INJURY MITIGATION TECHNOLOGY APPLICATIONS AND THE RELATIONSHIPS TO VEHICLE MASS, PRICE, AND FUEL ECONOMY

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ABSTRACT

Managing the vehicle level trade-offs between motor vehicle safety performance consequent to the application of new injury control technologies and the potential increasing mass effects consequent to application of those technologies on the one hand, and the needs and desires for increased fuel economy through reduction in vehicle mass on the other hand, is a complex and vexing challenge. Historically, most studies of vehicle safety performance and fuel economy have focused upon the collision injury performance of vehicles as a function of vehicle mass. This study examines the connection from a somewhat different perspective by examining vehicle level attribute data (price, mass, and fuel economy) from both public and commercial sources for changes that register at a make/model level in the model years in which newly emerging safety technologies have been made standard.

The installation of injury mitigation technologies over the period 1998 through 2010 has been studied at the make/model/model year level for base or near-base model vehicles sold in the United States. The introduction and application of 28 safety technologies has been collected from multiple automotive reporting services (including: edmunds.com, Ward's Automotive, msn.com, iihs.org, and safercar.gov). A census of technology presence has been tabulated by: technology, manufacturer, make, model, model year, body style, and technology presence as standard or optional equipment. Corresponding base vehicle price, mass and fuel economy data have also been tabulated using publicly available sources for such vehicle level attribute data. Unique vehicle make/model combinations were paired for model years immediately prior to the installation of a new emerging safety technology and the model year of first standard installation of the particular technology. This also includes models for which a technology was optional and then became standard equipment. Changes in the vehicle level mass, price, and fuel economy were calculated and tabulated for multiple specific technologies and the change results are presented herein.

INTRODUCTION

A considerable variety of factors influence the safety content of vehicles. These include regulatory activity, customer demands, safety initiatives by individual manufacturers, manufacturers' competitiveness and safety concerns, etc. New technologies usually cannot be simply added into an existing vehicle architecture without extensive re-engineering of multiple vehicle level systems and sometimes major reconfiguration of manufacturing facilities for components and vehicle assemblies. Market acceptance, affordability, supply chain capacity and capability, indeterminate safety technology effectiveness, and uncertainties over possible unintended consequences are all factors that limit the rapidity of injury mitigation technology insertion into the stream of commerce. Consequently, injury mitigation technologies tend to propagate in a consistent pattern with a low initial penetration rate, often appearing as optional features and then gradually becoming standard features on a greater proportion of the new vehicle fleet in successive years. This pattern was characterized and reported upon in Lange, et al. [1] for a multiple injury control technologies.

SAFETY TECHNOLOGIES

Safety or injury mitigation technologies were selected based on their suitability to the analysis. Technologies with limited data sets were avoided. The technologies included in this study are:

- Anti-Lock Brakes (ABS) - on all four wheels.
- Dynamic Head Restraints - includes all systems of varying complexity that move the head restraint in response to a collision.
- Energy Management Feature - refers to seat belt load limiting devices.
- Head Airbag - includes all types of airbags for side impact head protection.
- Pretensioners - seat belt devices that apply tension to safety belt webbing and take up belt slack early in a collision to couple the occupant to the vehicle center of mass early in a crash to lengthen the ride down time for energy absorption.
- Side Airbag - includes all varieties of side impact airbags and deployment locations.
- Stability Control - computer controlled system to prevent the loss of or restore control over a vehicle by way of sensors and application of brakes, steering, and other vehicle systems.
- Tire Pressure Monitoring System (TPMS) - monitors all four tires and indicates when a default low pressure is reached, audibly and/or visually.

PRICE, MASS, AND FUEL ECONOMY

Vehicle price, mass, and fuel economy were obtained from electronic versions of Ward's Automotive Yearbooks. The data includes multiple variants and trim levels for vehicles sold in the U.S. Safety features specified in the Ward's data were matched with the price, mass, and fuel economy data. Data regarding some of the injury mitigation technologies in this study were only available from NHTSA's Safercar database. This resource includes both crash testing data as well as manufacturer submitted survey data for multiple injury mitigation technologies that are of interest to the National Highway Traffic Safety Administration (NHTSA). Some data was collected from motor vehicle manufacturers' websites and the websites of Edmunds and MSN Autos.

Although data is available for pickup trucks as well as other light duty vehicles, pickup trucks are excluded from this analysis as variation in body style and bed length confounds the selection of consistent year on year vehicle model level pairings that are necessary for the analyses discussed herein.

CALCULATIONS

After matching mass, fuel economy, and price to a specific injury mitigation technology, an analysis was performed to match closely related trim levels in successive years in which the technology became standard in the second year. Often, it was preferable to use pairings where a technology was optional one year and standard in the next. The key vehicle parameters are based on the optional technology not being present, so it is a good indicator of the association between the technology's presence and change in the key parameters of this study. When patterns of insertion were unclear or there was doubt over the sampling, the vehicle model was excluded from these analyses. Thirty to sixty matched vehicle pairs resulted per application for each technology from which fleet wide changes in the key parameters of vehicle mass, fuel economy and price were calculated.

