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16. Abstract

NHTSA issued a final rule to upgrade FMVSS No. 301, Fuel System Integrity, on December 1, 2003, to amend the prior standards in rear and side impacts. By increasing the impact speeds and using a moving deformable barrier, the amended test conditions are more comparable with real-world crashes than the prior standards. The rear impact upgrade phased in during model years 2007 to 2009, whereas the new side impact test went into effect in model year 2005.

The analysis of the rear impact upgrade shows a statistically significant reduction in post-crash fires ranging from 50 to 60 percent. In addition, the rear impact upgrade would reduce 35 percent of the fatalities caused by rear impact fires. NHTSA believes that the rear impact upgrade will save an estimated 23 lives per year, if all vehicles meet the rear impact upgrade. However, the data do not currently show that the side impact upgrade resulted in a statistically significant reduction in side impact fires.

The statistical analysis does not show any significant affiliated effect of the rear impact upgrade on frontal impact fires and first-event-rollover fires. The statistical inference of the rear impact upgrade should not apply to other crash modes.

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LIST OF ABBREVIATIONS

AIS	Abbreviated Injury Scale
CFR	Code of Federal Regulations
CY	calendar year
ESC	electronic stability control
FARS	Fatality Analysis Reporting System, a census of fatal crashes in the United States since 1975
GVWR	gross vehicle weight rating
LTV	light trucks and vans, includes pickup trucks, SUVs, minivans, and full-size vans
MDB	moving deformable barrier
MY	model year
NASS-CDS	National Automotive Sampling System-Crashworthiness Data System
NCAP	New Car Assessment Program: Ratings of new vehicles since 1979 based on performance in frontal impact tests
NCSS	National Crash Severity Study
NHTSA	National Highway Traffic Safety Administration
NPRM	Notice of Proposed Rulemaking
NVPP	National Vehicle Population Profile
PSU	primary sampling unit
RATWGT	ratio inflation factor

Executive Summary

Post-crash fires are infrequent but critically dangerous events. In 1991 to 2001, 2.5 to 2.8 percent of passenger cars and LTVs involved in fatal crashes experienced post-crash fires. To reduce deaths and injuries caused by post-crash fires, NHTSA issued a final rule to upgrade FMVSS No. 301, Fuel System Integrity, on December 1, 2003, and the upgrade concentrates on rear and side impacts. The rear impact upgrade is to strike the rear of the subject vehicle at 80 km/h (50 mph) by a 1,368 kg (3,015 lbs) moving deformable barrier (MDB) at 70 percent overlap with the subject vehicle. The side impact upgrade requires the subject vehicle to be hit laterally by a 1,368 kg (3,015 lbs) MDB at 53 km/h (33 mph). The amended test conditions are more comparable with real-world crashes than the prior standards. In addition, the amended rear impact test is a substantial upgrade of the prior standard, as evidenced by numerous cars of the 1990s leaking from the fuel system after being subjected to the proposed test. The rear impact upgrade phased in during model years 2007 to 2009, whereas the new side impact test went into effect in model year 2005.

The purpose of this evaluation is to assess whether there was a significant decrease in post-crash fires after the upgrade of FMVSS No. 301. The analysis first concentrated on the association between the upgraded standards and post-crash fires, and then the fatality-reducing effect of the amended standard was assessed later. The upgraded standards in rear impacts (FMVSS No. 301 amendment phased in 2007 to 2009) and in side impacts (FMVSS No. 301 amended in 2005) were analyzed individually. The analysis of the upgraded standard in rear impacts, based on FARS data from 2003 to 2011, shows a statistically significant reduction in post-crash fires ranging from 50 to 60 percent. Based on NASS-CDS data from 1991 to 2011, approximately 62 percent of the cases of fatally injured occupants in rear impacts with post-crash fires were caused by burns, as opposed to impact trauma. As a result, the upgraded standard in rear impacts would prevent approximately 35 percent of the fatalities caused by rear impact fires. From 2007 to 2011, there was an average of 65 fatalities per year caused by post-crash fires in rear impacts, so NHTSA believes that the rear impact upgrade will save an estimated 23 lives per year, if all passenger cars and LTVs meet the rear impact upgrade. However, the current data do not show that the side impact upgrade resulted in a statistically significant reduction in preventing post-crash fires in side impacts.

Another question in this evaluation is whether the rear impact upgrade potentially have had any affiliated effect on reducing post-crash fires in other crash modes, such as frontal impacts and first-event rollovers. Based on FARS data from 2003 to 2011, the analysis does not show any statistically significant reduction in frontal impact and first-event-rollover fires after the rear impact upgrade took effect.

1: Introduction

1.1: FMVSS No. 301 Upgrade

Post-crash fires are rare events but may result in fatalities. According to NHTSA's Fatality Analysis Reporting System, from 1991 to 2001, 2.5 to 2.8 percent of cases of fatally injured occupants in light vehicles[1] were involved in post-crash fires. NHTSA issued the final rule to upgrade the requirements of the fuel system integrity on December 1, 2003. The purpose of the FMVSS No. 301 upgrade is to reduce deaths and injuries occurring from post-crash fires that result from fuel spillage[2] [3] during and after motor vehicle crashes, and resulting from ingestion of fuels during siphoning.

The amendment of FMVSS No. 301 focuses on the rear and side impact tests, and there are no changes for the frontal impact and first-event-rollover tests. The followings are the rear and side impact amendments from the Code of Federal Regulations.[4]

Rear Impacts: The rear impact test of the prior FMVSS No. 301 required the entire rear of the subject vehicle to be hit by a 1,814 kg (4,000 lbs) moving rigid barrier at speeds up to 48 km/h (30 mph). The upgraded rear impact test requires striking the rear of the subject vehicle at 80 km/h (50 mph) ± 1 km/h with a 1,368 kg (3,015 lbs) moving deformable barrier at 70 percent overlap with the subject vehicle. The upgrade seeks to more closely simulate real world crash events involving rear impact fires. The test speed is substantially increased, and the offset configuration concentrates the impact on a narrower area than the prior, full-width impact. Furthermore, the finite mass, 1,368 kg (3,015 lbs), of the MDB makes the upgraded test essentially more severe for a lighter vehicle: Due to the laws of conservation of momentum, a lighter vehicle will experience a higher velocity change as a result of being hit by the MDB. A percentage of vehicles manufactured on or after September 1, 2006, and all vehicles manufactured on or after September 1, 2008, must certify to the FMVSS No. 301 rear impact upgrade.

NHTSA is not exactly sure how vehicles were modified to meet the rear impact upgrade, but the agency is currently awarding a contract to study the modifications and their cost to consumers in detail. However, NHTSA believes that the principal modifications in vehicles to meet the upgraded standard are to the tank packaging (location and surrounding structure/shielding relative to crash/intrusion zone) and fuel filler neck packaging (design and surrounding structure).

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[1] Gross vehicle weight rating is less than 4,536 kg (10,000 pounds).

[2] Fuel spillage in barrier crashes: Fuel spillage in any fixed or moving barrier crash test shall not exceed 20 g from impact until motion of the vehicle has ceased, and shall not exceed a total of 142 g in the 5-minute period following cessation of motion. For the subsequent 25-munite period, full spillage during any 1 minute interval shall not exceed 28 g.
Fuel spillage in rollovers: Fuel spillage in any rollover test, from the onset of rotational motion, shall not exceed a total of 142 g for the first 5 minutes of testing at each successive 90^0 increment. For the remaining test period, at each increment of 90^0 fuel spillage during any 1 minute interval shall not exceed 28 g.

[3] Fuel spillage does not include wetness resulting from capillary action.

[4] 49 CFR parts 400 to 571 revised October 1, 2012.

Side Impacts: The MDB test configuration of FMVSS No. 214, Side Impact Protection, is used to replace the side impact test of the prior FMVSS No. 301, which required a 1,818 kg (4,000 lbs) moving barrier at 32 km/h (20 mph) to strike the side of the subject vehicle with the center of the barrier aimed at the driver's seating reference point. In the upgraded FMVSS No. 301 side impact test, the subject vehicle is hit laterally on either side by a 1,368 kg (3,015 lbs) MDB at 53 km/h (33 mph) ± 1 km/h. Vehicles manufactured on or after September 1, 2004, must certify to the FMVSS No. 301 side impact upgrade.

FMVSS No. 214 side impact test results in higher crash forces and subjects the fuel system integrity to greater impact. Therefore, the upgraded FMVSS No. 301 side impact test is more realistic and more stringent than the prior standard. Since most vehicles have already passed the FMVSS No. 214 side impact test, NHTSA expected that a great proportion of vehicles have complied with the upgraded FMVSS No. 301 side impact test before September 1, 2004.[5]

1.2: Lead Time

Rear Impacts: NHTSA published a Notice of Proposed Rulemaking of the FMVSS No. 301 upgrade on November 23, 2000.[6] After reviewing comments of the docket, NHTSA planned a 6-year phase-in schedule after publishing the final rule of the FMVSS No. 301 upgrade on December 1, 2003. NHTSA further required the certification percentages[7] of the rear impact upgrade in the final 3 years of the phase-in schedule. The following table shows the required and actual percentages of the rear impact upgrade certification in model year (MY) 2006 to 2009 and later.

Table 1: Certification Percentage of FMVSS No. 301 Rear Impact Upgrade

MY	Required Certification Percentage	Actual Certification Percentage
2006	-	18.23%
2007	40%	57.40%
2008	70%	82.93%
2009 and Later	100%	100%

The actual certification percentages were obtained by combining the registration data[8] with the certification information from the manufacturers. Table 1 suggests that manufacturers in general met or beat NHTSA's phase-in schedule. NHTSA's phase-in schedule started in MY 2007, but manufacturers had the option to identify which of their make/models have already certified to the rear impact upgrade in MY 2006.

Side Impacts: NHTSA required that all vehicles in MY 2005 and later must certify to the side impact upgrade, and there was no phase-in schedule for the FMVSS No. 301 side impact upgrade.

[5] Final Regulatory Evaluation, FMVSS No. 301 Upgrade, November 2003, NHTSA, Docket No. 2003-16523-2.
[6] 65 FR 67693, Docket Number 2000-8248.
[7] 68 FR 67068 - Federal Motor Vehicle Safety Standards; Fuel Systems Integrity.
[8] Provided by R. L. Polk & Co.

1.3: Survey Sampling: Proportion of Compliance in Rear Impact Upgrade

Table 1 shows the actual certification percentage of the FMVSS No. 301 rear impact upgrade. Although the manufacturers did not identify which make/models have already certified to the rear impact upgrade until MY 2006, certain make/models potentially could have already complied with the rear impact upgrade in MY 2005 or earlier. Vehicles with curb weight less than 1,588 kg (3,500 lbs) are of the greatest interest, because the effect of rear impacts is essentially the most severe for these lighter-than-average vehicles. Thus, vehicles with curb weight less than 1,588 kg (3,500 lbs) in MY 2005 or earlier were considered as the target population in the survey sampling. To estimate the compliance proportion of the FMVSS No. 301 rear impact upgrade in MY 2005 or earlier, a survey sampling was designed in 2012.

The data collection was, in effect, accomplished in two stages. NHTSA had already tested various vehicles in 1999 as part of its research program prior to upgrading FMVSS No. 301. Thirteen vehicles in MY 1996 to 1999 were tested, of which 11 had curb weight less than 1,588 kg (3,500 lbs), and two vehicles weighed greater than 1,588 kg (3,500) pounds. The exact sampling scheme was not documented, but it was likely a judgment survey sampling comprising a variety of body styles and manufacturers, including some make/models with high sales, and concentrating on vehicles weighing less than 1,588 kg (3,500 lbs). Even though a known sampling scheme is required when estimating population parameters, the test results of these vehicles were considered valid information for the corresponding make/models and their corporate twins. However, the test results of the two vehicles weighing greater than 1,588 kg (3,500 lbs) were excluded from the statistical analysis, since they did not belong to the target population.

