is generally higher than in the RB test. However, the RB test results in a significant change in velocity (Δv) over a much shorter time than the ODB test, leading to a higher average acceleration for the un-deformed part of the vehicle. Consequently, it is possible that in general, for the undeformed part of the vehicle, intrusion is more important than average acceleration for the ODB test, whereas, average acceleration (deceleration during impact) is more important for the RB test.

The above discussion points to two main issues in frontal impact crashes; i) intrusion and ii) average acceleration (deceleration of the un-deformed part of the vehicle upon impact). Fundamentally these two factors revolve around the amount of available energy to be transferred to the occupant and the rate at which this energy is transferred. The stiffness of the vehicle front end structure is currently an important aspect of energy management in the characterization of the vehicles in ODB and RB tests. A study by Agaram [2000] using different frontal impact excitation pulse shapes (but maintaining the same Δv and displacement) has shown that the simulated peak acceleration response of the unbelted HYBRID III dummy is considerably lower if the "stiffness" is higher in the initial stages of impact in the RB test. There are several theoretical models by Shi et al. [2003] and Wu et al. [2003] that suggest similar findings. This clearly indicates that the response of the dummy is dependent on the characteristics of the deceleration pulse of the vehicle upon impact. However, based on a separate definition that takes into account the maximum crush and the maximum acceleration and time period of the crash pulse, Park et al. [1999] indicated that LTVs with a lower "overall stiffness" have shown an improvement in the vehicle crash "safety" rating in the RB test. A study by Nolan and Lund [2001], based on vehicles subjected to the ODB test, indicates that vehicle designs that minimize intrusion, by proportionately stiffening the front end structure and occupant compartment, can result in an improvement in the vehicle's safety rating for that test. However, a report from NHTSA [2003], using an analysis of FARS data and an estimate of stiffness from NCAP tests, indicates that stiffening the front end of a vehicle increases occupant risk in car-to-car crashes. To complicate these results further, stiffness is never well defined, as reported by Nusholtz et al [2004, 2005]: The force-deformation (F-d) response in frontal impact tests is non-linear; the term "stiffness" is an undefined parameter and only relates to a general unspecified trend. Nonetheless stiffness does not seem to be a significant variable in terms of occupant risk. Instead, other parameters such as vehicle mass, belt use, and age are much more significant as reported by Padmanaban [2003] and Kahane [2003]. Occupant risk is also very dependent on crash severity as reported by Malliaris et al. [1985].

Velocity tends to be a good predictor of the severity of a crash: The higher the velocity of the crash the greater the severity and the higher the injury risk. The prediction of severity and injury risk can be further improved by using average acceleration instead of velocity. This assumes that the motion of the un-deformed part of the vehicle contains more of the necessary information than velocity to determine the injury risk and, that other variables such as intrusion contribute indirectly, as a function of average acceleration, and not directly as a function of the motion of the interior structures.

The relationship between intrusion and average acceleration is dependent on several factors, which includes the crash mode, seatbelt usage, and most importantly the severity of the crash. However, when different classes of impact severities are considered, the relationships between these two parameters (acceleration and intrusion) and their influence on injuries/fatalities keep changing. Over the entire range of possible crash velocities, intrusion correlates with average acceleration and both of them correlate with injuries/fatalities in the field; however, for the low crash velocity range, only a weak correlation is

noticed. Finally, in a domain where the velocity is "high", there is an inverse correlation between the two parameters: Increased average acceleration implies decreased intrusion. In addition, injuries and fatalities can occur without intrusion.
Consequently, the relationship of intrusion and injury could be poorly understood. Intrusion may be rightfully accused of causing the majority of the fatalities and injuries in the field, it may be a correlative variable that has little or no relevance, it may be somewhere in the middle, or it could be none of the above. It could be that the rate of intrusion is the critical value and intrusion is just a correlate. Assuming that intrusion is an important factor for causing injuries/fatalities, then some forms of intrusion control are also important. To accomplish this task, an estimator of crashworthiness with respect to intrusion would be needed. However, it is difficult to attribute the complex two-dimensional intrusion profile with a single descriptor that measures the crashworthiness of the vehicle. Nonetheless, several procedures have been developed to rate performance of vehicles based on intrusion (the EuroNCAP and IIHS ODB tests) with a metric that gauges the overall intrusion into the passenger compartment of the vehicle.
In this study, a mathematical model is used to assess the influence of parameters that control intrusion on the fatality risk. The fatality risk is evaluated for both belted and unbelted occupants and any differences in the characteristics of the fleet, that influences occupant risk, are highlighted. An attempt is made to estimate the trade-offs inherent in implementing intrusion control. This is accomplished through field data obtained from FARS, NASS, and State databases and a fleet model developed by Nusholtz et al. [2003]. Using this data the correlation between the fatality risk and the intrusion rating obtained from ODB vehicle crash tests is assessed. Two separate analyses are conducted to deal with the IIHS and EuroNCAP test data independently.

THEORETICAL MODEL

A fleet model is developed to investigate the effect of stiffness and intrusion on the fatality risk as a function of impact velocity. The fatality risk for both belted and unbelted restraint conditions is assessed. This model is derived from an existing model originally developed by Nusholtz et al. [2003] that was used to understand the effects of vehicle size and mass on injury outcome.
The vehicle is idealized as a mass attached to a non-linear spring, impacting against a rigid barrier at a prescribed velocity. The lumped mass represents the motion of the reaction surface (instrument panel, steering wheel). A similar type of model is used by Shi [2003] for determining the crush pulse to minimize occupant risk.
For each impact velocity, a Monte Carlo simulation of 1000 crashes is performed, each using a random sample of the fleet populations of mass and the force-deformation response of the spring. The average acceleration (A) of the lumped mass is computed using the model. Using the relationship shown in Equation 1 the fatality risk (R) is evaluated from average acceleration. This equation is obtained by modifying the relationship reported by Evans [1994] which deals with occupant risk and closing velocity.

$$R_{unbelted} = \left(\frac{A}{C}\right)^{3.54} \qquad (1a).$$

$$R_{belted} = \left(\frac{A}{C}\right)^{4.57} \qquad (1b).$$

The distribution of the mass is obtained from NCAP tests. The force-deformation (F-d) response of the non-linear spring that is used for simulation is derived from 22 NCAP tests. For modeling purposes, instead of using the actual F-d trace of each vehicle, two separate parametric models, a two-step model and a linear elastic model as shown in Figure 6, are used to describe the F-d response. The two-step model is a better representation of the actual F-d response but the linear elastic model is also used to evaluate the effect of the type of F-d model on the fatality risk.