The engine size and drive configuration were closely controlled to minimize influence on increases in price, mass, and fuel economy. These are typically the most influential factors in changes in all three of these characteristics, and can have a significant impact on all three in the same model year. While some trim levels changed in name each year, the closest applicable trim level was applied in the subsequent year from a price standpoint as required. Occasionally, a one year jump in model years was acceptable if the correlation was better between the trim levels. Manufacturers also will skip a model year on occasion, for example, continuing to sell a 2007 model year vehicle into 2008 and then introducing the 2009 model year vehicle at the end of 2008 with no production of a 2008 model year vehicle.

Differences for each matched vehicle pair were calculated and have been plotted for each vehicle characteristic and each injury mitigation technology. Distributions by technology were plotted for each characteristic using boxplots. The lower and upper limit values of a box represent respectively the 25th and 75th percentile points for the parametric distribution. Points plotting above or below the vertical lines extending from the boxes are outliers, i.e., changes unusually high or low with respect to the collected data sample. Statistics for the distribution of the change in price, mass, and fuel economy corresponding to each of the injury mitigation technologies studied were calculated and reported. Statistics calculated are: mean, standard deviation, minimum, first quartile (25th percentile), median, third quartile (75th percentile), and maximum.

As many different factors that are not considered in this analysis can affect major changes in the vehicle parameters we studied, it is unlikely that extreme difference values for any of the characteristics are due solely to the addition of the particular technology. Quartile values and the interquartile range (distance between the first and third quartiles) may be more likely to provide insight into the potential effects of technology additions.

Curb Weight

For the entire data set, the average curb weight was calculated for each model year. The results are summarized in Table 1 and graphically illustrated in Figure 1. The trend indicates an increase in the fleet average curb weight from 3,339 lb with a standard deviation of 763.5 lb in 1996, to 3,989.3 lb with a standard deviation of 881.9 lb in 2010.

For the injury mitigation technologies studied, the average curb weight differences ranged from 33.9 lb for dynamic head restraints to 72.2 lb for side air bags. The first quartile for most technologies was 0 or slightly less than zero. This small difference from a zero value would indicate that in general, addition of most of these injury mitigation technologies had a small adverse effect on vehicle mass consequent to the addition of the technologies. The smallest interquartile range is for tire pressure monitors (0,10), a technology with little mass effect. The results are summarized in Figure 2 and Table 2.

Manufacturer's Suggested Retail Price (MSRP)

The MSRP for the data set was calculated for each model year and summarized in Figure 3 and Table 3. MSRP increases steadily from $25,536 with a standard deviation of $15,835 in 1996, to $38,015 with a standard deviation of $22,468 in 2010.

For the safety technologies studied, average MSRP differences ranged from $320 for stability control additions to $1,174 for ABS additions. However, the amount of variation in differences is large for each technology, exceeding $1000 in every case. Further work needs to be done to understand actual price effects due to specific additions of single technologies. In many cases, multiple safety technologies and other features may be introduced in a single mode year change and the price changes may not reflect the true costs or affordability effects of the addition of an injury control technology on an individual basis. The results are summarized in Figure 4 and Table 4.

Fuel Economy

The average city and highway fuel economy for the data set was calculated for each model year and summarized in Figure 5 and Table 5. It should be noted that the drop in fuel economy seen in 2008 is attributable to the Environmental Protection Agency's revised testing standards that lowered average fuel economy and were intended to more closely reflect real world driving conditions. Fuel economy on average decreased for both city and highway driving during the time period of the study. The fleet average city cycle fuel economy in 1996 was 21.30 mpg with a standard deviation of 5.72 mpg; that value changed to 18.99 mpg with a standard deviation of 5.67 mpg in 2010. In the highway cycle, average fuel economy was 27.46 mpg with a standard deviation of 6.45 mpg; that value changed to 25.27 mpg with a standard deviation of 5.80 mpg in 2010.

For the injury mitigation technologies studied, neither set of differences between city and highway cycle fuel economy provide clear trends or significant positive or negative effects. Values for each injury control technology are generally spread across positive and negative values and interquartile ranges are generally centered around zero. The results are summarized in Figures 6 (city cycle) and 7 (highway cycle) and Tables 6 (city cycle) , and 7 (highway cycle).