NHTSA accomplished the second-stage of the data collection in 2012. Removing the make/models that have already been tested in the first stage, the sampling frame of the second stage included vehicles sold for one or more years during MY 1996 to 2000, with curb weight less than 1,588 kg (3,500 lbs) in all of those MYs. Corporate twin-vehicles were categorized together as a single make/model. For example, the Chrysler Cirrus and Plymouth Breeze were categorized together with the Dodge Stratus. The sale of each make/model in a specific MY was referred to the R.L. Polk registrations and restricted to the condition, calendar year (CY) = MY + 1. For instance, the sale of a make/model in MY 1996 was estimated by its registrations in MY 1996 and CY 1997. Furthermore, since vehicles with analogous curb weight and body type would tend to have similar test results, make/models were categorized into three strata, i.e., sedans weighing less than 1,361 kg (3,000 lbs), SUV/CUV/pickup trucks weighing less than 1,588 kg (3,500 lbs), and sedans weighing between 1,361 kg (3,000 lbs) and 1,588 kg (3,500 lbs). The systematic sampling scheme with probability proportional to size (the sales in MY 1996 to 2000) was applied in each stratum, and 13 make/models were randomly selected for the compliance test. In addition, the Honda Accord was non-randomly chosen because of its large sales, and two make/models with curb weights greater than 1,588 kg (3,500 lbs) were selected for the compliance test. However, the test results of these two make/models weighing greater than 1,588 kg (3,500 lbs) only represented themselves and were not considered in the statistical analysis.

The two-stage data collection was used to estimate the proportion of compliant vehicles weighing less than 1,588 kg (3,500 lbs) before MY 2006. NHTSA purchased one sampling unit of each selected make/model (the sampling unit could be in any MY from 1996 to 2000) and subjected them to the upgraded FMVSS No. 301 rear impact test. Because of the non-random selection, the 11 tests in 1999 and the test of the Honda Accord in 2012 just represented themselves. Conversely, the 13 tests in 2012 represented the target population excluding the make/models in the first stage and the Honda Accord. The following table shows the test results in 1999 and 2012.

Table 2: Compliance Test of FMVSS No. 301 Rear Impact Upgrade

Test-Year	Curb Weight ≤ 3500 lbs		Curb Weight > 3500 lbs	
	Pass	Fail	Pass	Fail
1999	5	6	2	0
2012	5	9	1	1

Assuming there was no compliance variation within the same make/model, the sales-weighted estimate of the compliance proportion in MY 2005 or earlier is 39.94 percent with 9.99 percent standard error. The design of the survey sampling and the estimating procedure are provided in Section 9.1.

The primary conclusion from the estimated compliance proportion is that the FMVSS No. 301 rear impact upgrade clearly requires some redesign or modification of vehicles, because the majority (60.06%) of vehicles weighing less than 1,588 kg (3,500 lbs) in MY 1996 to 2000 would not have complied with the rear impact upgrade. Even among the heavier vehicles, for which FMVSS No. 301 rear impact upgrade is a relatively less severe test, one of the four sampling units in MY 1996 to 2000 did not meet the upgraded test requirements.

1.4: Evaluation Purpose

The main goal of the evaluation is to test whether the rate of post-crash fires decreased when the upgraded FMVSS No. 301 took effect. If the effect is noteworthy, then the corresponding benefit will be analyzed. The upgraded FMVSS No. 301 first will be assessed based on fatality data. If the effect is significant in fatality data, then registration data will be used for further analysis. FARS will be applied when evaluating the upgrade in fatality data, and FARS together with Polk data will be used when assessing the upgrade on registered vehicles. The extent to which reductions in post-crash fires translate into life-savings will be evaluated based on the data from the National Automotive Sampling System-Crashworthiness Data System in this evaluation.

Vehicles with gross vehicle weight ratings (GVWR) of 4,536 kg (10,000 lbs) or less are considered as the target population in this evaluation. Since the heavier vehicles above this weight class have more structure to absorb collision forces, it is logical to expect that heavier vehicles are less likely to experience post-crash fires.

Since the upgraded FMVSS No. 301 concentrates on rear and side impacts, the effect of rear and side amendments will be assessed first. Starting with a frequency table of MY versus post-crash fires, initial information, such as a long-term decreasing/increasing tendency in the rate of fires, would be available. Setting distinct criteria, such as the group of MY and status of the upgrade, further statistical analysis will be provided for the upgraded FMVSS No. 301 evaluation in the following sections.

2: Analysis Setting

2.1: Impact Directions and Rollover

The principal impact, i.e., the most severe damaged location in a crash event, was applied to the evaluation, but subsequent crash events were not considered. In collision crash events, the o'clock position is adopted to distinguish rear, side, and frontal principal impacts. The following table presents the type of principal impact and the associated o'clock position in collision crash events.

Table 3: Principal Impact and O'Clock Position

Type of Impact	O'Clock Position
Rear	5, 6, or 7
Side	2, 3, 4, 8, 9, or 10
Frontal	11, 12, or 1

A rollover event is any vehicle rotation of 90 degree or more about any true longitudinal or lateral axis. A first-event rollover is defined as a rollover occurring as the first harmful event or the most harmful event caused by the first harmful event, such as curb, ditch, fence, shrubbery, snow bank, mail box, or shifting cargo. Post-crash fires caused by first-event rollovers are considered in this evaluation.

2.2: Model Year and Calendar Year Setting

The upgraded FMVSS No. 301 focuses on rear and side impacts, and there are not any amendments in the area of frontal impacts and first-event rollovers. Therefore, it is necessary to evaluate the upgraded FMVSS No. 301 separately by rear, side, frontal impacts, and first-event rollovers. Setting appropriate ranges of MYs and CYs will increase the accuracy of the evaluation. The settings of MYs and CYs in distinct types of impact are presented as the following:

Rear Impacts: Statistical analysis will be precise if confounding factors can be removed, and it can be achieved by setting appropriate intervals of MYs and CYs. The effect of the rear impact upgrade thus will be evaluated in the following three distinct ranges of MYs and CYs:

1. NHTSA's phase-in schedule of the rear impact upgrade started in MY 2007, and all vehicles in MY 2009 and later must certify to the FMVSS No. 301 upgrade. In the first range setting of MYs and CYs, MY was restricted from 2004 to 2011, and CY was limited from 2003 to 2011.
2. A large interval of CYs could contain unexpected confounding factors, such as changes of economic climates or adjustments of gasoline prices, which could affect the accuracy of statistical analysis. Shortening the interval of CYs can remove most of the

unanticipated confounding factors. In the second range setting of MYs and CYs, MY was set from 2004 to 2011, and CY was restricted from 2008 to 2011.

3. Reinfurt[9] analyzed the data from National Crash Severity Study and claimed that a post-crash fire is more likely to occur in an older vehicle. Based on Reinfurt's research, the age of a vehicle should be considered as a fire-related confounding factor, and it is recommended to group vehicles with similar ages when making statistical analysis. In the last range setting of MYs and CYs, the ages of vehicles were restricted by the condition, CY ≤ MY + 3, where MY was from 2004 to 2011. Such condition ensured that the analyzed vehicles were new, i.e., 3 years old or less. For example, if CY is 2011, only vehicles in MY 2008 to 2011 will be evaluated.

The range settings of MYs and CYs that are deliberated above to assess the effect of the rear impact upgrade are summarized as the following:

1. 2003 ≤ CY ≤ 2011 and 2004 ≤ MY ≤ 2011,
2. 2008 ≤ CY ≤ 2011 and 2004 ≤ MY ≤ 2011,
3. CY ≤ MY + 3, where 2004 ≤ MY ≤ 2011.

Side Impacts: In 1994, NHTSA conducted the compliance test of the prior FMVSS No. 301 in side impacts, and only one out of 43 subject vehicles exceeded the fuel-leakage criteria of the test. Because of the low failure rate, CY was unrestricted to ensure that there will be sufficient cases of post-crash fires in side impacts when making the evaluation. MY was set from 1995 to 2011 to assess whether there was a long-term tendency in the rate of side impact fires.

Frontal Impacts: There are not any amendments in frontal impacts; however, the upgraded FMVSS No. 301 in rear or side impacts may have had affiliated effects in frontal impact fires. To evaluate the long-term variation in the rate of frontal impact fires, MY was set from 1995 to 2011, and CY was unrestricted.

First-Event Rollovers: There are not any amendments in first-event rollovers. To assess whether the upgraded FMVSS No. 301 in rear or side impacts have potentially affected the rate of first-event-rollover fires, MY was set from 1995 to 2011, and CY was unrestricted.

3: Analysis Method

Based on a particular property, such as the group of MY and the status of the upgrade, vehicles involving post-crash fires were separated into two groups for statistical analysis. The 2-by-2 contingency table was applied to test whether there was a statistically significant association between a particular property and post-crash fires. The odds ratio was utilized as an initial analysis to measure the strength of the association and to estimate the fire-reducing effectiveness.

Furthermore, the Pearson's chi-squared test and Fisher's exact test were used as statistical analysis to support the conclusion of dependence/independence between a particular property

[9] Reinfurt, D. W. (1981, June). A Statistical Evaluation of the Effectiveness of FMVSS 301: Fuel System Integrity. Report 7 of 7. (report No. DOT HS 805 969). Washington, DC: National Highway Traffic Safety Administration.

and post-crash fires. In some cases, the *z*-test was used to assess whether there was a statistically significant difference in the rate of fires between one group and the other. The *z*-test of two-sample proportions was applied in the analysis of post-crash fires per vehicle registration year.

3.1: Odds Ratio and Effectiveness

Considering two binary variables, X and Y, and denoting n_{ij} as the frequencies in i^{th} row and j^{th} column. A 2-by-2 contingency table is presented as the following:

Table 4: 2-by-2 Contingency Table

	Y = 1	Y = 0
X = 1	n_{11}	n_{10}
X = 0	n_{01}	n_{00}

The odds ratio provides the preliminary information to assess whether X is independent of Y. Denoting X = 1 as the experimental group and X = 0 as the control group, the odds ratio is the quotient of the odds when X = 1 and the odds when X = 0. The following is the definition of odds ratio when X = 1 is the experimental group in Table 4: $Odds\ Ratio = \frac{Odds_{X=1}}{Odds_{X=0}} = \frac{\left(\frac{n_{11}}{n_{10}}\right)}{\left(\frac{n_{01}}{n_{00}}\right)} = \frac{n_{11}n_{00}}{n_{10}n_{01}}$. **Equation 1**

Accompanying with the odds ratio, the effectiveness is defined as the following:

$Effectiveness = 1 - Odds\ Ratio = 1 - \frac{n_{11}n_{00}}{n_{10}n_{01}}$. **Equation 2**

The effectiveness in Equation 2 indicates the likelihood reduction/increase in Y = 1 when X shifts from 0 to 1. If X and Y are mutually independent, then the odds ratio should be close to 1, and the effectiveness would approximate to 0. Thus, the odds ratio and effectiveness initially assess the strength of dependence/independence between two binary variables.

3.2: Pearson's Chi-Squared Test and Fisher's Exact Test

Further statistical analysis is needed to determine whether there is a statistically significant association between two variables. Statistical tests, such as the Pearson's chi-squared test and Fisher's exact test, were adopted in this evaluation. Based on Table 4, the null hypothesis, H_0, and the alternative hypothesis, H_a, are set as the following:

H_0: X is independent of Y

H_a: X is not independent of Y. **Equation 3**

The *p*-values of the Pearson's chi-squared test and Fisher's exact test were provided in this evaluation. If the *p*-value is less than the level of significance[10], then H_0 in Equation 3 is rejected. Otherwise, there is not sufficient evidence to reject H_0, and H_a is concluded.

[10] The level of significance is set at 0.05 in this evaluation.

Some statisticians have claimed that the Fisher's exact test is too conservative, i.e., less likely to reject H_0, while H_0 is false. Thus, the statistical inference in this evaluation was mainly referred to the Pearson's chi-squared test. Since applying the Pearson's chi-squared test to evaluate the independence is based on the approximation to the chi-square distribution, each cell is required to have large frequencies. A common rule is 5 or more frequencies in each cell. If the number of frequencies in any cell is not sufficiently large, the statistical inference would not be accurate, and the associated conclusion will not be presented in this evaluation.

3.3: Z-Test of Two-Sample Proportions

To assess the effect of a binary variable in post-crash fires, the target population is separated into two groups. With the independent samples in each group, the following table presents the associated number of fires, sample size, and sample proportion.