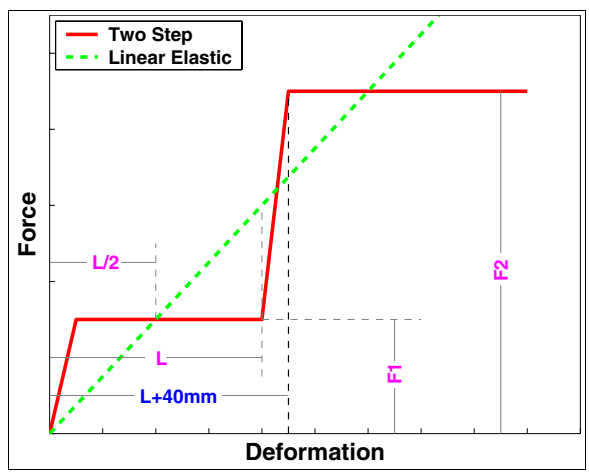


Figure 6. Schematic of the force-deformation response that is used in the mathematical model.

In general, the two-step model has a stiffer response in the initial stages when compared with the linear

model. By using the linear model we are assuming that the two-step model is stiffer than real world crashes and that the linear model is softer than real world. The difference could have an influence on the fatality risk output from the model. It should be noted that even though the F-d response is different between the linear and two-step models, the area under the curve, up to the crush length L, is maintained constant.

The parameters shown in Figure 6 that define the F-d response (for each model) are obtained by curve fitting the data obtained from each NCAP test. The F-d response parameters evaluated from all 22 NCAP tests are used to determine the mean and the standard deviation. This data is used for simulating changes to the stiffness of the fleet. The mass and the parameters (F1, F2 and L) are assumed to be normally distributed in the analysis. The amount of available crush is proportional to the parameter L (L+40 mm is used as available crush). For each run at a given impact velocity, the time (Δt) taken to consume the available crush is determined to estimate the average acceleration. Intrusion is assumed to start after the available crush is consumed. At each pre-selected impact velocity, several simulations are performed by changing the parameters mentioned above using the Monte Carlo procedure to obtain the distribution of the fatality risk. This information is used to calculate the average risk at each velocity. With the accident velocity distribution reported by Malliaris et al. [1997], the cumulative fatality risk up to each impact velocity is then calculated.

In order to understand the influence of stiffness change of the fleet on the fatality risk, case studies are conducted in which the F-d response of the fleet is changed, by increasing and decreasing the initial stiffness (F1 in Figure 6) by ±10% and ±20% from its nominal value.

A model validation study is conducted to gain confidence in the mathematical models and their underlying assumptions by comparing the assessed fatality risk with accident data. The results from this study clearly indicated that the model is capable of capturing the fatality risk. The details involved in the model validation and their results can be obtained from a previously published study [Nushlotz, 2006].

RESULTS

One of the main aspects of this study is to evaluate the effect of stiffness (a parameter that controls intrusion) on the fatality risk. This investigation is carried out by changing the stiffness of the fleet by ±10% and ±20% from the nominal value. The results from these case studies are shown in terms of cumulative fatality risk which takes into account both the fatality risk at a particular impact velocity and the likelihood of accidents at that impact velocity. The accident velocity distribution is obtained from the study by Malliaris et al. [1997] and it is reproduced in Figure 7. A gamma function is fitted through the data to facilitate the analysis.

The results obtained from the linear elastic model are shown in Figure 8. The title at the top of each plot shows the amount by which the stiffness has been changed from the nominal value. For example, a stiff/soft factor of 10% indicates that the fleet stiffness is changed to 90% and 110% from the nominal value and two separate analyses are conducted. As expected the cumulative fatality risk is lower for the belted when compared with the unbelted case. For the unbelted case, the cumulative fatality risk is always lower for a softer vehicle when compared with a relatively stiffer vehicle. However, for the belted case, the cumulative fatality risk for softer vehicles is lower only up to a certain impact velocity. Beyond that point, relatively stiffer vehicles seem to have a lower cumulative fatality risk.

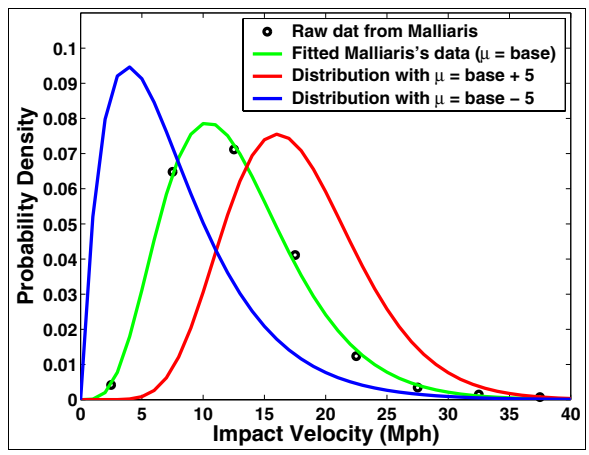


Figure 7. Accident velocity distribution.

