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A Market Systems Analysis of the U.S. Sport Utility Vehicle Market Considering Frontal Crash Safety Technology and Policy

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Abstract
Active safety features and adjustments to the New Car Assessment Program (NCAP) consumer-information crash tests have the potential to decrease the number of serious injuries on United States (U.S.) roadways each year, according to previous studies. However, literature suggests that risk reductions, particularly in the automotive market, are often accompanied by adjusted consumer risk tolerance, and so these potential safety benefits may not be fully realized due to changes in consumer purchasing or driving behaviour. This article approaches safety in the new vehicle market, particularly in the Sport Utility Vehicle and Crossover Utility Vehicle segments, from a market systems perspective. Crash statistics and simulations are used to predict the effects of design and policy changes on occupant crash safety, and discrete choice experiments are conducted to estimate the values consumers place on vehicle attributes. These models are combined in a market simulation to forecast how consumers respond to available vehicle alternatives. The model is tested for a scenario where active safety features are implemented across the new vehicle fleet and a scenario where the U.S. frontal NCAP test speed is modified. Results exhibit evidence of consumer risk adjustment and support adding active safety features and lowering the NCAP frontal test speed, as these changes are predicted to improve the welfare of both firms and society.

Keywords: Automotive vehicle design, crashworthiness, market systems, safety policy.

Introduction
Automotive crash safety has improved considerably in recent decades, due in large part to advancements in vehicle designs, safety features, and regulatory standards. These advances can be modeled computationally to estimate their impacts on occupant injuries and other vehicle-related outcomes like fuel use, costs, and travel time. Actual safety improvements often fall short of model-based estimates due to the complex ways that vehicle users react to changes in designs, prices, and policies. Previous research suggests that when design improvements reduce a user's risk of injury, that user will make a behavioral adjustment in a way that typically increases his or her risk, diminishing the expected safety improvement [1].
Regardless of how much consumers compensate for risk, economists typically agree that rational people make decisions that maximize their perceived utility [2]. Safety considerations as well as other attributes may contribute to utility in different ways, and while consumers prefer safer vehicles, the ways that they consider safety in the purchasing decision is not well-understood. Two common methods for estimating purchasing behavior are to use surveys and interviews to acquire "stated-choice" data, or to analyze actual purchase records using "revealed-choice" data. Previous stated-choice studies reveal that consumers claim to value

safety features [3], though survey bias and variation among different cultures limit the applicability of these results. Revealed-choice studies attempt to discern the ways consumers value safety in relation to other attributes including fuel efficiency and costs [4], but they are limited because they do not consider modern safety features, costs, and transparency of safety information to consumers. The present study uses a common stated-choice method for estimating the importance of various product features through analyzing vehicle buyers' choices along with the specifications of the available vehicles. It assumes that consumers make rational choices to maximize their utility among the set of available vehicles. This process is referred to as discrete choice analysis [5], and the resulting model produces probabilistic estimates of a vehicle buyer's choice given a finite set of vehicle alternatives.

Aside from interpreting consumer perception, we must also understand how the design of the vehicle itself affects occupant safety. The two factors of occupant safety are crashworthiness, or how a vehicle protects its occupants in the event of a crash, and crash avoidance, or how a vehicle evades or reduces the severity of a crash [6]. Crashworthiness has been studied in the context of design optimization [7] as well as by analyzing on-road crash statistics [8]. A key finding of these studies is that increased vehicle mass and size correspond with improved on-road safety, both of which can be explained using fundamental physics. Advanced active safety features such as forward collision warning and emergency brake assistance are emerging in new vehicles to improve crash avoidance, and preliminary analyses estimate their potential to save thousands of lives in the United States (U.S.) each year [9]. However, the aforementioned consumer risk compensation may attenuate these projected safety benefits.

The U.S. National Highway Traffic Safety Administration (NHTSA) promotes better crashworthiness through mandates and consumer-information tests such as the New Car Assessment Program (NCAP) five-star rating system. Since NCAP scores are posted on the window stickers of new cars and therefore likely influence consumer demand, manufacturers have an incentive to optimize vehicle designs to these particular tests. The 35-mile-per-hour frontal test is of particular focus, but it is an unusually severe test given that approximately 98 percent of frontal crashes in the U.S. are at slower speeds [10]. A previous simulation-based analysis suggests that a slower standard could decrease serious injury rates in on-road crashes [11], and the present study examines this question accounting for consumer decision-making.