Table 5: Sample Proportions of Two Groups

	Fires	Sample Size	Sample Proportion
Group 1	x_1	n_1	$\widehat{P_1}\ (x_1/n_1)$
Group 2	x_2	n_2	$\widehat{P_2}\ (x_2/n_2)$

The following presents the null hypothesis and the alternative hypothesis for testing two population proportions. If one population proportion is greater than the other, then the effect of a binary variable is statistically significant.

H_0: $P_1 = P_2$

H_a: $P_1 < P_2$. **Equation 4**

In any hypothesis test, the probability distribution is under the assumption that H_0 is true. If H_0 in Equation 4 is true, then there is only one population proportion that applies to both samples. The pooled estimate of the variance of $(\widehat{P_1} - \widehat{P_2})$ is used when carrying out a hypothesis test with H_0 stating $P_1 = P_2$.

Denoting $\hat{P}$ as $(x_1 + x_2)/(n_1 + n_2)$ and applying the pooled estimate of the variance, the following is the test statistic of Equation 4: $Z = \frac{\widehat{P_1} - \widehat{P_2}}{\sqrt{\hat{P}(1-\hat{P})(\frac{1}{n_1}+\frac{1}{n_2})}}$. **Equation 5**

The test statistic in Equation 5 is called the z-test of two-sample proportions. If the p-value of the z-test is less than the level of significance, then H_0 in Equation 4 is rejected. Otherwise, there is not sufficient evidence to reject H_0, and H_a is concluded.

4: Fires in Rear Impacts

Before NHTSA proposed the upgraded FMVSS No. 301, the agency had previously performed fuel leakage tests in the New Car Assessment Program . The NCAP set the test speed to be 8 km/h (5 mph) higher than the corresponding speed in the prior FMVSS No. 301. The NCAP rear impact test was performed at 56 km/h (35 mph) on subject vehicles in MY 1979 to 1981, and fourteen out of 52 vehicles (26.9%) exceeded the fuel-leakage criteria of the rear impact upgrade.[11] The high failure rate suggests that there could be a substantial opportunity to reduce the fuel leakage and the rate of post-crash fires in rear impacts. Additionally, the upgraded FMVSS No. 301 rear impact test (50 mph) is considerably more stringent than the prior test (30 mph), because the barrier's impact kinetic energy (KE[12]) is increased by about 110 percent. As a result, most of the vehicles in 2000 would not have been able to meet the test requirements of the FMVSS No. 301 rear impact upgrade. Based on this reason, in NHTSA's regulatory impact analysis, the agency specified that there should be a high effectiveness against the fuel-leakage and post-crash fires in rear impacts for vehicles that met the rear impact upgrade. The fire-reducing effectiveness of the rear impact upgrade was specifically anticipated to be 50 to 75 percent in NHTSA's final regulatory evaluation.[13]

4.1: Model Year Versus Rear Impact Fires in FARS

Utilizing FARS in CY 2003 to 2011 and MY 2004 to 2011, a frequency table of MY versus rear impact fires is presented as the following:

Table 6: Frequency Table of Model Year Versus Rear Impact Fires in FARS

MY	No Fires	Fires	Rate of Fires
2004	1,320	35	2.58%
2005	1,135	29	2.49%
2006	949	22	2.27%
2007	732	19	2.53%
2008	451	5	1.10%
2009	240	2	0.83%
2010	168	1	0.59%
2011	68	1	1.45%

Because of the variation in the rate of fires, Table 6 suggests that MY and rear impact fires would be associated. Since NHTSA's phase-in schedule of the rear impact upgrade began in MY 2007 (September 1, 2006), and 57.40 percent of the vehicles in MY 2007 actually certified to the rear impact upgrade, it is reasonable to separate the vehicles into the MY $\leq$ 2007 and MY > 2007 groups for further statistical analysis.

Limiting our analysis to MY 2004 to 2011 and restricting the range of CYs to remove potentially fire-related confounding factors and to control the ages of vehicles, three distinct intervals of CYs were set, i.e., $2003 \leq CY \leq 2011$, $2008 \leq CY \leq 2011$, and $CY \leq MY + 3$. The following table presents the statistical outputs of the group of MY versus rear impact fires in three distinct ranges of CYs.

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[11] Final Regulatory Evaluation, FMVSS No. 301 Upgrade, November 2003, NHTSA, Docket No. 2003-16523-2, pp. III-10.

[12] The barrier's initial KE = ½ [the barrier's mass (m_b) x test speed (v_b) x test speed (v_b)]. Thus, the prior barrier impact KE is ½ [1814 kg x 13.4 m/sec x 13.4 m/sec] = 162860 joules, and the upgraded barrier impact KE is ½ [1368 kg x 22.35 m/sec x 22.35 m/sec] = 341673 joules.

[13] Final Regulatory Evaluation, FMVSS No. 301 Upgrade, November 2003, NHTSA, Docket No. 2003-16523-2.

Table 7: Model Year Versus Rear Impact Fires in FARS

CY 2003-2011 and MY 2004-2011			
	No Fires	Fires	Rate of Fires
MY ≤ 2007	4,136	105	2.48%
MY > 2007	927	9	0.96%
Odds Ratio	38.24%		
Fire-Reducing Effectiveness	61.76%		
Pearson's Chi-Squared Test	x^2 = 8.1645		***p*-value = 0.0043**
Fisher's Exact Test	-		***p*-value = 0.0029**
CY 2008-2011 and MY 2004-2011			
MY ≤ 2007	2,335	55	2.30%
MY > 2007	916	9	0.97%
Odds Ratio	41.71%		
Fire-Reducing Effectiveness	58.29%		
Pearson's Chi-Squared Test	x^2 = 6.2145		***p*-value = 0.0127**
Fisher's Exact Test	-		***p*-value = 0.0110**
CY ≤ MY + 3 and MY 2004-2011			
MY ≤ 2007	2,759	71	2.51%
MY > 2007	927	9	0.96%
Odds Ratio	37.73%		
Fire-Reducing Effectiveness	62.27%		
Pearson's Chi-Squared Test	x^2 = 8.0992		***p*-value = 0.0044**
Fisher's Exact Test	-		***p*-value = 0.0037**

Table 7 shows that the rate of fires in the MY > 2007 group was considerably smaller than the corresponding rate in the MY ≤ 2007 group in each range of CYs. Since the average of the odds ratios in Table 7 is approximately 40 percent, the group of MY and rear impact fires should be associated. The common value of the estimated fire-reducing effectiveness is close to 60 percent. Thus, if a rear hit vehicle in the MY ≤ 2007 group switches to the MY > 2007 group, then the likelihood of incurring a rear impact fire would be reduced by around 60 percent.

Since each cell contains more than 5 frequencies, the statistical inference from the Pearson's chi-squared test and Fisher's exact test is reliable in Table 7. The associated bold-faced *p*-values indicate that there is sufficient evidence to reject H_0 in Equation 3. Based on the statistical tests, we can conclude with confidence that there was a statistically significant relationship between the group of MY and rear impact fires.

Separating the rear hit vehicles into the MY > 2007 and MY ≤ 2007 groups shows the statistically significant effect of the group of MY. Based on the group of MY, the average of the estimated fire-reducing effectiveness is around 60 percent, which is consistent with NHTSA's anticipation, i.e., 50 to 75 percent. However, NHTSA planned a 3-year phase-in schedule for the rear impact upgrade (40%, 70%, 100%) in MY 2007 to 2009, and not all make/models initially certified to the FMVSS No. 301 rear impact upgrade in the same MY. It is not accurate to assess the effect of the rear impact upgrade merely by grouping vehicles according to their MYs. The associations between the rear impact upgrade and rear impact fires will be analyzed with more precision in the next section.

4.2: Rear Impact Upgrade Versus Rear Impact Fires in FARS

Although NHTSA's phase-in schedule of the rear impact upgrade began in MY 2007 (September 1, 2006), the manufacturers already had the option to identify the status of the rear impact upgrade in MY 2006. The manufacturers notified NHTSA which of their make/models certified to the FMVSS No. 301 rear impact upgrade in MY 2006 to 2008, and all vehicles in MY 2009 and later were required to certify to the rear impact upgrade. Based on the information from the manufacturers, NHTSA listed the make/models that certified to the rear impact upgrade in MY 2006 to 2008. It was assumed that no make/model certified to the rear impact upgrade in MY 2005 or earlier, although some vehicles would have been able to comply, as evidenced by the estimated proportion of compliance in Section 1.3. However, NHTSA did not have a comprehensive list of compliant vehicles in MY 2005 or earlier. As a result, the agency could not evaluate the exact effect of the compliance with the rear impact upgrade in MY 2005 or earlier. Applying NHTSA's certification list of the rear impact upgrade and separating vehicles into the certified and uncertified groups was the best available strategy to estimate the effect of the rear impact upgrade. Nevertheless, the effectiveness could be underestimated, because some of the uncertified vehicles may have already been able to comply and thus needed relatively little or no modification to meet the FMVSS No. 301 rear impact upgrade.

Since the status of the rear impact upgrade was not always available for every make/model in each MY, NHTSA's certification list of the rear impact upgrade was not even fully complete in MY 2006 to 2008. For example, the Honda Civic and Acura MDX AWD were manufactured in MY 2006 and 2007, but their corresponding statuses of the rear impact upgrade were not available. A rear impact crash was considered as a missing observation, if the corresponding status of the rear impact upgrade was not available. Applying the same ranges of CYs in Table 7, the following table shows the number of missing observations and missing rate in distinct ranges of CYs.

Range of CYs	Missing Obs.	Missing Rate
$2003 \leq CY \leq 2011$	58	1.30%
$2008 \leq CY \leq 2011$	40	1.36%
$CY \leq MY + 3$	43	1.31%

The missing observations were removed before making any statistical analysis. Since the missing rate was below 1.5 percent in each range of CYs, the deletion would not seriously affect the statistical inference.

Using the same ranges of MYs and CYs in Table 7 and separating vehicles into the certified and uncertified groups, the following table presents the statistical outputs of the rear impact upgrade versus rear impact fires in distinct ranges of CYs.

Table 8: Rear Impact Upgrade Versus Rear Impact Fires in FARS

CY 2003-2011 and MY 2004-2011			
	No Fires	Fires	Rate of Fires
Uncertified	3,010	69	2.24%
Certified	1,303	16	1.21%
Odds Ratio	53.57%		
Fire-Reducing Effectiveness	46.43%		
Pearson's Chi-Squared Test	x^2 = 5.1482		***p*-value = 0.0233**
Fisher's Exact Test	-		***p*-value = 0.0230**
CY 2008-2011 and MY 2004-2011			
Uncertified	1,680	40	2.33%
Certified	1,160	12	1.02%
Odds Ratio	43.45%		
Fire-Reducing Effectiveness	56.55%		
Pearson's Chi-Squared Test	x^2 = 6.6888		***p*-value = 0.0097**
Fisher's Exact Test	-		***p*-value = 0.0099**
CY ≤ MY + 3 and MY 2004-2011			
Uncertified	1,986	44	2.17%
Certified	1,199	14	1.15%
Odds Ratio	52.70%		
Fire-Reducing Effectiveness	47.30%		
Pearson's Chi-Squared Test	x^2 = 4.4388		***p*-value = 0.0351**
Fisher's Exact Test	-		***p*-value = 0.0395**

Table 8 shows that the rate of fires in the certified group was substantially lower than the corresponding rate in the uncertified group in each range of CYs. Since the average of the odds ratios is close to 50 percent, the rear impact upgrade and rear impact fires should be related. The common value of the estimated fire reducing effectiveness in Table 8 is around 50 percent. If an upgrade-uncertified rear hit vehicle passes the upgraded rear impact test, the probability of experiencing a rear impact fire would be reduced by about 50 percent.

Since each cell has more than 5 frequencies, the statistical conclusions from the Pearson's chi-squared test and Fisher's exact test are precise in Table 8. The associated bold-faced *p*-values suggest that there is sufficient evidence to reject H_0 in Equation 3. Therefore, there was a statistically significant association between the rear impact upgrade and rear impact fires.