Figure 9 shows the cumulative fatality risk obtained from the two-step model. For both belted and unbelted cases, the fatality risk for the softer vehicle is lower than the stiffer vehicles. Unlike the linear model, for the belted case, the results show that there is no cross over from a softer to a stiffer vehicle response, to minimize occupant risk as impact velocity increases, although the gap in fatality risk continued to decrease with an increase in impact velocity. The results clearly indicate that there is considerable reduction in fatality risk if there is a reduction in the stiffness of the fleet, especially at lower impact velocities. Also, the reduction in fatality risk for the unbelted case is much greater than

the belted case. The results shown in Figures 8 and 9 take into account the impact velocity up to a maximum of 40 mph. For numerical reason the model is not able to predict accurately beyond 40 mph. However, since the accident velocity distribution shown in Figure 7 indicates very few accidents beyond an impact velocity of 40 mph, the cumulative fatality risk should not be greatly altered after 40 mph.

The results shown in Figures 8 and 9 indicate that stiffness changes to the fleet influence the cumulative fatality risk to a varying degree depending on the impact velocity. As a result, any change to the accident velocity distribution clearly affects the cumulative fatality risk. A case study is conducted to understand the trends in fatality risk with a change in the accident velocity distribution. If it is assumed that the accident velocity distribution is related to the current driving environment and driving behavior, then changes to factors such as imposed speed limits, driver perception of appropriate speed, road conditions, etc., might have an influence on the velocities at which accidents occur. Assuming that the overall shape of the accident distribution is similar to the distribution reported by Malliaris et al. [1997], two separate distributions are constructed by shifting the mean by an amount of ±5 mph.

The resulting accident velocity distribution obtained by shifting the mean is shown in Figure 7. Only the two-step model is used in this study. The results shown in Figure 10 indicate that the cumulative fatality risk is not only lower at low velocities but the overall risk is also reduced by lowering the mean accident velocity distribution. For the distribution where the accident velocities are lower, a relatively softer vehicle minimizes the fatality risk. However, upon increasing the mean of the accident velocity distribution, a clear cross over from softer to stiffer vehicles is seen at an impact velocity little over 30 mph. As a result, this case study indicates that the accident velocity distribution plays a significant role in determining the optimum stiffness characteristics of the fleet.

Since, in general, most safety rating tests are evaluated at the higher end of the accident velocity distribution, it is possible that the vehicles designed for higher impact velocities may not be able to provide an increased amount of safety benefit at lower impact velocities. Also, the safety rating obtained from vehicle crash tests puts an emphasis on minimizing the intrusion into the occupant compartment which leads to an increase in the stiffness of the vehicle. Stiffer vehicles that minimize intrusion at higher impact velocities may not provide adequate safety at lower impact velocities. As a result, the overall fatality risk, which is dependent on accidents occurring at lower, intermediate, and higher impact velocities, may not show significant improvement in real world safety.

In order to understand whether the inferences from the mathematical model apply to real world vehicle crashes, the intrusion rating obtained from vehicle crash tests is used to see whether there is any correlation with fatalities. The details of this analysis are addressed in the following discussion.

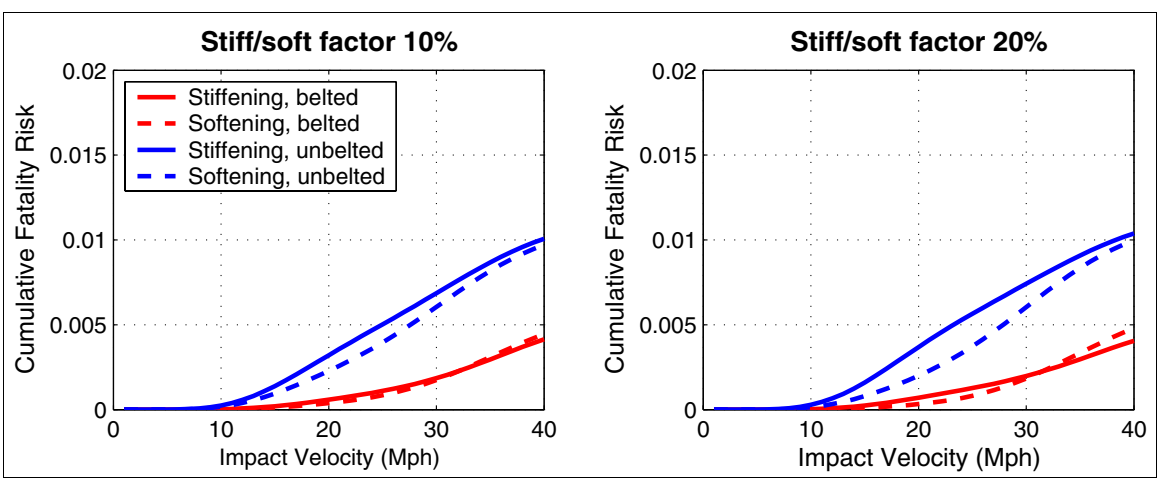


Figure 8. Cumulative fatality results obtained from the linear elastic F-d model.