In this article, a market systems framework is developed to incorporate safety considerations in both engineering attributes and consumer choice within the Sport and Crossover Utility Vehicle (SUV/CUV) markets in the U.S. The paper links engineering analyses and estimated consumer demand for vehicles, laying a foundation to understanding how vehicle attributes, including safety, attract consumer demand and thereby influence the composition of the U.S. vehicle fleet. Frontal crashworthiness modeling is used to link observed vehicle attributes with on-road injury probabilities. A discrete choice experiment [12] reveals heterogeneous consumer preferences for new SUV/CUV models. The crashworthiness and consumer choice models are combined to project expected safety outcomes by simulating the behavior of utility-maximizing consumers as they choose from the available options in the 2006 new vehicle market. Results are examined for the business-as-usual case and compared with posited scenarios in which (1) implementation of new active safety measures changes the speeds at which crashes occur on U.S. roadways, and (2) modifications to the U.S. NCAP frontal crash test speed influence manufacturer-optimized designs and therefore crash outcomes. The results reveal trends in consumer purchasing patterns that quantify the amount of the expected safety benefit that is diminished by changing consumer preferences.

Modeling

The two main steps in the modeling process are to simulate how design decisions of manufacturers influence the vehicle attributes perceived by consumers, and to estimate how consumers use available information on vehicle attributes to make purchase decisions within the new SUV/CUV market. These are then brought together with a market systems model that simulates how market shares for different vehicles may change according to the scenario.

Design for frontal crashworthiness

Previous research suggests that current crash test ratings may not significantly affect consumer demand [13], due largely to a coarse ranking system and little variability in the rankings. Safety quantified in a new way to reflect an occupant's expected probability of injury given a frontal crash may significantly affect demand and therefore also a firm's profit-maximization objective with respect to the safety of the vehicles they produce. This metric is used throughout this study, and by using it we assume that either consumers already accurately recognize the safety benefits of high vehicle mass, or public crash test ratings would be modified to account for these considerations. Such changes to crash test ratings would provide consumers with more information to enable informed purchase decisions.

Hoffenson et al. (2011) present a method using this metric for simulating and optimizing for frontal crashworthiness using existing physics-based vehicle and occupant crash models, accounting for variability in crash conditions to estimate how optimized vehicle designs affect serious injury rates [11]. The outcome is an equation that models the impact of vehicle mass m on the expected probability of serious injury given a frontal crash $E[P]$, where the coefficients corresponding with each of the scenarios of interest are provided in Table 1:

[ ] (1)

Table 1 Coefficients for Equation (2) under various conditions

Scenario	NCAP test speed	On-road crash speeds	α_1	α_2
Baseline	35 mph	Current	18.39	-0.7483
Slower crashes	35 mph	20% slower	14.71	-0.7483
Much slower crashes	35 mph	40% slower	11.03	-0.7483
Slower NCAP test	30 mph	Current	15.22	-0.7436
Faster NCAP test	40 mph	Current	103.0	-0.9534

Estimation of consumer choice

Stated-choice data is required to build a consumer demand model because the newly quantified safety metric used here is not available to consumers. A stated-choice experiment reveals the influences of the new safety metric, as if it were available to consumers, along with other attributes, and the data are used to estimate a random coefficients multinomial logit choice model [14] using a hierarchical Bayes techique [15], which projects the vehicles consumers will choose based on the attributes of the alternatives. The attributes are country of origin, fuel economy, personal safety, acceleration performance, two- or four-wheel drive, manual or automatic transmission, two or three rows of seats, and purchase price.