It is noteworthy that the average of the estimated fire-reducing effectiveness in Table 8 is 10 percentage points lower than the corresponding value in Table 7. A presumed explanation is that certain vehicles would have already complied with the rear impact upgrade in MY 2005 or earlier, and their subsequent statuses of the rear impact upgrade were not changed in MY 2006 or later. Compliant vehicles in MY 2005 or earlier might require little or no upgrading, so their contribution to the estimated fire-reducing effectiveness was limited. Thus, the exact fire-reducing effectiveness of the rear impact upgrade for previously non-compliant vehicles may be underestimated, if vehicles are separated into the certified and uncertified groups without any further consideration.

However, the agency was not able to precisely distinguish compliant vehicles in MY 2005 or earlier from NHTSA's certification list of the rear impact upgrade. Therefore, the fire-reducing effectiveness of the rear impact upgrade in Table 8 would be underestimated. Nevertheless, an accurate range of the estimated fire-reducing effectiveness ought to be built. It is reasonable to consider the average estimate in Table 8 as a lower bound and the corresponding value in Table 7 as an upper bound. As a result, the range of the estimated fire-reducing effectiveness of the rear impact upgrade based on FARS is from 50 to 60 percent, which overlaps with NHTSA's prediction in 2003, i.e., 50 to 75 percent.

4.3: Model Year Versus Rear Impact Fires in Polk

The target population in Section 4.1 and 4.2 is the cases of fatalities, and the evaluation includes estimating the fire-reducing effectiveness and testing the association between the rear impact upgrade and rear impact fires. However, the estimated fire-reducing effectiveness would be biased due to compliant vehicles in MY 2005 or earlier. To confirm the statistical inference from FARS, the fire-reducing effectiveness ought to be estimated from a different population. Concerning registered vehicles with and without rear impact fires, the registration data was adopted. To assess the effect of the rear impact upgrade, the main evaluation in the following sections will focus on testing the difference between the rates of rear impact fires in the upgrade-certified and upgrade-uncertified registered vehicles.

The registration data was obtained from R. L. Polk's National Vehicle Population Profile, and NVPP provides the number of registered vehicles on July 1 in each CY. The total number of registered vehicles would be poorly estimated, if MY = CY and MY = CY + 1 are included. Therefore, the restriction, MY < CY, is always applied when using Polk.

Section 1.2 shows that the actual certification percentage of the rear impact upgrade in MY 2007 was 57.40 percent, and Section 4.1 indicates that there was a statistically significant association between the group of MY and rear impact fires when separating cases of fatal crashes by MY 2007. Based on previous statistical inference from FARS, it is reasonable to separate the registered vehicles into the MY ≤ 2007 and MY > 2007 groups for an initial evaluation.

To remove fire-related confounding factors and to control the age of vehicles, our analysis limited MY from 2004 to 2010 and applied three distinct ranges to CY, i.e., 2005 ≤ CY ≤ 2011, 2008 ≤ CY ≤ 2011, and CY ≤ MY + 3. The table on the next page shows the statistical outputs of the group of MY versus rear impact fires in distinct scenarios. Since rear impact fires are extremely infrequent events, the rate of rear impact fires in Table 9 is presented in billion registration years, i.e., the total number of registered vehicles on the road for one year.

Table 9: Model Year Versus Rear Impact Fires in Polk

CY 2005-2011 and MY 2004-2010			
	Fires	Registration Years	Fires/Billion Registration Years
MY ≤ 2007	82	327,901,334	250.0752
MY > 2007	6	69,746,745	86.0255
Fire-Reducing Effectiveness	65.60%		
z test	*z* = 2.6446		***p*-value = 0.004**
CY 2008-2011 and MY 2004-2010			
MY ≤ 2007	55	235,232,528	233.8112
MY > 2007	6	69,746,745	86.0255
Fire-Reducing Effectiveness	63.21%		
z test	*z* = 2.4237		***p*-value = 0.0075**
CY ≤ MY + 3 and MY 2004-2010			
MY ≤ 2007	67	277,889,648	241.1029
MY > 2007	6	69,746,745	86.0255
Fire-Reducing Effectiveness	64.32%		
z test	*z* = 2.5269		***p*-value = 0.0060**

Table 9 shows that the rate of fires in the MY ≤ 2007 group was nearly three times greater than the corresponding rate in the MY > 2007 group in each range of CYs. The large difference strongly suggests that these two groups of MY may have distinct likelihood of experiencing rear impact fires. The average of the estimated fire-reducing effectiveness is around 65 percent. Thus, there would be an approximate 65 percent reduction in the probability of incurring a rear impact fire, if a registered vehicle in the MY ≤ 2007 group shifts to the MY > 2007 group.

The statistical inference in Table 9 is based on the hypothesis statement in Equation 4 and the *z* test of two-sample proportions in Equation 5. The bold-faced *p*-values in Table 9 indicate that there is sufficient evidence to reject H_0. Thus, the rate of rear impact fires in the MY ≤ 2007 group was statistically concluded to be significantly greater than the corresponding rate in the MY > 2007 group. The conclusion implies that separating the registered vehicles into the MY > 2007 and MY ≤ 2007 groups shows the statistically significant effect of the group of MY.

4.4: Rear Impact Upgrade Versus Rear Impact Fires in Polk

The purpose of this evaluation is to assess whether the rear impact upgrade significantly took effect on rear impact fires. Because some vehicles may have already complied with the rear impact upgrade in MY 2005 or earlier, and certain make/models certified to the rear impact upgrade in MY 2006, it is not accurate to assess the effect of the rear impact upgrade by simply grouping the registered vehicles based on their MYs. To precisely estimate the effect of the rear impact upgrade in this section, the registered vehicles were separated according to their statuses of the rear impact upgrade.

However, the status of the rear impact upgrade was not always available for every make/model in each MY. For example, the Honda Odyssey was manufactured in MY 2006 and 2007, but the corresponding statuses of the rear impact upgrade were not provided. Applying the restriction, MY < CY, a registered vehicle was considered as a missing observation, if the corresponding status of the rear impact upgrade was not available. Applying the same ranges of CYs in Table 9, the following table presents the number of missing observations and missing rate in distinct ranges of CYs.

Range of CY	Missing Obs.	Missing Rate
2005 ≤ CY ≤ 2011	4,859,186	1.45%
2008 ≤ CY ≤ 2011	4,316,778	1.65%
CY ≤ MY + 3	3,268,461	1.53%

The missing observations were deleted before making any statistical analysis. Since the missing rate in each range of CYs was around 1.5 percent, the deletion would not seriously affect the statistical inference.

Based on NHTSA's certification list of the rear impact upgrade in MY 2006 to 2008, the registered vehicles were separated into the certified and uncertified groups. It was assumed that no make/model certified to the rear impact upgrade in MY 2005 or earlier, and all make/models certified to the rear impact upgrade in MY 2009 and later. Applying the same ranges of MYs and CYs in Table 9, the following table presents the statistical outputs of the rear impact upgrade versus rear impact fires in distinct ranges of CYs.

Table 10: Rear Impact Upgrade Versus Rear Impact Fires in Polk

CY 2005-2011 and MY 2004-2010			
	Fires	Registration Years	Fires/Billion Registration Years
Uncertified	58	232,520,000	249.4409
Certified	12	97,959,549	122.4995
Fire-Reducing Effectiveness	50.89%		
z test	$z = 2.2899$		***p*-value = 0.0110**
CY 2008-2011 and MY 2004-2010			
Uncertified	40	161,660,000	247.4329
Certified	10	95,545,098	104.6626
Fire-Reducing Effectiveness	57.70%		
z test	$z = 2.5093$		***p*-value = 0.0060**
CY ≤ MY + 3 and MY 2004-2010			
Uncertified	33	125,140,000	263.7047
Certified	10	85,854,396	116.4763
Fire-Reducing Effectiveness	55.83%		
z test	$z = 2.3272$		***p*-value = 0.0100**

Table 10 shows that the rate of rear impact fires in the uncertified group was more than two times of the corresponding rate in the certified group in each range of CYs. The essentially different rates strongly suggest that the rear impact upgrade took effect on rear impact fires. The average of the estimated fire-reducing effectiveness in Table 10 approximates to 55 percent. Thus, if an upgrade-uncertified registered vehicle passes the upgraded rear impact test, the likelihood of experiencing a rear impact fire would be reduced by nearly 55 percent.

Applying the hypothesis statement in Equation 4 and the *z* test of two-sample proportions in Equation 5, the bold-faced *p*-values in Table 10 show that there is sufficient evidence to reject H_0. Therefore, the rate of rear impact fires in the uncertified group was statistically concluded to be significantly higher than the corresponding rate in the certified group. The conclusion suggests that the rear impact upgrade affected rear impact fires.

Since NHTSA did not have a complete list of compliant vehicles in MY 2005 or earlier, it is not possible to obtain an unbiased estimate of the fire-reducing effectiveness for previously non-compliant vehicles. Nevertheless, a range of the estimated fire-reducing effectiveness can be constructed. The average values of the estimated fire-reducing effectiveness in Table 9 and Table 10 were respectively considered as the upper and lower bounds. As a result, the range of the estimated fire-reducing effectiveness of the rear impact upgrade based on Polk is from 55 to 65 percent, which is consistent with NHTSA's prediction in 2003, i.e., 50 to 75 percent.

The ranges of the estimated fire-reducing effectiveness in Polk (55% to 65%) and FARS (50% to 60%) are partially overlapping. However, it is noticeable that the upper and lower bounds in Polk are roughly 5 percentage points higher than the corresponding bounds in FARS. The estimates of the fire-reducing effectiveness in FARS were based on two binary variables, such as certified/uncertified versus fires/no fires. However, the corresponding estimates in Polk were based on the exposure data, i.e., registrations of vehicles. In statistics, exposure data may contain unsuspected confounding factors that possibly affect the estimation. In this evaluation, potentially fire-related confounding factors in Polk seemed to raise the estimated fire-reducing effectiveness. Therefore, the statistical inference in FARS was adopted, because it was less likely to be affected by unpredictably fire-related confounding factors. As a conclusion, the range of the estimated fire-reducing effectiveness of the FMVSS No. 301 rear impact upgrade is from 50 to 60 percent.

5: Benefit Analysis in Rear Impact Fires

The prevention of rear impact fires would not necessarily save lives in every fatal crash in rear impacts, because not every fatality was definitely caused by burns. Some occupants may have received ultimately fatal injuries from impact trauma before the post-crash fire started. Others might conceivably have died from a combination of burns and impact trauma, either of which, by itself, might have been non-fatal.

NASS-CDS was applied in the benefit analysis, since it is the only available data base recording the occupants' injuries. NASS-CDS documents the occupants' injuries based on the data from the hospitals, treatment facilities, and autopsies. The injury severity has always been assessed with the Abbreviated Injury Scale, which rates injuries from 1 (minor) to 6 (maximum). Several versions of the AIS have been applied over the years. NASS-CDS was based on the 1985 revision of the AIS from 1988 to 1992, the 1990/1998 revisions from 1993 to 2009, and the 2005/2008 revision after 2009. These three versions of the AIS use a scale from 1 to 6 and have the same names for each level, but some specific types of injuries may have changed levels. The divergence among the distinct AIS versions was not considered in this evaluation.

The percentage of fatalities attributable to burns and the life-saving effectiveness will be first estimated in the following sections. Second, applying the life-saving effectiveness to the adjusted baseline fatalities, the benefit in absolute number of lives saved per year will be assessed in the subsequent section.

5.1: Percentage of Fatalities Attributable to Burns

An occupant often experienced more than one injury in a real-world crash. In the case of a fatality, it is not always certain whether one specific or a combination of injuries would have caused the fatality. Thus, it is necessary to review cases of fatalities involving rear impact fires to estimate the percentage of the fatalities that may be entirely attributed to burns as opposed to impact trauma.

Applying NASS-CDS in 1991 to 2011, there were 59 cases of fatally injured occupants involving major or minor rear impact fires, and their associated injuries were known and reported to NASS-CDS. Although NASS-CDS is the only accessible data base with the occupants' injuries and associated AIS, the exact cause of a fatality is frequently unknown. Therefore, to estimate the percentage of fatalities attributable to burns, we assumed that multiple injuries with the same AIS were equally likely to cause a fatality. The percentage of fatalities attributable to burns was assessed by the following fault tree. The following fault tree did not comprise all the theoretically possible combinations of injuries, but it did include all the combinations that actually occurred in the 59 NASS-CDS cases of fatally injured occupants.