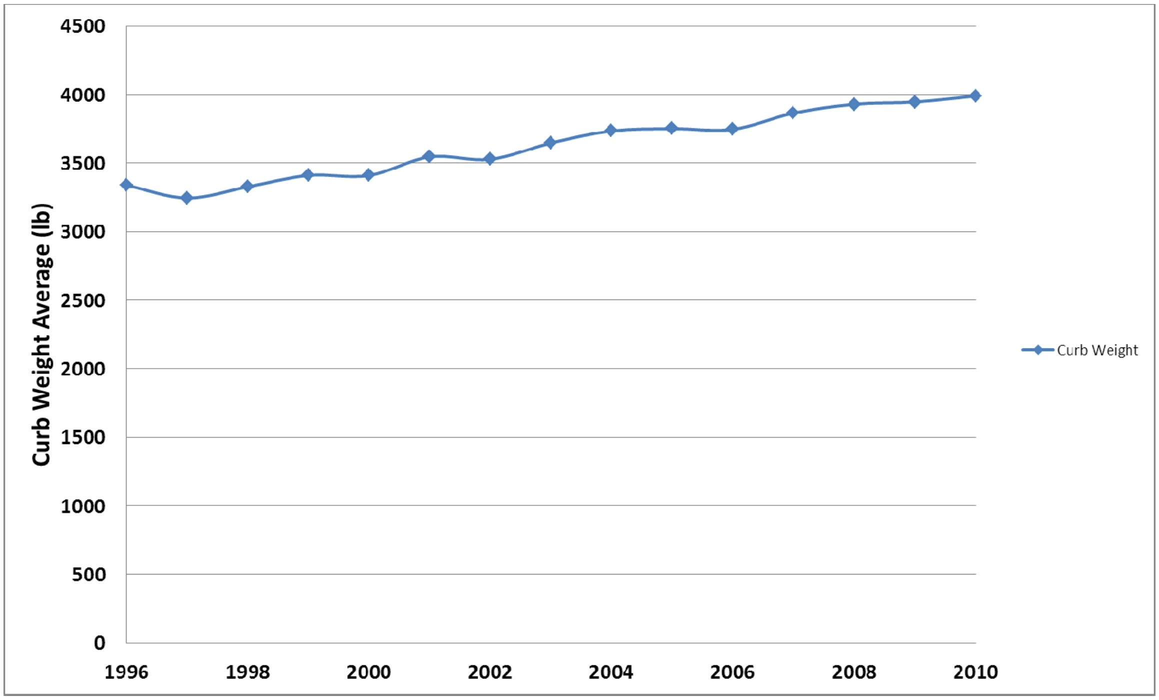

Figure 1. Curb weight average for data set by model year.

Table 1.
Summary of curb weight data by model year

Year	Curb Weight Average (lb)	Standard Deviation	Weight Delta (lb)
1996	3339.0	763.5	
1997	3245.2	696.1	-93.8
1998	3327.7	753.7	82.6
1999	3410.9	746.9	83.2
2000	3410.1	759.9	-0.8
2001	3545.9	826.5	135.8
2002	3527.8	734.6	-18.1
2003	3646.7	792.1	118.9
2004	3734.9	852.1	88.2
2005	3751.6	822.3	16.7
2006	3746.3	795.3	-5.2
2007	3865.0	780.1	118.7
2008	3929.9	847.2	64.9
2009	3945.9	864.1	16.0
2010	3989.3	881.9	43.4