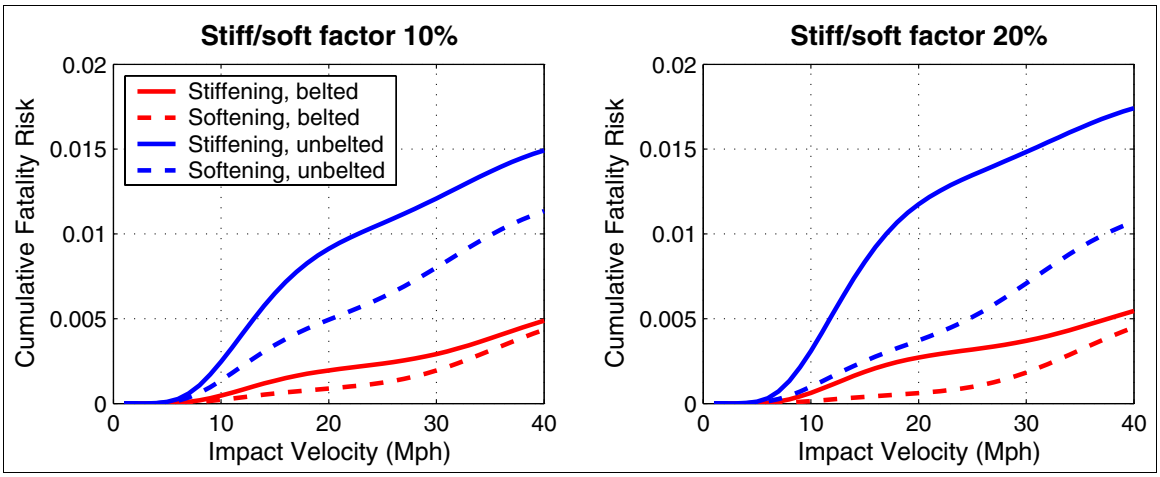


Figure 9. Cumulative fatality results from the two-step F-d model.

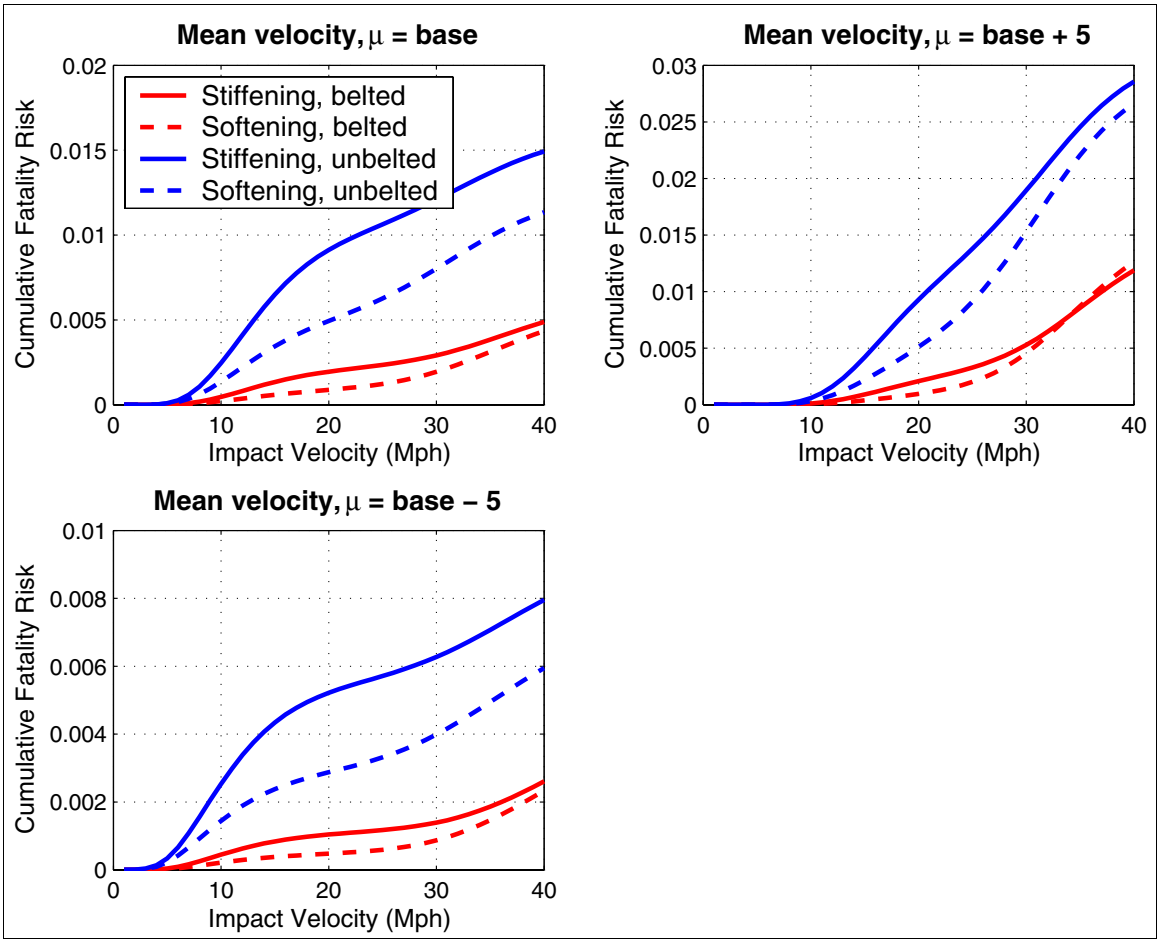


Figure 10. Influence of accident velocity distribution on the cumulative fatality risk (two-step F-d model and variation in stiffness is ±10% from the nominal value).

Analysis of Field Data

Determination of which vehicles are intrusion resistant should come from the accident data. However, a review of the NASS and FARS databases indicates that there is not enough data in NASS for each individual vehicle and not enough information in the FARS records to be able to determine intrusion resistance for the different vehicle make/models. Therefore, it is assumed that the vehicle intrusion ranking obtained from the IIHS ODB tests can serve as a surrogate for vehicle intrusion resistance. To facilitate the analysis, numerical values are assigned to the IIHS intrusion ratings: "good", "acceptable", "marginal" and "poor" ratings are mapped to values of 4, 3, 2 and 1, respectively. This integer parameterization can then be used to compare intrusion with fatality risk obtained from State accident databases and the Fatality Analysis Reporting System (FARS). Care is taken to include data from only those vehicles for which enough fatalities are recorded to make the results statistically meaningful. Details involved in the data collection method and subsequent analysis are presented in the following discussion. A discussion on the EuroNCAP rating as an estimate of intrusion and its correlation with fatality risk is also included.