Fault Tree: Percentage of Fatalities Attributable to Burns

- If burns were the only reported injury, then the prevention of rear impact fires would have saved the occupant's life. The probability of fatalities attributable to burns was presumed to be 100 percent.

- If the occupant did not experience any burns in a rear impact fire, then the prevention of rear impact fires would not have saved the occupant's life. The probability of fatalities attributable to burns was presumed to be 0 percent.

- If the AIS of burns was lower than the maximum AIS of the other injuries (impact trauma), then the prevention of rear impact fires would not have potentially saved the occupant's life. The probability of fatalities attributable to burns was presumed to be 0 percent.

- If the AIS of burns was 6, which was higher than the maximum AIS of the other injuries (impact trauma), and

  - If the maximum AIS of the other injuries (impact trauma) was less than 5, then the probability of fatalities attributable to burns was presumed to be 100 percent.

  - If there was a single impact trauma injury with AIS 5, then the probability of fatalities attributable to burns was presumed to be 50 percent.

  - If there were two impact trauma injuries with AIS 5, then the probability of fatalities attributable to burns was presumed to be 25 percent.

- If the AIS of burns was 5, and

- If the maximum AIS of the other injuries (impact trauma) was less than 5, then the probability of fatalities attributable to burns was presumed to be 100 percent.

- If there was single impact trauma injury with AIS 5, then the probability of fatalities attributable to burns was presumed to be 50 percent.

- If there were two impact trauma injuries with AIS 5, then the probability of fatalities attributable to burns was presumed to be 25 percent.

Based on the fault tree, each of the 59 NASS-CDS cases of fatally injured occupants was categorized according to the probability of fatalities attributable to burns. The corresponding distribution is presented in the following table:

Table 11: Distribution of Fatalities Attributable to Burns

Percentage of Fatalities Attributable to Burns	No. of Cases
100%	38
50%	4
25%	2
0%	15
Total	59

Weighing each case of fatally injured occupant in Table 11 by the corresponding Ratio Inflation Factor in NASS-CDS, the estimated percentage of fatalities attributable to burns is 62.23 percent with 7.46 percent standard error.

5.2: Life-Saving Effectiveness

The life-saving effectiveness indicates the reduction in the likelihood of experiencing fatal burns in a rear impact fire, if an upgrade-uncertified vehicle passes the upgraded rear impact test. The life-saving effectiveness is defined as the product of two parameters, the fire-reducing effectiveness and percentage of fatalities attributable to burns. In statistics, estimating the variance of the product of two parameters is complicated. Therefore, a simpler estimating procedure of the life-saving effectiveness is preferred. To determine whether it is appropriate to simplify the estimating procedure, it is necessary to compare the dispersion of the estimated fire-reducing effectiveness and percentage of fatalities attributable to burns.

Adopting the statistical inference in Table 8 and Section 5.1, the table on the next page summarizes the estimates and standard errors of the fire-reducing effectiveness and percentage of fatalities attributable to burns. Since these two parameters were estimated in the same measure unit, i.e., percentage points, the standard errors of the estimates can be directly compared. In addition, the ratio of the standard error and estimate is also provided for the dispersion comparison.

Table 12: Summary of Estimated Parameters

	Estimate	Standard Error	Ratio
Fire-Reducing Effectiveness			
CY 2003-2011 and MY 2004-2011	46.43%	19.53%	42.06%
CY 2008-2011 and MY 2004-2011	56.55%	19.87%	35.13%
CY ≤ MY + 3 and MY 2004-2011	47.30%	21.94%	46.38%
Percentage of Fatalities Attributable to Burns	62.23%	7.46%	11.99%

The standard error of the estimated fire-reducing effectiveness in each range of CYs is comparatively high. The ratio of the standard error and estimate in the percentage of fatalities attributable to burns is close to 12 percent; however, the corresponding ratio in the fire-reducing effectiveness is greater than 35 percent in each range of CYs. Table 12 suggests that most of the variation of the estimated life-saving effectiveness would be from the estimated fire-reducing effectiveness. For the purpose of convenience, it is reasonable to consider the estimated percentage of fatalities attributable to burns as constant.

Shortening the range of CYs is the best way to remove potentially fire-related confounding factors, such as changes of economic climates or adjustments in gasoline prices. Thus, the estimated fire-reducing effectiveness ranging from CY 2008 to 2011 was considered to be the most accurate, and it was adopted to estimate the life-saving effectiveness. Applying two times standard error to construct the confidence interval, the following table presents the estimation of the life-saving effectiveness.

Table 13: Estimation of Life-Saving Effectiveness

	Estimate	Confidence Interval
Fire-Reducing Effectiveness	56.55%	(16.82%, 77.31%)
Percentage of Fatalities Attributable to Burns	62.23%	-
Life-Saving Effectiveness	35.19%	(10.43%, 47.96%)

Table 13 shows that the likelihood of experiencing fatal burns in a rear impact fire would be reduced by 35.19 percent, if an upgrade-uncertified vehicle passes the upgraded rear impact test. Since the confidence interval of the life-saving effectiveness in Table 13 does not include 0, we statistically conclude that the rear impact upgrade significantly reduced the likelihood of suffering fatal burns in rear impact fires.

5.3: Benefit: Lives Potentially Savable in Rear Impacts

The benefit of the FMVSS No. 301 rear impact upgrade will be presented in the absolute number of lives saved per year. The number of lives saved is defined as the product of the life-saving effectiveness and adjusted baseline fatalities. The number of the adjusted baseline fatalities is the amount of fatalities that would have occurred, if no vehicles had certified to the rear impact upgrade. Because of NHTSA's three-year phase-in schedule in the rear impact upgrade, the estimate of the adjusted baseline fatalities depends on the chosen base years. Two equally ranged intervals of CYs, 2001 to 2005 and 2007 to 2011, were applied as the base years.

Assuming no make/model certified to the rear impact upgrade in MY 2005 or earlier, the adjusted baseline fatalities would equal the actual fatalities involving rear impact fires when CY is in 2001 to 2005. However, some of the fatalities caused by rear impact fires happened in make/models that certified to the rear impact upgrade in MY 2006 and later. To estimate the adjusted baseline fatalities when CY is in 2007 to 2011, the life-saving effectiveness of the rear impact upgrade needs to be removed.

Denoting

F_1 = fatalities caused by rear impact fires in uncertified make/models, and

F_2 = fatalities caused by rear impact fires in certified make/models,

the number of the adjusted baseline fatalities was estimated by the following formula:

$$Adjusted\ Baseline\ Fatalities = F_1 + \frac{F_2}{(1 - Life\ Saving\ Effectiveness)}.$$

Applying the statistical inference of the life-saving effectiveness in Table 13, the following table shows the estimated benefit of the rear impact upgrade in two distinct intervals of base years.

Table 14: Statistical Inference of Benefit

	CY 2001-2005	CY 2007-2011
F_1: Fatalities in Rear Impact Fires (Uncertified)	530	295
F_2: Fatalities in Rear Impact Fires (Certified)	0	18
Fatalities in Rear Impact Fires	530	313
Adjusted Baseline Fatalities	530	323
Adjusted Baseline Fatalities/Year	106	65
Estimation of Benefit	37	23
Interval Estimation of Benefit	(11, 51)	(7, 31)

Even after the adjustment, the number of the adjusted baseline fatalities in Table 14 is comparatively small when the CY is in 2007 to 2011. The substantial difference between the adjusted baseline fatalities in two distinct ranges of base years might be potentially caused by the nationwide reduction in the travel frequencies in 2008 and the effect of other safety equipment. The estimated benefit in CY 2007 to 2011 was considered as a better indication of the future trends, since the estimation that based on the recent base years would represent the current actualities of transportation more precisely. Based on the evaluation, there were 313 cases of fatally injured occupants caused by rear impact fires in CY 2007 to 2011. Adjusting the baseline fatalities to account for no vehicles certifying to the rear impact upgrade, it is estimated that there would have been 65 fatalities per year in rear impact fires. Applying the estimated life-saving effectiveness in Table 13 (35.19%), the estimated lives saved per year in rear impacts is 23 (65*0.3519), if all vehicles in the fleet met the rear impact upgrade. As a conclusion, the estimated benefit of the rear impact upgrade is 23 lives per year, and the corresponding interval estimation is from 7 to 31 (65*0.1043 to 65*0.4796) lives.

ESC was suspected to be an important fire-related confounding factor in engineering. To test whether ESC significantly took effect on rear impact fires, two logistic regression models were created based on FARS. One model contained two independent variables, the rear impact upgrade and ESC, and the other model considered the rear impact upgrade as the only independent variable. The dependent variable was the log odds ratio of a post-crash fire in a rear impact. Section 9.2 provides the corresponding statistical outputs. Table 28 suggests that it is not appropriate to consider ESC in the model, since the *p*-value of ESC (0.3064) is substantially greater than 0.05, the level of significance (*p*-value must be less than 0.05 for statistical significance). Table 29 provides the associated fire-reducing effectiveness of the rear impact upgrade in each logistic regression model, and there is no significant difference between two effectiveness values, i.e., 38.30% versus 42.50%.

Furthermore, ESC reduces the likelihood of

1. A first-event rollover on a single-vehicle,
2. A run-off-road crash on a single-vehicle, and
3. Culpable involvements in collisions with other vehicles.

However, the FMVSS No. 301 rear impact upgrade is proposed to prevent fires after being struck in the rear by another vehicle, i.e., a type of crash involvement that usually is not in any of the above three categories, where ESC is effective. The purposes of these two safety equipment are basically distinct.

As a result, ESC is not a statistically significant variable in rear impact fires, and the estimated fire-reducing effectiveness of the rear impact upgrade is not affected by ESC. Therefore, the statistical inference of the FMVSS No. 301 rear impact upgrade in Section 4 and 5 is accurate.

6: Fires in Side Impacts

The MDB test condition of FMVSS No. 214, Side impact Protection, was applied to the FMVSS No. 301 side impact upgrade, since FMVSS No. 214 exposes the subject vehicles to a higher level of crash forces, impact velocity, and absorbed crush energy than the prior FMVSS No. 301 side impact test. Most manufacturers responded that the test condition of the FMVSS No. 301 side impact upgrade was more stringent and more representative of real-world crashes than the prior side impact test.

Subject vehicles in MY 1997 to 2000 were hit at 61.6 km/h (38.5 mph) in the NCAP MDB side impact test, and three out of 103 vehicles (2.9%) exceeded the fuel-leakage criterion of the FMVSS No. 301 side impact upgrade. In addition, NHTSA conducted the MDB compliance test of FMVSS No. 214, and one out of more than 100 vehicles exceeded the fuel-leakage standard of the FMVSS No. 301 side impact upgrade. Because of the low failure rates in the NCAP MDB side impact test and MDB compliance test of FMVSS No. 214, NHTSA predicted that upgrading the prior FMVSS No. 301 side impact test to FMVSS No. 214 may slightly reduce the rate of post-crash fires in side impacts and provide minor benefits in injuries and fatalities.

NHTSA required that all make/models in MY 2005 and later must certify to the FMVSS No. 301 side impact upgrade, and there was no phase-in schedule. Applying FARS in CY 1995 to 2011 and restricting MY in 1995 to 2011, the following frequency table is used to detect whether the side impact upgrade took effect on side impact fires.

Table 15: Frequency Table of Model Year Versus Side Impact Fires in FARS

MY	No Fires	Fires	Rate of Fires
1995	10,651	220	2.02%
1996	8,680	189	2.13%
1997	8,884	184	2.03%
1998	8,028	172	2.10%
1999	8,170	165	1.98%
2000	7,586	145	1.88%
2001	6,471	146	2.21%
2002	5,768	122	2.07%
2003	4,819	100	2.03%
2004	3,975	86	2.12%
2005	3,191	72	2.21%
2006	2,430	51	2.06%
2007	1,685	41	2.38%
2008	1,065	29	2.65%
2009	426	3	0.70%
2010	273	7	2.50%
2011	126	2	1.56%

Table 15 shows no specific pattern in the rate of fires in MY 1995 to 2011, but the corresponding rate in MY 2009 substantially decreased. Further statistical analysis is needed to test whether there was a statistically significant association between MY and side impact fires.