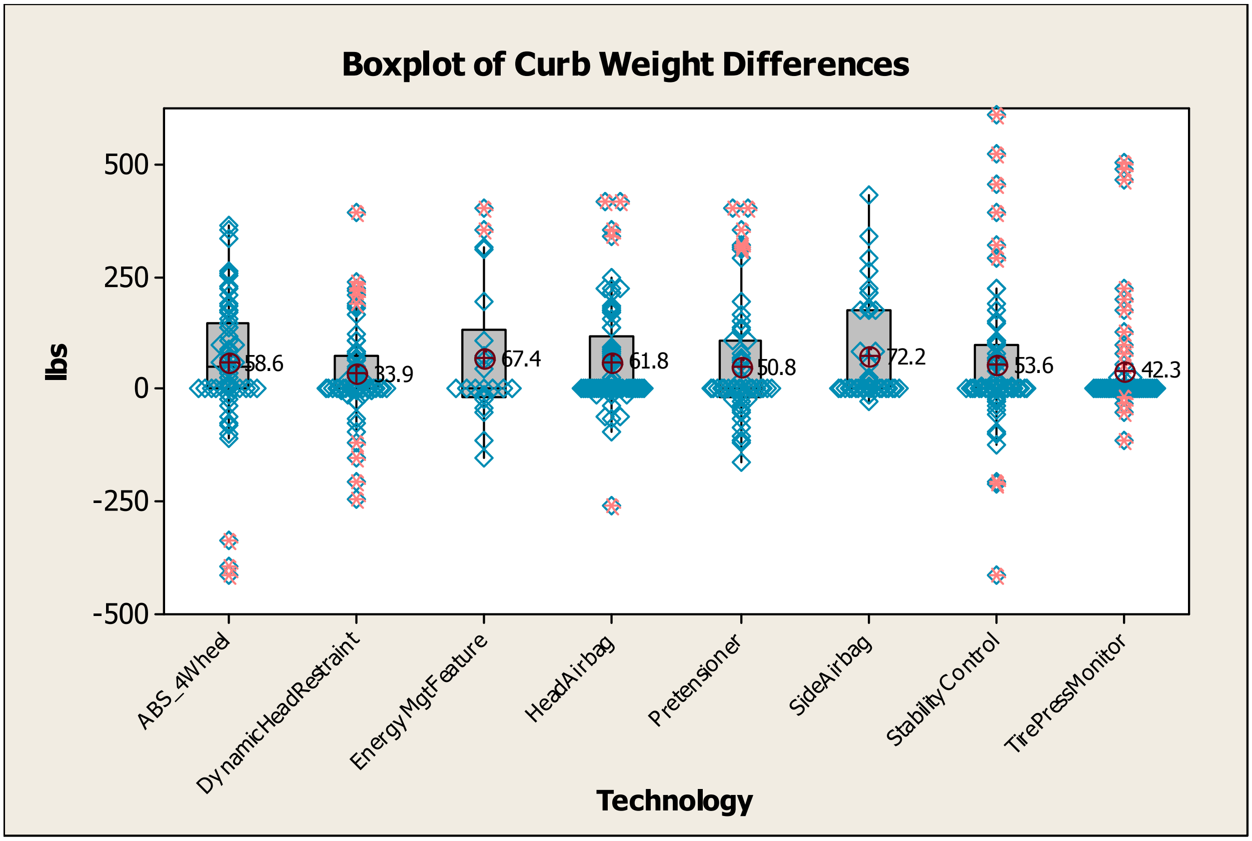

Figure 2. Boxplot of curb weight differences.

Table 2.
Statistical summary of curb weight differences by technology

Technology	Count	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
ABS_4Wheel	63	58.6	147.1	-415	0	50	148.0	362
DynamicHeadRestraint	61	33.9	104.7	-246	0	0	74.5	394
EnergyMgtFeature	22	67.4	152.6	-152	-15.3	0	131.3	405
HeadAirbag	73	61.8	117.8	-259	0	0	117.0	419
Pretensioner	54	50.8	135.0	-163	-19	0	110.0	405
SideAirbag	41	72.2	115.3	-25	0	0	176.5	433
StabilityControl	65	53.5	162.9	-415	0	0	100.5	612
TirePressMonitor	54	42.3	122.1	-115	0	0	10.3	505

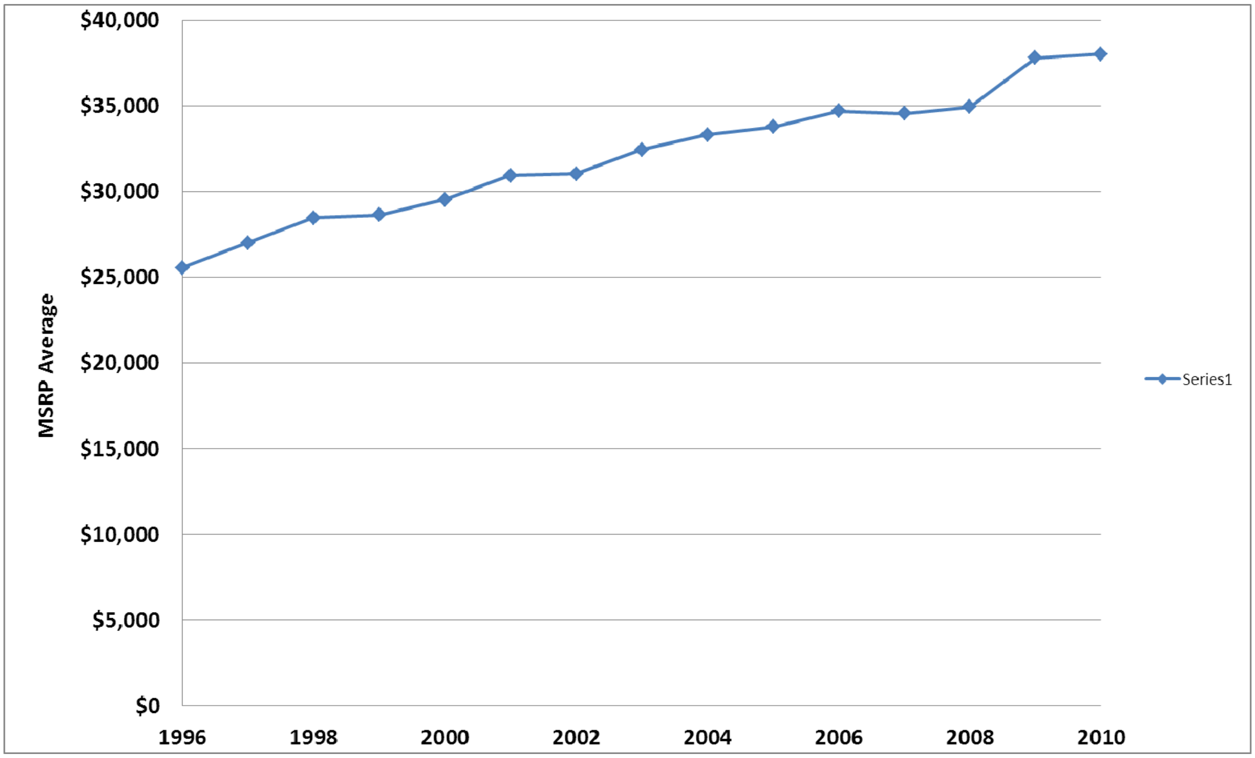

Figure 3. MSRP average by model year for data set.