The IIHS Intrusion Rating and Relative Fatality Risk are obtained from the IIHS web site and an analysis of the FARS database, respectively. The analysis of the FARS database includes data between the calendar years 1980-1999 for only car-to-car crashes that resulted in exactly one driver fatality: Therefore, the relative fatality risk for an average vehicle would be 50%. The model year of both vehicles involved in the accident is in between 1981-1998. Only those vehicles that are involved in ten or more accidents are included, but if sufficient data is not available, vehicles that are close to the subject vehicle are considered. Two different types of relative fatality risk are examined: raw and mass adjusted.

In order to adjust for mass, a logistic model developed earlier by Padmanaban [2003] is used. The risk adjustment, as a function of mass, is done for each individual vehicle; then the mass adjusted risk for each group of vehicles ("Good", "Acceptable", etc.) is assessed by aggregating the mass adjusted risk from individual vehicles. Vehicles that meet the data collection requirements are arranged as per the intrusion rating (Good, Acceptable, Marginal or Poor) obtained from IIHS ODB tests. Using the data obtained for each rating group, the average and the standard deviation of the relative fatality risk and mass adjusted relative fatality risk are evaluated. Table 1 indicates a summary of the relative fatality risk for both belted car-to-car and all car-to-car crashes. In some cases, information for the "Marginal" rated group is not provided as it is based on limited data. The correlation between the relative fatality risk and the intrusion rating shown in Figures 11 and 12 indicates very little correlation between the two: R^2 values of 0.074 and 0.13 respectively.

Table 1.
Summary of relative fatality risk (%) for belted and all car-to-car crashes

Crash type	Good (%)	Acceptable (%)	Marginal (%)	Poor (%)
	Avg* (std)	Avg (std)	Avg (std)	Avg (std)
Belted Car-to-car	17.8 (9.8)	33.8 (23.4)	23.5 (---)	35.0 (21.7)
All car-to-car	30.6 (13.9)	38.2 (23.4)	50.7 (15.2)	48.9 (20.6)

*Avg is Average; std is standard deviation

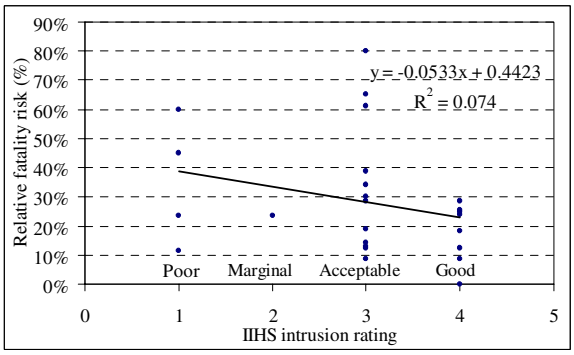


Figure 11. Correlation between relative fatality risk and intrusion for belted car-to-car crashes.

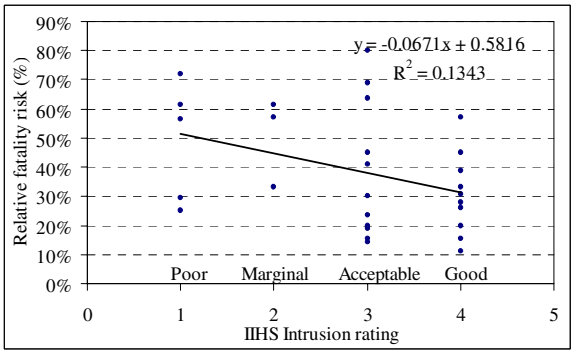


Figure 12. Correlation between relative fatality risk and intrusion for all car-to-car crashes.

A summary of the mass adjusted relative fatality risk for the belted and all car-to-car crashes with respect to each intrusion rating category is shown in Table 2.

Table 2.
Summary of weight adjusted relative fatality risk (%) for belted and all car-to-car crashes

Crash type	Good (%)	Acceptable (%)	Marginal (%)	Poor (%)
	Avg* (std)	Avg (std)	Avg (std)	Avg (std)
Belted Car-to-car	28.8 (14.3)	35.7 (17.8)	22.5 (---)	37.5 (20.8)
All car-to-car	39.2 (15.8)	36.6 (16.0)	40.8 (9.4)	46.2 (19.1)

*Avg is Average; std is standard deviation

It can be ascertained that the mass adjusted relative fatality risk between rating groups (e.g. "Good" and "Poor") has become less discernable when compared with the relative fatality risk. Figures 13 and 14 show the correlation between the mass adjusted relative fatality risk and the intrusion rating for the belted and all car-to-car crashes, respectively. Comparison of the correlation coefficient (R^2) between Figures 11 through 14 also shows that when the relative fatality risk is adjusted for mass, the correlation between the relative fatality risk and intrusion diminishes further, as depicted by the correlation coefficient.

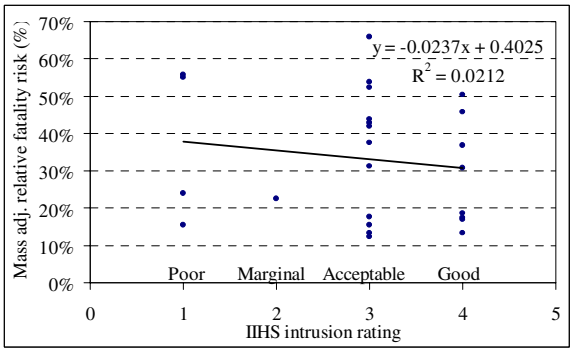


Figure 13. Correlation between mass adjusted relative fatality risk and intrusion for belted car-to-car crashes.