The experiement is conducted as a choice-based conjoint survey [12], where respondents choose among three or four product alternatives each described by a combination of the eight attributes listed above, including a "none" option. Respondents were screened and recruited through the Amazon Mechanical Turk online worker database and asked 20 versions of the conjoint question [16]. The screening process was designed to ensure that the subjects had an interest in purchasing a new SUV or CUV within the next five years and that they paid attention to each question. An additional question was asked regarding the respondents' intentions if they ever chose "none," including the options to purchase a vehicle from a larger or smaller segment, purchase or drive a used vehicle, or not purchase or drive any vehicle.

Based on 407 responses, a mixed-logit choice model was estimated with hierarchical Bayes using Train's public Matlab code [5]. Using montonicity assumptions and testing prior knowledge of quadratic and linear relationships, the form of the final utility function *U* for consumer *i* and alternative *j* considers each of the eight attributes from the survey, given as:

(2)

The utility of the outside good alternative is set to $U_i = 0$ by construction. All priors of the parameters were distributed normally with the exception of fuel economy, personal safety, acceleration, and the second price parameter, which were each distributed lognormally. The parameter estimates indicate a high degree of preference heterogeneity, and all the mean parameter estimates are highly significant except for one of the four brand nationalities.

Market systems overview

The market systems framework integrates the models obtained through the crashworthiness simulation process and mixed-logit choice estimation within a market simulation. We predict the market shares and profits for vehicle manufacturers assuming the alternatives available to consumers consist of the 2006 new SUV/CUV market.[1] We assume that the preferences of the new SUV/CUV buyer population correspond to a weighted combination of the preferences of the survey respondents. Profits are projected by taking a sales-weighted average of the vehicle invoice prices and the estimated vehicle costs as detailed by Frischknecht (2009) [17].

Our market simulation includes the 108 vehicles classified as an SUV or CUV of the 473 total vehicles in the 2006 market. However, the net safety and fuel economy outcomes depend on the actions of those individuals that choose not to purchase an SUV/CUV. While the estimation is based on consumers who are considering an SUV/CUV purchase, those who do not purchase from the segment are assumed to choose one of the first three options in Table 2. We further assume that those consumers choose vehicles representative of observed sales-weighted fleet average specifications, provided in Table 2 and derived from observed sales volumes and U.S. EPA data [18]. The mixed category values are a combination of the others based on the stated shares from the final survey question.

Table 2 Average vehicle attributes of non-SUVs/CUVs in the 2006 fleet

Option	Stated share (%)	Mass (kg)	Fuel econ (mpg)	Engine pwr (hp)	0-60 time (s)	Price (US$)
Smaller new vehicle	25.6	1,527	25.47	195	7.6	23,810
Larger new vehicle	9.8	2,214	16.91	277	7.4	23,980
Pre-2006 vehicle	62.7	1,718	20.11	177	10.9	0
Mixed vehicles	-	1,718	21.19	192	9.7	8,608

Results

The market systems model was simulated with several variations to understand the effect on the social and private outcomes of different safety scenarios. The questions of interest are:

1. Assuming that crash avoidance technologies will effectively reduce the frontal crash speeds on U.S. roadways, how will the market respond to such changes?
2. Assuming that manufacturers adjust their designs to optimize for consumer-information tests, how will the market respond to a change in the NCAP test speed?

Outcomes include the numbers and types of vehicles sold to those individuals in the market, firm profits, fleet fuel consumption, and total expected serious injuries. Since the objectives of policy-makers would likely be to reduce the latter two quantities and the objectives of firms

[1] 2006 vehicle data were chosen because of availability; the same methodology may apply for any model year.

should be to increase profits, particular attention is paid to the relationships among these quantities. The results are examined under extreme scenarios of non-purchaser behavior.

The baseline scenario consists of the current distribution of crash speeds and today's NCAP regulations. Table 3 presents observed and predicted values for the quantities of interest. The prices from the survey were scaled from 2012 to 2006 dollars using the Consumer Price Index [19] before evaluation by the choice model, and all results are reported in 2006 U.S. dollars.