Table 3.
Summary of MSRP data by model year

Year	Average MSRP	Standard Deviation	Price Delta
1996	$25,536	$15,835	
1997	$26,994	$16,119	$1,458
1998	$28,446	$16,475	$1,452
1999	$28,628	$15,877	$182
2000	$29,521	$15,063	$893
2001	$30,933	$17,029	$1,413
2002	$31,014	$16,932	$80
2003	$32,417	$16,562	$1,403
2004	$33,306	$17,767	$889
2005	$33,751	$18,599	$446
2006	$34,688	$20,045	$937
2007	$34,526	$20,307	-$163
2008	$34,912	$19,899	$386
2009	$37,782	$23,628	$2,871
2010	$38,015	$22,468	$232

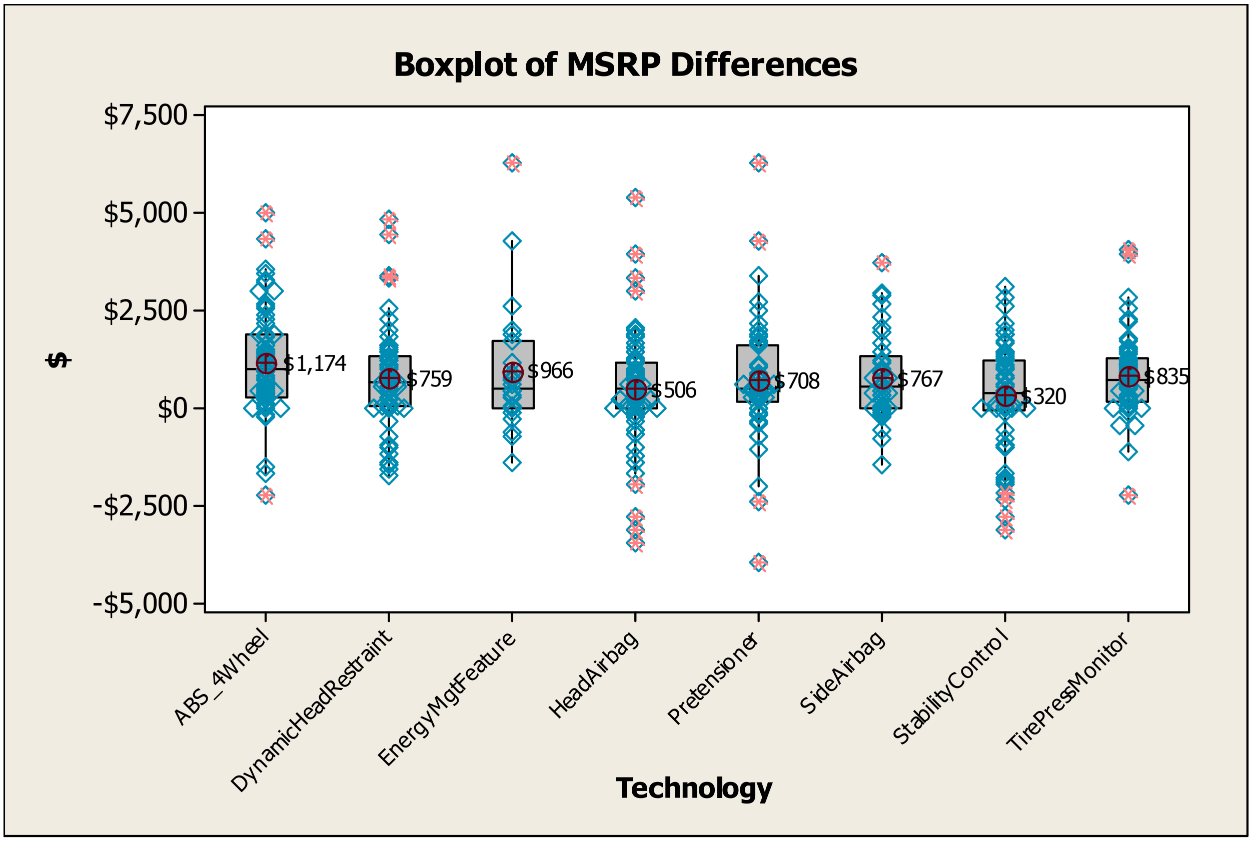

Figure 4. Boxplot of MSRP differences.

Table 4.
Statistical summary of MSRP differences by technology

Technology	Count	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
ABS_4Wheel	63	$1,174	$1,350	-$2,220	$290	$1,015	$1,900	$5,000
DynamicHeadRestraint	61	$759	$1,275	-$1,735	$43	$675	$1,306	$4,880
EnergyMgtFeature	22	$966	$1,717	-$1,390	-$25	$520	$1,750	$6,290
HeadAirbag	73	$505	$1,391	-$3,485	$0	$495	$1,178	$5,430
Pretensioner	54	$708	$1,538	-$4,000	$155	$500	$1,593	$6,290
SideAirbag	41	$767	$1,083	-$1,460	$3	$530	$1,320	$3,755
StabilityControl	65	$320	$1,355	-$3,160	-$85	$380	$1,238	$3,110
TirePressMonitor	54	$835	$1,079	-$2,230	$169	$743	$1,281	$4,090