A statistical t-test is conducted to analyze whether the mean relative fatality risk of a particular "intrusion" rating group can be differentiated from the other groups. The t-test is conducted for both the relative fatality risk and the mass adjusted relative fatality risk. The results from the statistical t-test for belted and all car-to-car crashes are shown in Tables 3 and 4 respectively. The confidence level is set at 95% for performing the t-statistical analysis. The critical t-value determined based on sample size and this confidence level are also listed within brackets in the table. For the belted case, there is limited data for the "Marginal" rated vehicles and it is not considered for analysis.

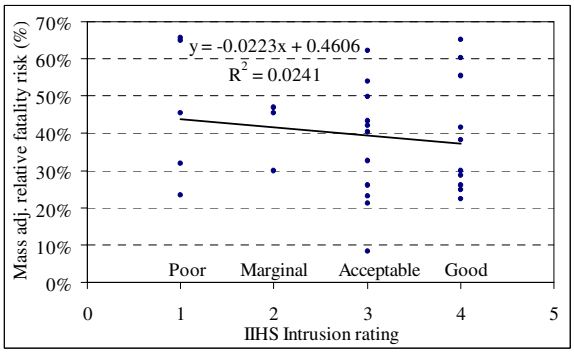


Figure 14. Correlation between mass adjusted relative fatality risk and intrusion for all car-to-car crashes.

Based on the data shown in Tables 3a and 4a, it can be assessed that the differences in the means of the relative fatality risk between "Good" and "Acceptable" as well as "Good" and "Poor" are statistically not significant at the 95% confidence level. However, considering that the computed t-value is closer to the critical t-value, it can be ascertained that there could be a differentiation between groups at lower confidence levels. For example, the t-value estimated between "Marginal" and "Good" ratings for the all car-to-car crashes is close to the critical value, indicating that the means can be differentiated at the 95% confidence level. The mass adjusted relative fatality risk shown in Tables 3b and 4b indicate a much lower t-value when compared with the t-value shown in Tables 3a and 4a, respectively. This indicates that when the relative fatality risk is adjusted for mass, the correlation between the "intrusion" rating and relative fatality risk diminishes considerably. In other words, there is no statistically significant correlation between the "intrusion" rating and mass adjusted relative fatality risk.

Intrusion and Severe Injury Risk obtained from Newstead, et al. [2002] is also used to highlight some aspects concerning the current study. They used the accident data obtained from several State databases (Florida, Ohio, and Pennsylvania). Only car-to-car crashes are considered in their analysis. Basically, this study is included to show whether the trends shown above, using the FARS database, are any different from the accident data collected from the state databases. The correlation between the mass adjusted severe injury risk and intrusion

measurements from IIHS ODB tests is analyzed. The intrusion that affects the driver, which includes the left lower instrument panel and steering column, is considered. The results from this study are shown in Figure 15. It is clear from this figure that vehicles that show reduced intrusion in IIHS ODB tests do not show any significant difference in the mass adjusted severe injury risk when compared with other vehicles.

Table 3.
The data from t-statistical analysis showing the extent of separation of relative fatality risk between vehicle rating groups for *belted* car-to-car crashes

3a) Relative fatality risk

Intrusion rating	Good	Acceptable	Marginal	Poor
Good	0	1.81 (2.1)	---	1.95 (2.2)
Acceptable		0	---	0.10 (2.1)
Marginal			0	---
Poor				0

3b) Mass adjusted relative fatality risk

Intrusion Rating	Good	Acceptable	Marginal	Poor
Good	0	0.91 (2.1)	---	0.86 (2.2)
Accept		0	---	0.17 (2.1)
Marginal			0	---
Poor				0

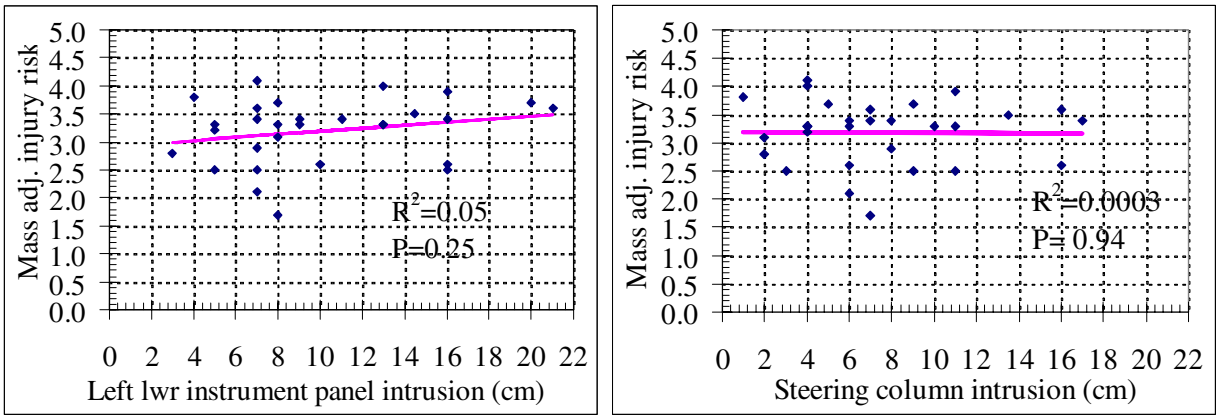
Table 4.
The data from t-statistical analysis showing the extent of separation of relative fatality risk between vehicle rating groups for *all* car-to-car crashes

4a) Relative fatality risk

Intrusion rating	Good	Acceptable	Marginal	Poor
Good	0	0.90 (2.1)	2.16 (2.2)	2.06 (2.2)
Acceptable		0	0.85 (2.2)	0.87 (2.1)
Marginal			0	0.13 (2.4)
Poor				0

4b) Mass adjusted relative fatality risk

Intrusion rating	Good	Accept	Marginal	Poor
Good	0	0.37 (2.1)	0.16 (2.2)	0.75 (2.16)
Accept		0	0.42 (2.2)	1.04 (2.1)
Marginal			0	0.45 (2.4)
Poor				0



(15a) **(15b)**

Figure 15. Correlation between the mass adjusted severe injury risk and intrusion measurements obtained from IIHS tests: a) left lower instrument panel; b) steering column.