Based on NHTSA's schedule of the FMVSS No. 301 side impact upgrade, it is reasonable to separate vehicles into the MY < 2004 and MY ≥ 2005 groups for initially testing the effect of the side impact upgrade. Applying the same range of MYs in Table 15, the following table presents the statistical outputs of the group of MY versus side impact fires.

Table 16: Model Year Versus Side Impact Fires in FARS

MY 1995-2011			
	No Fires	Fires	Rate of Fires
MY < 2004	76,223	1,601	2.06%
MY ≥ 2005	6,005	133	2.17%
Odds Ratio	105.45%		
Fire-Reducing Effectiveness	-5.45%		
Pearson's Chi-Squared Test	x^2 = 0.3380		***p*-value = 0.5610**
Fisher's Exact Test	-		***p*-value = 0.5446**

Table 16 shows that the rate of fires in the MY < 2004 group was close to the corresponding rate in the MY ≥ 2005 group. Since the odds ratio in Table 16 is approximately 100 percent, there should be no association between the group of MY and side impact fires. The estimated fire-reducing effectiveness is negative in Table 16, and the negative estimate suggests that a reduction in the probability of experiencing a side impact fire would be unlikely, even if a side hit vehicle in the MY < 2004 group switches to the MY ≥ 2005 group.

Since each cell contains more than 5 frequencies in Table 16, the statistical inference based on the Pearson's chi-squared test and Fisher's exact test is reliable. The bold-faced *p*-values indicate that there is not sufficient evidence to reject H_0 in Equation 3. We concluded that there was not a statistically significant association between the group of MY and side impact fires.

The low failure rates in the NCAP MDB side impact test and MDB compliance tests of FMVSS No. 214 suggests that a large proportion of vehicles may have already complied with the side impact upgrade before NHTSA requested the upgrade certification. Compliant vehicles in MY 2004 or earlier may provide little or no contribution to the estimated fire-reducing effectiveness. However, NHTSA did not have a comprehensive list of compliant vehicles in MY 2004 or earlier, so an unbiased estimate of the fire-reducing effectiveness for previously non-compliant vehicles cannot be obtained. In theory, the statistical inference in Table 16 merely indicates that there was no statistically significant association between the group of MY and side impact fires. Nevertheless, because of the extremely low failure rates in the NCAP MDB side impact test and MDB compliance test of FMVSS No. 214, it is appropriate to conclude that the side impact upgrade did not affect the rate of side impact fires.

7: Affiliated Effect of Rear Impact Upgrade

The FMVSS No. 301 upgrade amended the test conditions in rear and side impacts, whereas there was no change in testing other configurations, such as frontal impacts and rollovers. Section 4 shows that the estimated fire-reducing effectiveness of the FMVSS No. 301 rear impact upgrade is from 50 to 60 percent. However, in Section 6, the effect of the FMVSS No. 301 side impact upgrade was concluded not to be significant.

Because the estimated fire-reducing effectiveness of the rear impact upgrade is substantively high, it is reasonable to question whether the rear impact upgrade would have potentially prevented post-crash fires in other crash modes, i.e., if the vehicle modifications undertaken to comply with the rear impact upgrade had any ancillary or serendipitous benefits in other types of crash events. Considering all crash events except rear impacts, the affiliated effect of the rear impact upgrade in all other crash modes will be initially assessed in the following section. In addition, the affiliated effect of the rear impact upgrade in frontal impacts and first-event rollovers will be evaluated individually in the subsequent sections. However, even if there were a statistically significant reduction in the rate of fires in any other crash mode, it would not necessarily be sufficient evidence to conclude a cause-and-effect relationship between the affiliated effect of the rear impact upgrade and post-crash fires in any other crash mode.

7.1: Fires in All Crash Events Excluding Rear Impacts

Using FARS and applying the same ranges of MYs and CYs in Table 7, the table on the next page presents the distribution of crash events in distinct crash modes.

Table 17: Distribution of Crash Events in FARS

CY 2003-2011 and MY 2004-2011		
	Crash Events	Percentage
Frontal	37,461	59.84%
Side	11,358	18.14%
Rear	5,177	8.27%
First-Event Rollover	4,382	7.00%
Subsequent Rollover	3,937	6.29%
Others and Unknown	291	0.46%
CY 2008-2011 and MY 2004-2011		
Frontal	24,899	60.44%
Side	7,519	18.25%
Rear	3,315	8.05%
First-Event Rollover	2,724	6.61%
Subsequent Rollover	2,435	5.91%
Others and Unknown	304	0.74%
CY ≤ MY + 3 and MY 2004-2011		
Frontal	26,601	60.43%
Side	7,883	17.91%
Rear	3,766	8.56%
First-Event Rollover	2,908	6.61%
Subsequent Rollover	2,752	6.25%
Others and Unknown	110	0.24%

Table 17 shows that around 8.3 percent of crash events were caused by rear impacts in each range of CYs. Since crash events in rear impacts were relatively infrequent, the affiliated effect of the rear impact upgrade may not be applicable to all other crash modes. Before making any further statistical analysis, the rear impact crashes were removed from the data.

Section 4.1 presents a statistically significant association between the group of MY and rear impact fires when separating rear hit vehicles by MY 2007. Therefore, to assess the affiliated effect of the rear impact upgrade in all other crash modes, it is reasonable to separate hit vehicles (excluding rear impacts) into the MY ≤ 2007 and MY > 2007 groups. Using FARS and applying the same ranges of MYs and CYs in Table 7, the table on the next page shows the statistical outputs of the group of MY versus post-crash fires in all other crash modes in distinct ranges of CYs.

Table 18: Model Year Versus Fires in All Other Crash Modes in FARS

CY 2003-2011 and MY 2004-2011			
	No Fires	Fires	Rate of Fires
MY ≤ 2007	40,304	1,086	2.62%
MY > 2007	15,621	418	2.61%
Odds Ratio	99.31%		
Fire-Reducing Effectiveness	0.69%		
Pearson's Chi-Squared Test	x^2 = 0.0060		***p*-value = 0.9383**
Fisher's Exact Test	-		***p*-value = 0.9535**
CY 2008-2011 and MY 2004-2011			
MY ≤ 2007	22,995	640	2.71%
MY > 2007	13,873	373	2.62%
Odds Ratio	96.60%		
Fire-Reducing Effectiveness	3.40%		
Pearson's Chi-Squared Test	x^2 = 0.0918		***p*-value = 0.7619**
Fisher's Exact Test	-		***p*-value = 0.7926**
CY ≤ MY + 3 and MY 2004-2011			
MY ≤ 2007	25,886	683	2.57%
MY > 2007	13,835	373	2.63%
Odds Ratio	102.58%		
Fire-Reducing Effectiveness	-2.58%		
Pearson's Chi-Squared Test	x^2 = 0.1095		***p*-value = 0.7408**
Fisher's Exact Test	-		***p*-value = 0.7436**

Table 18 shows that the rate of fires in the MY ≤ 2007 group was close to the corresponding rate in the MY > 2007 group in each range of CYs. Since the average of the odds ratios in Table 18 is approximately 100 percent, there should be no association between the group of MY and fires in all other crash modes. The estimated fire-reducing effectiveness is close to 0 percent in each range of CYs, so even if a hit vehicle (excluding rear impacts) in the MY ≤ 2007 group switches to the MY > 2007 group, there would not be any reduction in the likelihood of experiencing a fire in all other impacts. The low estimated fire-reducing effectiveness additionally suggests the lack of association between the group of MY and fires in all other crash modes.

Since each cell contains more than 5 frequencies in Table 18, the statistical inference from the Pearson's chi-squared test and Fisher's exact test is precise. The bold-faced *p*-values show that there is not sufficient evidence to reject H_0 in Equation 3. Thus, we concluded that there was not a statistically significant association between the group of MY and fires in all other crash modes.

The lack of statistically significant association between the group of MY and fires in all other crash modes is the only theoretical conclusion in Table 18. Since Table 17 shows a low percentage of crash events in rear impacts, it is reasonable to infer that the rear impact upgrade provided no substantially affiliated effect on preventing fires in all other crash modes. Therefore, it is not appropriate to apply the statistical inference of the rear impact upgrade to all other crash modes. Nevertheless, the affiliated effect of the rear impact upgrade may individually be applicable to another crash mode. Two other crash modes, frontal impacts and first-event rollovers, will be separately analyzed in the following sections.

7.2: Fires in Frontal Impacts

The FMVSS No. 301 frontal impact test is to strike a subject vehicle at 48 km/h (30 mph) with a fixed collision barrier, and there is no amendment to the FMVSS No. 301 frontal impact test. The NCAP frontal impact test increased the impact speed up to 56 km/h (35 mph), and 10 out of 406 vehicles (2.46%) have exceeded the fuel-leakage criteria of the FMVSS No. 301 frontal impact test since 1979. Restricting the subject vehicles of the NCAP frontal impact test in MY 1995 to 2000, four out of 232 vehicles (1.7%) did not meet the fuel-leakage standard of the FMVSS No. 301 frontal impact test.

Since the affiliated effect of the rear impact upgrade might have potentially prevented post-crash fires in frontal impacts, vehicles in recent MYs were presumed to have comparatively lower rates of frontal impact fires. Applying the same range of MYs in Table 15, the following frequency table of MY versus frontal impact fires is used to detect whether there was a long-term decreasing tendency in the rate of frontal impact fires.

Table 19: Frequency Table of Model Year Versus Frontal Impact Fires in FARS

MY	No Fires	Fires	Rate of Fires
1995	28,303	805	2.77%
1996	22,717	653	2.79%
1997	24,089	692	2.79%
1998	21,700	610	2.73%
1999	22,690	666	2.85%
2000	21,402	630	2.86%
2001	18,337	552	2.92%
2002	16,268	471	2.81%
2003	14,117	395	2.72%
2004	12,207	333	2.66%
2005	10,202	301	2.87%
2006	8,038	234	2.83%
2007	6,200	148	2.33%
2008	4,056	96	2.31%
2009	1,761	59	3.24%
2010	1,235	35	2.76%
2011	644	19	2.87%

Neither a specific pattern nor a substantial variation appears in the rate of fires in Table 19; however, the corresponding rate in MY 2009 is relatively higher. To assess whether there was a reduction in the rate of frontal impact fires potentially contributed by the affiliated effect of the rear impact upgrade, further statistical analysis is needed.

NHTSA's phase-in schedule of the rear impact upgrade began in 2007, and Table 7 shows that separating the rear hit vehicles into the MY > 2007 and MY ≤ 2007 groups presents the statistically significant effect of the group of MY. To evaluate the potentially affiliated effect of the rear impact upgrade, it is reasonable to cluster the frontal hit vehicles in Table 19 into the

MY > 2007 and MY ≤ 2007 groups. Using FARS and applying the same range of MYs in Table 15, the following table shows the statistical outputs of the group of MY versus frontal impact fires.

Table 20: Model Year Versus Frontal Impact Fires in FARS

MY 1995-2011			
	No Fires	Fires	Rate of Fires
MY ≤ 2007	226,333	6,492	2.79%
MY > 2007	7,701	209	2.64%
Odds Ratio	94.62%		
Fire-Reducing Effectiveness	5.38%		
Pearson's Chi-Squared Test	x^2 = 0.6037		***p*-value = 0.4372**
Fisher's Exact Test	-		***p*-value = 0.4654**

Table 20 shows that the rate of fires in the MY ≤ 2007 group was close to the corresponding rate in the MY > 2007 group. Since the odds ratio in Table 20 is approximately 95 percent, there should be no association between the group of MY and frontal impact fires. The estimated fire-reducing effectiveness is around 5 percent. Therefore, if a frontal hit vehicle in the MY ≤ 2007 group shifts to the MY > 2007 group, there would be merely 5 percent reduction in the likelihood of suffering a frontal impact fire. The low estimated fire-reducing effectiveness further suggests that the group of MY and frontal impact fires should not be related.