Table 3 Baseline market systems simulation results for new SUV/CUV segments

Quantity		Observed, all others do not buy/drive	Predicted, all others do not buy/drive	Predicted, all others buy/drive smaller	Predicted, all others buy/drive larger	Predicted, all others drive pre-2006	Predicted, others mixed
Sales-weighted market averages[2]	Mass	1,856 kg	1,802 kg	1,770 kg	1,850 kg	1,792 kg	1,792 kg
	Fuel econ.	20.0 mpg	21.7 mpg	22.1 mpg	21.1 mpg	21.5 mpg	21.6 mpg
	Engine pwr	225 hp	216 hp	214 hp	223 hp	212 hp	213 hp
	0-60 time	7.70 s	7.99 s	7.94 s	7.92 s	8.32 s	8.18 s
	Price[3]	$23,935	$23,873	$26,637	$26,657	$23,873	$24,872
Market totals	Firm profits	$6.55B	$5.55B	$7.12B	$7.50B	$5.55B	$5.79B
	Fuel use	2.36B gal	2.18B gal	2.43B gal	2.55B gal	2.50B gal	2.48B gal
	Expected inj.	4,230	4,323	4,966	4,811	4,903	4,910

We can see that the market simulation results in a similar market profile to the observed 2006 values, which to some extent validates our stated-preference model. The major differences are an increase in segment fuel economy and a decrease in firm profits, the former of which may be attributed to a shift in market preferences between 2006 and 2012 and bias in the survey responses. Discrepancies may also be due to the new safety metric that was not available to 2006 consumers. The model was calibrated to result in a nearly identical number of SUVs/CUVs sold. With this figure unchanged and the stated sales trends, the model predicts lower firm profits, lower fuel consumption, and more serious injuries than indicated by the observed 2006 data. Assuming that each of these vehicles is driven an average of 12,000 miles per year, the fuel consumed by this segment is lower by 7.5 percent due to the raised fuel economy. To calculate expected numbers of serious injuries in these vehicles, we assume 2.4 percent of vehicles crash each year, which is consistent with public data claiming 6-7 million vehicle crashes per year of approximately 250 million registered vehicles; if 70 percent of these crashes are frontal, then 1.6 percent of vehicles on the road are in a frontal crash of some severity in a given year. With the baseline results, this amounts to a slight increase in expected serious injuries as a consequence of the lower average vehicle mass.

The societal outcomes rely on the behavior of those who forgo a new SUV/CUV purchase, which in the baseline case is 13 percent of the market, and so results are given for several extreme scenarios of non-purchaser behavior. The results are largely intuitive, where smaller new vehicles tend to be lighter and more efficient, larger new vehicles are heavier and less efficient, and older vehicles are less powerful and slower. As expected, the scenario where individuals choose not to drive motor vehicles is the worst for the vehicle-producing firms and the best for society in terms of fuel consumption and injury rates. The mixed non-purchaser scenario, currently the best estimate of actual market behavior, is heavily weighted with pre-2006 vehicles, which is why the averages tend to be closer to that range.

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[2] The market-weighted averages for the "do not buy/drive" and "mixed" categories are for a smaller number of vehicles than the other categories.

[3] Prices when people continue driving older vehicles include a zero factor for those not purchasing that year.

Impact of Effective Active Safety Measures

Active safety measures have the potential to reduce the speeds at which crashes occur on the roads. If technologies such as forward collision warning and pre-crash braking become widely adopted and effectively reduce crash speeds, motor vehicle travel will be much less risky, and the formulation presented in Equation (1) will shift downward from the baseline scenario. Consequently, consumer behavior will shift as well to maximize utility, and so the market shares of each vehicle will be different depending on the extent by which the crash speeds are reduced. Table 4 presents the simulation results when crash speeds are reduced by an average of 20 percent and 40 percent, compared with the simulated results for the baseline scenario.