Analysis Using EuroNCAP Test Data is conducted using a similar procedure as mentioned above for the IIHS test data. However, in the FARS database there are fewer numbers of vehicles that have both the EuroNCAP rating and sufficient field accident data (to determine the actual fatality risk) to do a thorough analysis. Based on this limited data set, the results indicate similar trends between the safety rating and fatality risk as observed using the IIHS data mentioned above.

An analysis is also conducted using the data from a recently published study by Lie and Tingvall [2002] that deals with police reported car-to-car crashes in Sweden between the years 1994 and 2000. There are some deficiencies in the analysis process reported by Lie and Tingvall associated with the mass compensation for adjusting the fatality risk (see Appendix). An attempt is made to address these limitations by using the procedure reported by Evans and Frick [1992] and Kahane [2003]. The results from this study indicate that there is no statistically significant correlation between the mass adjusted fatality risk and the EuroNCAP rating.

DISCUSSION

Two different F-d models are used to estimate the effect of average stiffness change on the fleet wide occupant risk response: One that, in general, overestimates the risk as seen in NASS and one that, in general, underestimates the risk as seen in NASS. Both models do not estimate risk over 40 mph. The models are limited in their ability to predict the precise nature of the changes in occupant risk that is seen in the field and only are used for general trends. Occupant risk trends that are seen in both models can be expected to be seen in the field, although not necessarily at the velocities or magnitudes as estimated by the models.

The first observation is that when the vehicle fleet is stiffened there is an increase in risk at the low velocities and a decrease in risk at the high velocities. This is true for both F-d models and, for the range of variation evaluated, is independent of the amount of stiffness increase, velocity distribution, belted and unbelted distribution, and amount of crush available before intrusion begins. This result indicates that stiffening the vehicle to prevent intrusion has a complex relationship with occupant risk and it is dependent on a considerable number of confounding factors. It implies that stiffening the vehicles to prevent intrusion could increase or decrease the fleet wide occupant risk depending on factors such as velocity distribution, belted/unbelted distribution, mass distribution, etc.

Since the model evaluates the fatality risk based on the average deceleration of the vehicle during a crash, the energy absorption characteristics play a dominant role on the estimated fatality risk. Softer vehicles undergo more crush and minimize the average acceleration leading to lower fatality risk for low to medium impact velocities. Even though stiffer vehicles can minimize intrusion for crashes at higher impact velocities, at relatively low impact velocities there is little intrusion but higher average acceleration contributing to an increase in fatality risk. Another reason for relatively minor improvements in cumulative fatality risk for stiffer vehicles at higher impact velocities is attributed to a lower number of accidents at those velocities as per the accident velocity distribution.

Most "safety" vehicle evaluation procedures (NCAP, IIHS, EuroNCAP, etc.) typically assume(implicitly) that when occupant risk in vehicle crash tests conducted at relatively high impact velocities is reduced by stiffening the vehicle to prevent intrusion then there is also a reduction in risk at the lower impact velocities or at a minimum there is no significant increase in occupant risk. However, taking into account the accident velocity distribution and the safety merit offered by relatively softer vehicles at lower impact velocities, this may not be true and those vehicles may not show improvements in overall safety. The models indicate that reducing intrusion at "high" velocities by stiffening the front end of the vehicles should have little effect, or a slight negative effect, on overall risk. Since the models can only give general trends it is not completely unlikely that there is some overall reduction in occupant risk as a result of stiffening. However, The accident data analysis done in this paper using IIHS intrusion ratings as a surrogate for reduced intrusion at high impact velocities indicates that there is no benefit to the current fleet by stiffening the vehicle to reduce intrusion.

Three different case studies are conducted to compare the intrusion/safety rating with actual field data obtained from FARS and State databases. In the first case study, the intrusion rating obtained from the IIHS ODB tests is used. This study has shown that even though there is a fair correlation between the relative fatality risk and intrusion rating, the mass adjusted fatality risk has shown no statistically significant correlation with the intrusion rating. A recent study conducted by Farmer et al. [2005] using a different metric, in which the mass adjusted fatality risk is computed based on the number of vehicle registrations, which involves driver behavior and crash characteristics, also indicates that there is no clear correlation between the overall safety rating and fatality risk. However, a marginal change in the

fatality risk between the "Good" and "Poor" rated vehicles is noticed, which is also seen in the current study.

In the second case study, the data reported by Newstead et al. [2002] is utilized. The correlation between the mass adjusted severe injury risk and the intrusion measurements obtained from IIHS ODB is analyzed. This study deals with the data obtained from State databases and it helps to check the mathematical model predictions using separate databases. The results also indicate that the mass adjusted severe injury risk for the vehicles that have a minimum amount of intrusion (at the left lower instrument panel and steering column), in the IIHS ODB tests, have no statistically significant improvement over other vehicles.

In support of this result, Padmanaban [2003], using a logistic model, indicated that stiffness is not a statistically significant variable with respect to occupant risk. In contrast to that, a study by Kahane [2003] indicates that, for car-to-car crashes, stiffness is important and that "softer" is better, implying that stiffening to reduce intrusion may have an overall negative effect. Either result is consistent with the models and analysis presented here.

The second observation is that there is a difference in the effect of stiffening for the belted and the unbelted occupants. In all of the models presented here there is an overall dis-benefit, or almost no effect, for the unbelted to stiffening. For most of the models there is an overall benefit, or almost no effect to stiffening, for the belted. The implication is that optimized stiffness for the unbelted will be sub-optimized for the belted and optimized stiffness for the belted will be sub-optimized for the unbelted. Consequently, these results indicate that a common design solution in terms of stiffness characteristics of the fleet cannot be obtained for both belted and unbelted occupants. The optimal solution for the fleet will depend on the belted/unbelted distribution and will change with time as the percentage of belt usage increases. As a result the best solution might be to design for the belted only in anticipation of a high belt use in the future.