Since each cell has more than 5 frequencies in Table 20, the statistical inference from the Pearson's chi-squared test and Fisher's exact test is precise. The bold-faced *p*-values indicate that there is not sufficient evidence to reject H_0 in Equation 3. Thus, we concluded that there was not a statistically significant association between the group of MY and frontal impact fires. As a result, there was no potentially fire-related confounding factor reducing the rate of frontal impact fires. In addition, it is reasonable to further infer that there was no affiliated effect of the rear impact upgrade on frontal impact fires.

7.3: Fires in First-Event Rollovers

Rollovers are complicated crash events, and only first-event rollovers were considered in this evaluation. A first-event rollover is defined as a rollover occurring as the first harmful event or as the most harmful event when the first harmful event is basically a tripping mechanism, such as contacting a curb or a ditch.

There is no amendment to the FMVSS No. 301 first-event-rollover test. However, because of potentially fire-related confounding factors, such as the affiliated effect of the rear impact upgrade, vehicles in more recent MYs were presumed to have lower rates of first-event-rollover fires.

Applying the same ranges of MYs in Table 15, the frequency table of MY versus first-event-rollover fires on the next page is used to detect whether there was a long-term tendency in the rate of first-event-rollover fires.

Table 21: Frequency Table of Model Year Versus First-Event-Rollover Fires in FARS

MY	No Fires	Fires	Rate of Fires
1995	4,273	69	1.59%
1996	3,595	51	1.40%
1997	3,914	65	1.63%
1998	3,731	79	2.07%
1999	3,865	67	1.70%
2000	3,545	75	2.07%
2001	2,979	65	2.14%
2002	2,709	47	1.71%
2003	2,185	44	1.97%
2004	1,779	34	1.88%
2005	1,289	19	1.45%
2006	918	11	1.18%
2007	548	5	0.90%
2008	342	5	1.44%
2009	107	2	1.83%
2010	55	0	0%
2011	16	0	0%

Table 21 shows the possible difference in the rate of first-event-rollover fires, since there were a few variations in the rate of fires in MY 2006 and later, and the rate of fires in MY 2006 and some, but not all of the later MY seemed to be relatively lower than the corresponding rate in MY 2005 and earlier. To assess whether the affiliated effect of the rear impact upgrade had potentially affected the post-crash fires in first-event rollovers, further statistical analysis is necessary.

NHTSA's phase-in schedule of the rear impact upgrade started in 2007, and the group of MY is statistically significant when separating the rear hit vehicles into the MY > 2007 and MY ≤ 2007 groups. To assess the potentially affiliated effect of the rear impact upgrade, it is reasonable to separate the vehicles in Table 21 into the MY > 2007 and MY ≤ 2007 groups. Using FARS and applying the same range of MYs in Table 15, the following table shows the statistical outputs of the group of MY versus first-event-rollover fires.

Table 22: Model Year Versus First-Event-Rollover Fires in FARS

MY 1995-2011			
	No Fires	Fires	Rate of Fires
MY ≤ 2007	35,332	631	1.75%
MY > 2007	520	7	1.33%
Odds Ratio	75.38%		
Fire-Reducing Effectiveness	24.62%		
Pearson's Chi-Squared Test	x^2 = 0.5495		***p*-value = 0.4585**
Fisher's Exact Test	-		***p*-value = 0.6136**

Table 22 shows that the rate of fires in the MY > 2007 group was close to the corresponding rate in the MY ≤ 2007 group. Since the odds ratio approximates to 75 percent, the group of MY and first-event-rollover fires might not be related. The estimated fire-reducing effectiveness approximates to 25 percent in Table 22. The likelihood of experiencing a first-event-rollover fire would only be reduced by around 25 percent, if a first-event-rollover vehicle in the MY ≤ 2007 group switches to the MY > 2007 group. The low estimated fire-reducing effectiveness additionally implies that the group of MY and first-event-rollover fires would not be related.

Since each cell contains more than 5 frequencies in Table 22, the statistical inference from the Pearson's chi-squared test and Fisher's exact test is reliable. The bold-faced *p*-values indicate that there is not sufficient evidence to reject H_0 in Equation 3. As a result, there was not a statistically significant association between the group of MY and first-even-rollover fires.

ESC is especially effective in preventing rollovers. Therefore, ESC was suspected to be an important fire-related confounding factor in engineering. Two logistic regression models were made based on FARS to test whether ESC significantly affected first-event-rollover fires. One model considered the rear impact upgrade and ESC as the independent variables, whereas the other model used only the rear impact upgrade as the independent variable. The dependent variable was the log odds ratio of a post-crash fire in a first-event rollover. Section 9.3 shows the corresponding statistical outputs. Table 30 suggests that both the rear impact upgrade and ESC were not statistically significant factors in first-event-rollover fires, since the *p*-values of the rear impact upgrade (0.7438) and ESC (0.8149) are substantially greater than 0.05, the level of significance (*p*-value must be less than 0.05 for statistical significance). Furthermore, using the rear impact upgrade as the only independent variable, Table 30 statistically confirms that the affiliated effect of the rear impact upgrade did not significantly affect first-event-rollover fires, since the corresponding *p*-value (0.7662) is sufficiently large. Table 31 provides the associated fire-reducing effectiveness of the rear impact upgrade in each logistic regression model, and there is not a significant difference between two fire-reducing effectiveness values, i.e., 11.60% versus 10.50%. The small difference implies that ESC did not significantly prevent first-event-rollover fires. Furthermore, ESC originally intends to reduce the likelihood of rollovers, but not necessarily to decrease the probability of experiencing post-crash fires, given that a rollover has occurred.

As a result, ESC is not a statistically significant factor in first-event-rollover fires. The logistic regression models in Section 9.3 also confirm that the affiliated effect of the rear impact upgrade did not significantly affect the first-event-rollover fires.

8: Discussion

The survey sampling in Section 1.3 shows that the estimated proportion of compliant vehicles in MY 2005 or earlier approximates to 40 percent. Although compliant vehicles did not always certify to the rear impact upgrade in MY 2006 or later, a proportion of compliant vehicles could have already been able to certify to the rear impact upgrade before NHTSA made the upgraded requirement. As a result, the fire-reducing effectiveness of the rear impact upgrade would be underestimated in Section 4. NHTSA did not have a comprehensive list of the compliant vehicles in MY 2005 or earlier to improve the statistical inference in this evaluation.

The estimated benefit of the rear impact upgrade is comparatively low when the interval of the base years was ranged in CY 2007 to 2011. However, if the travel frequencies return to pre-2008 levels, the benefit of the rear impact upgrade would increase.

Based on FARS, approximate 60 percent of crash events in MY 2004 to 2011 were caused by frontal impacts, and more than 60 percent of post-crash fires in MY 2004 to 2011 occurred after involving frontal impacts. The rate of frontal impact fires, i.e., around 2.8 percent, has been homogeneous since MY 1995.

Based on vehicle types, i.e., passenger cars and LTVs, the statistical inference of the group of MY versus post-crash fires is respectively provided in Appendix. Because of the insufficient number of frequencies, the corresponding statistical outputs are not presented in this evaluation.

9: Appendix

9.1: Survey Sampling

The survey sampling was to estimate the proportion of vehicles weighing less than 1,588 kg (3,500 lbs) that could have already complied with the FMVSS No. 301 rear impact upgrade in MY 2005 or earlier. Therefore, the target population was the vehicles with curb weight under 1,588 kg (3,500 lbs) in MY 2005 or earlier. Applying Polk, the sales of make/models in MY 1996 to 2000 were used as the auxiliary variable. The following table shows the selected sampling units and the corresponding compliance test results of the rear impact upgrade in two distinct test years.

Table 23: Compliance Test of Rear Impact Upgrade

Test Year 1999			
Make/model	MY	Curb Weight (lbs)	Test Result
Chevrolet Metro	1998	1,898	Pass
Mazda Miata	1999	2,403	Pass
Geo Prizm	1996	2,623	Fail
Nissan Sentra	1998	2,663	Pass
Honda Civic	1998	2,685	Pass
Dodge Neon	1996	2,698	Fail
Suzuki Sidekick	1996	2,720	Fail
Ford Escort	1998	2,753	Fail
Volkswagen Jetta	1998	2,850	Fail
Chevrolet Cavalier	1998	2,936	Fail
Ford Mustang	1996	3,289	Pass
Chevy Blazer	1996	3,902	Pass
Plymouth Voyager	1996	3,990	Pass
Test Year 1999			
Volkswagen New Beetle	1998	2,877	Fail
Hyundai Elantra	2000	2,683	Fail
Saturn SL1	1996	2,382	Fail
Buick Century 4-Dr. Sedan	1997	3,368	Pass
Buick LeSabre	1999	3,443	Fail
Ford Contour	2000	2,778	Fail
Mazda Protégé	1996	2,468	Fail
Honda Accord	1997	3,089	Fail
Ford F-150 4x2 2-Dr. Reg Cab	1999	3,963	Pass
Dodge Avenger	1998	3,150	Fail
Toyota Rav4	1997	2,547	Fail
Mazda 626	1997	3,007	Pass
Olds Cutlass Supreme	1997	3,283	Fail
Ford Ranger	1998	3,092	Pass
Nissan Pickup	1997	3,041	Pass
Toyota Camry Solara	2000	3,217	Pass

Although the curb weight of the Buick LeSabre was 3,443 lbs in MY 1999, it was not included in the target population, since the corresponding curb weight in MY 2000 was greater than

3,500 lbs. Similarly, because of the curb weights, the Chevrolet Blazer, Plymouth Voyager, and Ford F-150 4x2 2-door regular cab in Table 24 did not belong to the target population. These over-weighed vehicles were removed before making any statistical analysis. Furthermore, it was assumed that there was not any compliance variation within the same make/model, since there was only one sampling unit in each make/model.

The 11 vehicles weighing less than 1,588 kg (3,500 lbs) in test year 1999 and the Honda Accord in test year 2012 were selected without a probability scheme. Therefore, it was assumed that a census was conducted in these twelve make/models when estimating the proportion of compliant vehicles.

Denoting

$$y_j = \begin{cases} 1, & if\ the\ j^{th}\ make/model\ passed\ the\ compliance\ test \\ 0, & if\ the\ j^{th}\ make/model\ failed\ the\ compliance\ test \end{cases},$$

x_j = total sales of the j^{th} make/model in MY 1996 to 2000,

N = total sales of make/models in test year 1999 and Honda Accord in test year 2012, and

τ = total number of compliant vehicles in test year 1999 and Honda Accord in test year 2012,

the following table shows the compliance test in 1999 and Honda Accord in test year 2012.

Table 24: Compliance Test in 1999 and Honda Accord in 2012

Make/model	x_j	y_j
Chevrolet Metro	236,762	1
Mazda Miata	87,690	1
Geo Prizm	1,330,377	0
Nissan Sentra	562,933	1
Honda Civic	1,506,724	1
Dodge Neon	973,598	0
Suzuki Sidekick	276,948	0
Ford Escort	1,270,091	0
Volkswagen Jetta	488,005	0
Chevy Cavalier	1,734,185	0
Ford Mustang	705,179	1
Honda Accord	1,929,149	0
	$\sum_{j=1}^{12} x_j$ = 11,101,641	

Considering the compliance test in Table 25 as a census, there was not any variance in the estimated proportion. Using the information of the auxiliary variable (sales in MY 1996 to 2000), the estimated proportion of compliance is presented on the next page.

$$P = \frac{\tau}{N} = \frac{\sum_{i=1}^{12} x_i\, y_i}{\sum_{i=1}^{12} x_i} = 27.92\%\ .$$

The estimated proportion of compliance only represents the make/models in Table 25, and it is necessary to estimate the proportion of compliance in the rest of the target population.

The vehicle types and the curb weight were presumed to affect the compliance test in 2012. After removing the make/models in Table 25 from the target population, the remaining make/models were categorized into three strata, namely, sedan under 1,361 kg (3,000 lbs), sedan between 1,361 kg (3,000 lbs) and 1,588 kg (3,500 lbs), and SUV/CUV/pickup truck under 1,588 kg (3,500 lbs). The following table shows the sample size in each stratum.