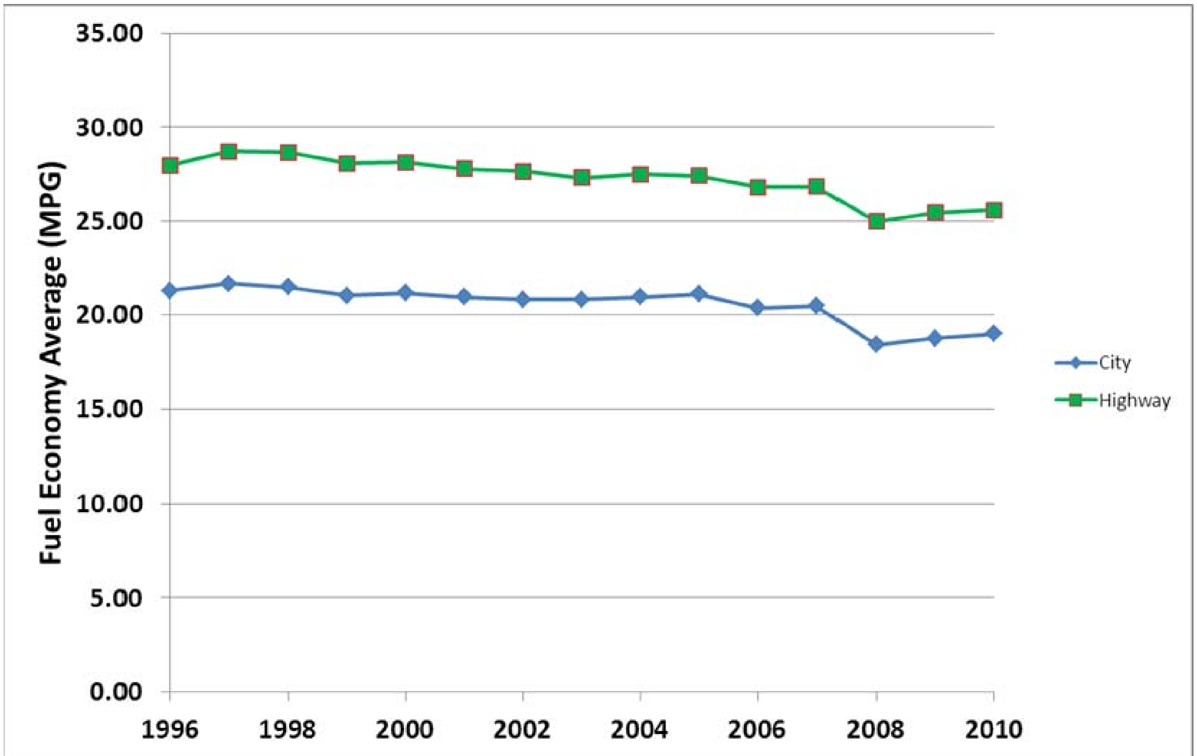

Figure 5. Fuel economy average by model year for data set.

Table 5.
Summary of fuel economy data

Year	Avg. City Fuel Ecomony (MPG)	Standard Deviation	City Fuel Economy Delta (MPG)	Avg. Highway Fuel Ecomony (MPG)	Standard Deviation	Highway Fuel Economy Delta (MPG)
1996	21.30	5.72		27.96	6.45	
1997	21.66	5.85	0.36	28.69	6.59	0.72
1998	21.48	5.61	-0.18	28.64	6.54	-0.05
1999	21.02	5.25	-0.45	28.06	5.93	-0.58
2000	21.15	5.98	0.13	28.13	6.71	0.07
2001	20.94	5.88	-0.22	27.78	6.34	-0.34
2002	20.80	5.90	-0.13	27.65	6.43	-0.13
2003	20.82	6.35	0.02	27.29	6.54	-0.36
2004	20.94	6.89	0.12	27.48	6.93	0.19
2005	21.10	6.86	0.16	27.40	6.70	-0.08
2006	20.36	6.45	-0.75	26.80	6.14	-0.60
2007	20.47	5.78	0.11	26.81	5.54	0.02
2008	18.40	5.21	-2.07	24.96	5.11	-1.85
2009	18.75	5.12	0.35	25.45	5.47	0.49
2010	18.99	5.67	0.24	25.57	5.80	0.13