The third observation revolves around driver behavior. The results obtained from shifting the mean of the accident velocity distribution indicate that stiffness of the fleet needs to be lowered if the velocity distribution mean is reduced from the baseline distribution. On the other hand, fleet stiffness has to be increased to minimize fatality risk for an increase in the mean of the accident velocity distribution. These studies indicate that the optimal stiffness of the fleet is dependent on the accident velocity distribution. If the vehicle driving speed is lowered, then a softer fleet will minimize the cumulative fatality risk. On the other hand, a stiffer fleet is required if the driving speed increases.

CONCLUSIONS

The results from this study are based on a limited amount of data; with the addition of more data in the future, there could be changes in the observed trends that are reported in this paper. More work is needed before the results can be generalized. With these limitations, the following conclusions can be drawn.

- The mathematical model indicates that limiting the vehicle's intrusion by stiffening the front end structure may reduce fleet wide occupant risk at the high velocities but it is counter indicated at low velocities.
- The optimal level of vehicle stiffness is different for the belted and the unbelted conditions: Vehicle impact response optimized for the belted may be counter indicated for the unbelted and vehicle impact response optimized for the unbelted may be counter indicated for the belted.
- The model indicates that the crossover (from the softer to a stiffer response) occurs at an impact velocity of approximately 25mph; however, the model is only able to capture the general trend and not able to predict the exact crossover in the field. The actual cross over will depend upon many factors not addressed in the current model and may be higher or lower than 25 mph.
- The model indicates reducing intrusion by stiffening the vehicle has limited value. It reduces occupant risk at the high velocities and increases it at the low velocities with little overall benefit. This is consistent with the field data.

Stiffening the front end of a vehicle to prevent intrusion has a complex effect on occupant risk. The restraint condition, the velocity of impact, the fleet composition, relative stiffness, etc., all play an interacting role in the determination of overall occupant risk. This does not mean that front end stiffness or intrusion reduction is not important, but stiffening the vehicle to reduce occupant risk is a double edged sword: It can in some cases reduce occupant risk and in other cases increase occupant risk.

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APPENDIX

One of the major limitations of the study by Lie and Tingvall [2002] is the lack of an adequate explanation for the procedure that is used for adjusting the fatality risk to account for mass compensation. As shown in Equation 2, a mass compensation factor of 7% for every 100 kg change in mass is used in their analysis. However, when Equation 3 is used to match the fatality risk reported by Lie and Tingvall, the value of the mass ratio exponent α, that is used to compensate for mass, is found to be lower than the values reported by other researchers. The value of the mass ratio exponent (α) turned out to be 2.3, which is lower than the values of 3.8 and 5.5 reported by Evans and Frick [1992] and NHTSA [2003], respectively.

$$R_{comp} = R_1 * \frac{1.07^{((M_{case} - M_{avg})/100)}}{1.07^{((M_{opp} - M_{avg})/100)}} \qquad (2)$$

$$R_{adj} = R_1 \left[\frac{M_{opp}}{M_{case}} \right]^{\alpha} \qquad (3)$$

where,

R_1= Raw fatality risk
M_{opp}= Mass of the opponent vehicle
M_{case}= Mass of the case vehicle
R_{comp}, R_{adj}= Mass adjusted fatality risk

Table 5 shows the adjusted fatality risk for different values of the mass ratio exponent. As mentioned above, the adjusted fatality risk when α is set at 2.3 results in values similar to those reported in the paper by Lie and Tingvall. However, using the same data, but with more widely accepted values of α, Table 5 indicates that there is no significant correlation between the safety rating and fatality risk.
Another limitation in the study by Lie and Tingvall is that variability in mass within each group is not considered in the analysis. The fatality risk is collectively adjusted for mass using the average mass of the struck and striking vehicles. However, there will be a difference in the adjusted fatality risk depending on whether the variation in the mass is considered or not. A case study is conducted to determine the influence of including mass variation, while assessing the adjusted fatality risk.
In this case study, the fatality risk is adjusted for mass by assuming that the variation in mass of the struck and striking vehicles is to be normally distributed. Assuming that the variation in mass is about 8% of the average value, a case study is conducted to determine the influence of mass variation on the adjusted fatality risk. The results are shown in Table 6. When the variation in mass is taken into account, although at lower values of α the adjusted fatality risk has shown a correlation between the safety rating and severe injury/fatality risk, at higher mass ratio exponent values this relationship is not noticeable. This study indicates that adjusted fatality risk, evaluated using a reasonable spread in mass distribution with an appropriate choice of α, has shown no clear relationship with the safety rating.

Table 5.
Mass adjusted severe/fatality risk for different safety rating groups

Euro NCAP Rating	Severe/fatality risk				
	Actual	Mass adjusted risk			
		Eq.2	Eq. 3, for different α		
			2.3	3.8	5.5
No class	0.92	0.98	0.99	1.05	1.11
2 stars	0.92	0.89	0.87	0.85	0.82
3 stars	0.61	0.75	0.79	0.93	1.13
4 stars	0.63	0.7	0.72	0.77	0.83

Table 6.
Change in adjusted severe injury/fatality risk when the variation in mass is accounted for in the analysis

	Adjusted severe injury/fatality risk			
EuroNCAP rating	Baseline	α =1.8	α =3.8	α =5.5
No class	0.98	1.0	1.15	1.35
2 Stars	0.88	0.90	0.94	0.99
3 Stars	0.75	0.76	1.01	1.36
4 Stars	0.7	0.72	0.84	1.00