Vehicle Type	Sedan		SUV/CUV/Pickup Truck
Curb Weight (lbs)	Weight < 3,000	3,000 ≤ Weight ≤ 3,500	Weight < 3,500
Sample Size	5	5	3

In addition, the primary sampling units were selected by applying a systematic sampling scheme with probability proportional to size (sales in MY 1996 to 2000) in each stratum.

Denoting

$$y_{ij} = \begin{cases} 1, & if\ the\ j^{th}\ PSU\ in\ i^{th}\ stratum\ passed\ the\ compliance\ test \\ 0, & if\ the\ j^{th}\ PSU\ in\ i^{th}\ stratum\ failed\ the\ compliance\ test \end{cases},$$

π_{ij} = probability of selecting the j^{th} PSU in i^{th} stratum,

n_i = sample size in i^{th} stratum,

w_{ij} = weight of the j^{th} PSU in i^{th} stratum, such that $w_{ij} = \frac{1}{n_i \pi_{ij}}$,

τ_i = total number of compliant vehicles in i^{th} stratum,

N_i = total sales in i^{th} stratum in MY 1996 to 2000, and

P_i = proportion of compliance in i^{th} stratum,

the table on the next page shows the compliance test in 2012.

Table 25: Compliance Test in 2012

Sedan: Weight < 3,000 lbs	x_j	π_{ij}	w_{ij}	y_{ij}
Saturn SL1	1,149,333	0.1748	1.1444	0
Mazda Protégé	303,046	0.0461	4.3403	0
Hyundai Elantra	281,743	0.0428	4.6684	0
Ford Contour	821,462	0.1449	1.6012	0
Volkswagen New Beetle	193,313	0.0294	6.8040	0
$N_{i \in Sedan\text{: Weight} < 3{,}000}$	6,576,489			
Sedan: 3,000 ≤ Weight ≤ 3,500 lbs	x_j	π_{ij}	w_{ij}	y_{ij}
Mazda 626	397,402	0.0238	8.4106	1
Dodge Avenger	253,010	0.0151	13.2105	0
Toyota Camry Solara	117,661	0.0070	28.4069	1
Olds Cutlass Supreme	234,277	0.0140	14.2668	0
Buick Century 4-Dr. Sedan	718,772	0.0430	4.6501	1
$N_{i \in Sedan\text{: } 3{,}000 \le \text{Weight} \le 3{,}500}$	16,711,939			
SUV/CUV/Pickup Truck	x_j	π_{ij}	w_{ij}	y_{ij}
Toyota Rav4	258,016	0.0500	6.6590	0
Nissan Pickup	304,002	0.0590	5.6517	1
Ford Ranger	1,266,761	0.2458	1.3563	1
$N_{i \in \text{SUV/CUV/Pickup Truck}}$	5,154,377			
$N_{i \in Sedan\text{: Weight} < 3{,}000} + N_{i \in Sedan\text{: } 3{,}000 \le \text{Weight} \le 3{,}500} + N_{i \in \text{SUV/CUV/Pickup Truck}} = 28{,}442{,}805$				

For the purpose of convenience, the systematic sampling scheme in Table 26 was considered as sampling with replacement, and the Hansen-Hurwitz estimator is adopted to estimate the proportion of compliance. In statistics, the estimate remains unbiased, but the corresponding variance would be overestimated.

The total number of compliant vehicles in i^{th} stratum was estimated as the following:

$$\hat{\tau}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} \frac{y_{ij}}{\pi_{ij}}.$$

The total number of vehicles in i^{th} stratum was also estimated by the Hansen-Hurwitz estimator (assuming N_i is unknown).

$$\hat{N}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} \frac{1}{\pi_{ij}}$$

The estimated proportion of compliance in i^{th} stratum was obtained by dividing $\hat{\tau}_i$ by $\hat{N}_i$.

$$\hat{P}_i = \frac{\hat{\tau}_i}{\hat{N}_i} = \frac{\frac{1}{n_i} \sum_{j=1}^{n_i} \frac{y_{ij}}{\pi_{ij}}}{\frac{1}{n_i} \sum_{j=1}^{n_i} \frac{1}{\pi_{ij}}} = \frac{\sum_{j=1}^{n_i} \frac{y_{ij}}{x_j}}{\sum_{j=1}^{n_i} \frac{1}{x_j}}$$

The following table shows the estimated proportion of compliance and the corresponding variance in each stratum:

Table 26: Estimation of Compliance Proportion in Test Year 2012

Vehicle Type	Sedan		SUV/CUV/Pickup Truck
Curb Weight (lbs)	Weight < 3,000	3,000 ≤ Weight ≤ 3,500	Weight < 3,500
$\widehat{P_i}$	0%	60.15%	51.28%
$\widehat{Var}(\widehat{P_i})$	0	0.0479	0.0833

Based on Table 27 and the sales of the target population, the estimated proportion of compliance in test year 2012 is 44.63 percent, and the corresponding variance is 0.0193.

Based on the distinct test year, the following table summarizes the sales of the target population, the estimated proportion of compliance ($\hat{P}$), and the corresponding variance.

Table 27: Estimation of Compliance Proportion

Test Year	Sales of Target Population	$\hat{P}$	$\widehat{Var}(\hat{P})$
1999 & Honda Accord	11,101,641	27.92%	0
2012	28,442,805	44.63%	0.0193

Applying the statistical inference in Table 28, the estimated proportion of compliance in the rear impact upgrade before MY 2006 is 39.94 percent with 9.99 percent standard error. Conversely, approximate 60 percent of vehicles weighing less than 3,500 pounds in MY 2005 or earlier did not meet the rear impact upgrade.

Because there was no probability sampling scheme in vehicles weighing more than 3,500 pounds, it is not possible to estimate the compliance proportion of vehicles weighting more than 3,500 pounds. It is only appropriate to report that three of the four sample units passed the compliance test of the rear impact upgrade.

9.2: Analysis of ESC in Rear Impact Fires

The dependent variable in the following two logistic regression models was the log odds ratio of a post-crash fire in a rear impact. However, the analyzed database was limited to

1. Make/models that have equipped with ESC before and after certifying to the FMVSS No. 301 rear impact upgrade, and
2. Make/models that have not equipped with ESC before and after certifying to the FMVSS No. 301 rear impact upgrade.

Our analysis excluded the make/models that shifted from without ESC to with ESC at the same time when they certified to the FMVSS No. 301 rear impact upgrade. Since a substantial portion of data observations were excluded, the following logistic regression models could not reliably interpret the effect of the rear impact upgrade in rear impact fires. However, the estimated fire-reducing effectiveness of the rear impact upgrade can still be roughly compared in a model that considered ESC versus a model that did not consider ESC.

Table 28: Logistic Regression in Rear Impact Fires

Independent Variables: Rear Impact Upgrade and ESC			
	Estimate	x^2	***p*-value**
Intercept	-3.6455	632.2694	< 0.0001
Rear Impact Upgrade	-0.4827	2.4413	0.1182
ESC	-0.3352	1.0460	0.3064
Independent Variable: Rear Impact Upgrade			
Intercept	-3.6986	720.8352	< 0.0001
Rear Impact Upgrade	-0.5530	3.3449	0.0674

Table 29: Fire-Reducing Effectiveness in Rear Impact Fires

Independent Variables: Rear Impact Upgrade and ESC		
Rear Impact Upgrade		
	Odds Ratio	61.70%
	Fire-Reducing Effectiveness	38.30%
ESC		
	Odds Ratio	71.50%
	Fire-Reducing Effectiveness	28.50%
Independent Variables: Rear Impact Upgrade		
Rear Impact Upgrade		
	Odds Ratio	57.50%
	Fire-Reducing Effectiveness	42.50%

9.3: Analysis of ESC in First-Event-Rollover Fires

The dependent variable in the following two logistic regression models was the log odds ratio of a post-crash fire in a first-event rollover. However, the analyzed database was limited to

1. Make/models that have equipped with ESC before and after certifying to the FMVSS No. 301 rear impact upgrade, and
2. Make/models that have not equipped with ESC before and after certifying to the FMVSS No. 301 rear impact upgrade.

Our analysis excluded the make/models that shifted from without ESC to with ESC at the same time when they certified to the FMVSS No. 301 rear impact upgrade. Since a substantial portion of data observations were excluded, the following logistic regression models cannot reliably interpret the affiliated effect of the rear impact upgrade in first-event-rollover fires. However, the estimated fire-reducing effectiveness of the rear impact upgrade can still be roughly compared in a model that considered ESC versus a model that did not consider ESC.

Table 30: Logistic Regression in First-Event-Rollover Fires

Independent Variables: Rear Impact Upgrade and ESC			
	Estimate	x^2	***p*-value**
Intercept	-4.1702	622.7233	< 0.0001
Rear Impact Upgrade	-0.1234	0.1068	0.7438
ESC	0.1247	0.0548	0.8149
Independent Variable: Rear Impact Upgrade			
Intercept	-4.1626	648.3349	< 0.0001
Rear Impact Upgrade	-0.1110	0.0884	0.7662

Table 31: Fire-Reducing Effectiveness in First-Event-Rollover Fires

Independent Variables: Rear Impact Upgrade and ESC		
Rear Impact Upgrade		
	Odds Ratio	88.40%
	Fire-Reducing Effectiveness	11.60%
ESC		
	Odds Ratio	113.30%
	Fire-Reducing Effectiveness	-13.30%
Independent Variables: Rear Impact Upgrade		
Rear Impact Upgrade		
	Odds Ratio	89.50%
	Fire-Reducing Effectiveness	10.50%

9.4: Vehicle Type Versus Rear Impact Fires in FARS

The estimates of the fire-reducing effectiveness of FMVSS No. 301 rear impact upgrade for passenger cars and LTVs are similar in Table 32 and 33.

Table 32: (Cars) Model Year Versus Rear Impact Fires in FARS

CY 2003-2011 and MY 2004-2011			
	No Fires	Fires	Rate of Fires
MY ≤ 2007	1,893	61	3.12%
MY > 2007	486	6	1.22%
Odds Ratio	38.31%		
Fire-Reducing Effectiveness	61.69%		
Pearson's Chi-Squared Test	x^2 = 5.3386		***p*-value = 0.0209**
Fisher's Exact Test	-		***p*-value = 0.0196**
CY 2008-2011 and MY 2004-2011			
MY ≤ 2007	1,061	33	3.02%
MY > 2007	477	6	1.24%
Odds Ratio	40.44%		
Fire-Reducing Effectiveness	59.56%		
Pearson's Chi-Squared Test	x^2 = 4.3731		***p*-value = 0.0365**
Fisher's Exact Test	-		***p*-value = 0.0355**
CY ≤ MY + 3 and MY 2004-2011			
MY ≤ 2007	1,277	40	3.04%
MY > 2007	486	6	1.22%
Odds Ratio	39.41%		
Fire-Reducing Effectiveness	60.59%		
Pearson's Chi-Squared Test	x^2 = 4.7755		***p*-value = 0.0289**
Fisher's Exact Test	-		***p*-value = 0.0287**

Table 33: (LTVs) Model Year Versus Rear Impact Fires in FARS

CY 2003-2011 and MY 2004-2011			
	No Fires	Fires	Rate of Fires
MY ≤ 2007	2,243	44	1.92%
MY > 2007	441	3	0.68%
Odds Ratio	34.68%		
Fire-Reducing Effectiveness	65.32%		
Pearson's Chi-Squared Test	x^2 = 3.4252		***p*-value = 0.0642**
Fisher's Exact Test	-		***p*-value = 0.0716**
CY 2008-2011 and MY 2004-2011			
MY ≤ 2007	1,274	22	1.70%
MY > 2007	439	3	0.68%
Odds Ratio	39.57%		
Fire-Reducing Effectiveness	60.43%		
Pearson's Chi-Squared Test	x^2 = 2.4130		***p*-value = 0.1203**
Fisher's Exact Test	-		***p*-value = 0.1641**
CY ≤ MY + 3 and MY 2004-2011			
MY ≤ 2007	1,482	31	2.05%
MY > 2007	441	3	0.68%
Odds Ratio	32.52%		
Fire-Reducing Effectiveness	67.48%		
Pearson's Chi-Squared Test	x^2 = 3.7918		***p*-value = 0.0515**
Fisher's Exact Test	-		***p*-value = 0.0611**

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