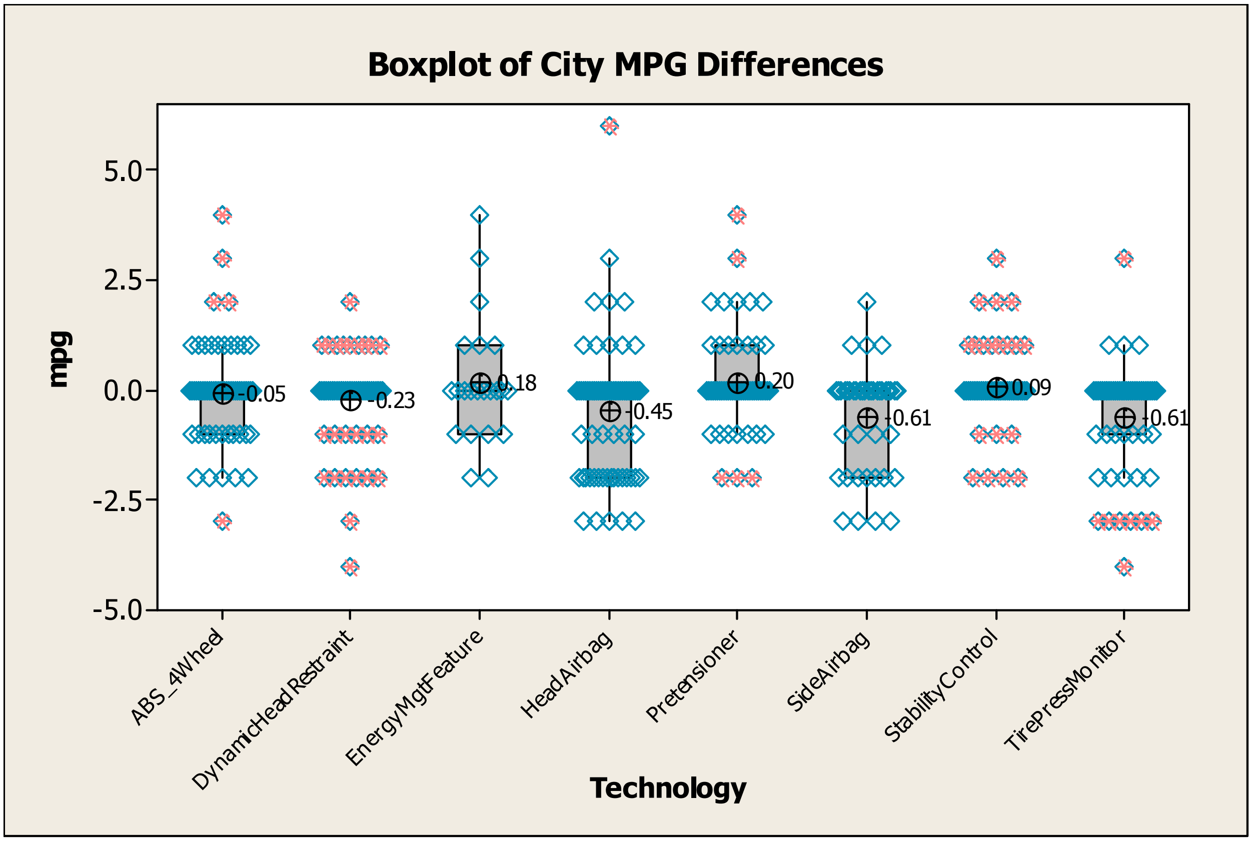

Figure 6. Boxplot of city fuel economy differences.

Table 6.
Statistical summary of city fuel economy differences by technology

Technology	Count	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
ABS_4Wheel	63	-0.048	1.156	-3	-1	0	0	4
DynamicHeadRestraint	61	-0.230	1.039	-4	0	0	0	2
EnergyMgtFeature	22	-0.182	1.435	-2	-1	0	1	4
HeadAirbag	73	-0.452	1.500	-3	-2	0	0	6
Pretensioner	54	0.204	1.139	-2	0	0	1	4
SideAirbag	41	-0.610	1.222	-3	-2	0	0	2
StabilityControl	65	0.092	0.861	-2	0	0	0	3
TirePressMonitor	54	-0.611	1.295	-4	-1	0	0	3

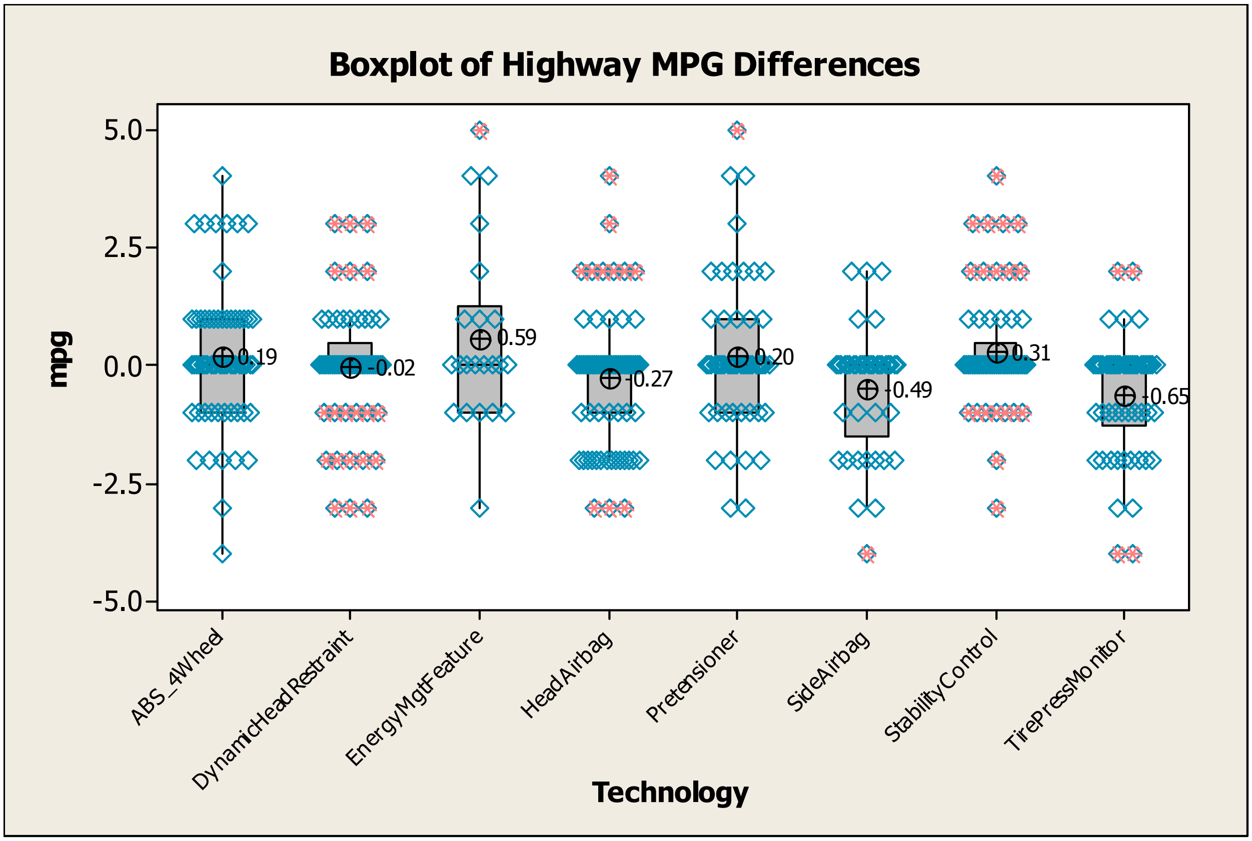

Figure 7. Boxplot of highway fuel economy differences.

Table 7.
Statistical summary of highway fuel economy differences by technology

Technology	Count	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
ABS_4Wheel	63	0.190	1.512	-4	-1	0	1	4
DynamicHeadRestraint	61	-0.016	1.297	-3	0	0	0.50	3
EnergyMgtFeature	22	0.591	1.943	-3	-1	0	1.25	5
HeadAirbag	73	-0.274	1.387	-3	-1	0	0	4
Pretensioner	54	0.204	1.595	-3	-1	0	1	5
SideAirbag	41	-0.488	1.325	-4	-1.50	0	0	2
StabilityControl	65	0.308	1.198	-3	0	0	0.50	4
TirePressMonitor	54	-0.648	1.261	-4	-1.25	0	0	2

DISCUSSION

In general, application of emerging injury mitigation technology seems not to have had significant disruptive effects on any of the three vehicle level parameters: mass, price, or fuel economy.

The modest impacts addition of injury mitigation technologies may have effected throughout the decade 1999 to 2009 on vehicle level price, mass, and fuel economy suggest that as manufacturers added the material cost and mass associated with safety technologies to base vehicles, other system level or architectural level changes may have been effected simultaneously so as to offset or compensate for the vehicle level cost and mass increases associated with the added safety equipment. Manufacturers have as well as possible attempted to integrate advanced, emerging, and new injury control technologies into vehicles without changing the market placement, affordability, or competitiveness of vehicles at the make/model level. This strategy of balancing vehicle level content and attributes to compensate for the added mass, fuel economy, and cost effects of emerging safety technologies may become more difficult to manage as fuel economy standards become more demanding. In the future, fuel economy standards will serve as a prime driver for major architectural revisions in vehicle size and mass and will demand relatively larger proportions of available research and engineering resources.

There are obvious limitations inherent in this type of analysis. While the general size of vehicles can be characterized, structural changes that result in vehicles with higher mass 'density' are difficult to characterize. A current vehicle's structure, controlling for external dimensions and materials would in most cases weigh much more than a vehicle of a decade ago, due to the greater injury control content and improved structures to manage a greater variety of collision load cases as well as address the structural needs and dynamic response of the rest of the vehicle.

Further, it is not possible to reconstruct the thousands of design decisions made by engineers developing each portfolio entry for each motor vehicle manufacturer. The study of association between certain injury mitigation features and mass, price and fuel economy is not meant to imply that addition of a technology caused a particular resulting increase or decrease. Rather, this study reports at a gross vehicle level the relationships registered over time, over the new vehicle fleet. Analyzing any feature with a myopic viewpoint that only considers the price or mass of the feature's components is erroneous. It is impossible to extract the true extent of the mass and price of a new injury mitigation technology as multiple elements of the vehicle structure, electronics, package, etc. would have undergone thoughtful consideration and incurred expenditure to enable the use of that feature.

CONCLUSIONS

Overall, there is little association between the addition of new safety technologies and changes in overall vehicle mass, price, and fuel economy. The addition of individual injury control technologies appears to have been largely offset by operational efficiencies or through applications of advanced designs and weight savings harvested elsewhere in the vehicle. Compared to the overall trends seen in the dataset of increasing curb weight, increasing price, and decreasing fuel economy, the individual safety technologies do not strongly correlate as contributors to these overall vehicle parameters.

REFERENCE

[1] Lange, R.L, Pearce, H.M., Jacuzzi, E.A. 2011. "Installation Patterns for Emerging Injury Mitigation Technologies, 1998 Through 2010." 21st Enhanced Safety of Vehicles Conference, Washington, DC.