Table 4 Market systems outcomes varying the distribution of frontal crash speeds

Quantity		Baseline scenario	20% reduced speeds	40% reduced speeds
Sales-weighted market averages	Vehicle mass (kg)	1,802	1,792	1,782
	Fuel econ. (mpg)	21.7	21.8	21.9
	Engine power (hp)	216	214	213
	0-60 time (s)	7.99	8.01	8.02
	Vehicle price ($)	27,010	26,880	26,780
Annual market totals[4]	Firm profits ($B)	5.79 (5.55 – 7.50)	5.90 (5.75 – 7.47)	5.97 (5.88 – 7.44)
	Fuel consumption (B gal)	2.48 (2.18 – 2.55)	2.46 (2.28 – 2.51)	2.45 (2.35 – 2.47)
	Expected serious injuries	4,910 (4,323 – 4,966)	4,012 (3,642 – 4,047)	3,043 (2,839 – 3,062)

As the crash speeds are reduced, safety improves for all vehicles and is deemed less important by consumers, who then tend to choose lighter, more fuel-efficient, less powerful, slower, less expensive vehicles. Despite the shift toward lighter vehicles, the expected injuries decrease due to a dominant shift in the equation that calculates this value. The broader societal outcomes include more sales in the SUV/CUV market, higher firm profits in this segment, less fuel consumption (depending on the behavior of non-purchasers), and fewer serious injuries. It is important to note that the decrease in injuries is less than it would be if consumers did not shift their purchasing behavior, in which case the expected number of injuries would be 3,459 and 2,594 for the 20- and 40-percent reduced speed scenarios, respectively. This demonstrates that consumer risk adjustment is lowering the predicted benefit (fewer serious injuries) of on-road frontal crash speed reduction by 14 and 21 percent.

Impact of Changing the Frontal NCAP Test Speed

The market share simulation model is also used to explore how consumer behavior would change if the NCAP frontal crash test speed were modified. This would result in a change in vehicle designs as well as a shift in the expected probability of injury given a crash. From an engineering analysis without consumer adjustments in purchasing or driving patterns, reducing the NCAP test speed from 35 to 30 miles per hour would result in a 21-percent reduction in expected serious injuries, and raising the test speed to 40 miles per hour would increase expected injuries by 11 percent [11]. However, as we saw with consumer risk adjustment in the previous subsection, market forces tend to diminish these expected benefits, and the results of simulating the market response to this change are provided in Table 5.

[4] Annual market totals are calculated assuming that the mix of non-purchaser behaviour revealed in the survey is valid; the numbers shown in parentheses represent the range of results under the scenarios from Table 3.

Table 5 Market systems outcomes varying the NCAP frontal test speed

Quantity		30-mph NCAP	35-mph NCAP	40-mph NCAP
Sales-weighted market averages	Vehicle mass (kg)	1,794	1,802	1,829
	Fuel economy (mpg)	21.8	21.7	21.3
	Engine power (hp)	215	216	221
	0-60 time (s)	8.00	7.99	7.94
	Vehicle price ($)	26,910	27,010	27,370
Annual market totals[4]	Firm profits ($B)	5.87 (5.69 – 7.48)	5.79 (5.55 – 7.50)	5.77 (5.42 – 7.55)
	Fuel consumption (B gal)	2.46 (2.25 – 2.52)	2.48 (2.18 – 2.55)	2.51 (2.09 – 2.62)
	Expected serious injuries	4,274 (3,849 – 4,315)	4,910 (4,323 – 4,966)	5,718 (4,864 – 5,798)

Here, we can see that lowering the NCAP test speed by 5 mph results in individuals purchasing vehicles that are on average lighter, more fuel-efficient, less powerful, slower, and less expensive than in the baseline scenario. Again, the shift toward lighter vehicles still results in a lower expected probability of serious injury due to the shifted curve in Equation (1). The predicted impact on society is that more vehicles are sold resulting in higher firm profits in the segment, and lower fuel consumption and fewer injuries are expected. The impact of raising the NCAP frontal crash test speed is the opposite. Now, the injury benefits of decreasing the test speed by 5 miles per hour is only 13 percent, which amounts to a consumer risk adjustment accounting for 38 percent of the expected safety benefit from the engineering analysis alone. From this analysis, a policy change to reduce the test speed is recommended in the interest of society and firms, though a more complete analysis is warranted to model other vehicle segments and use more recent vehicle data.

Conclusions

This article details the development of a market systems framework that incorporates safety attributes in a simulation of the new SUV/CUV market, using crashworthiness modeling and a consumer choice study. We combined tools from the engineering, decision theory, and economics disciplines for predicting market responses to technological or regulatory changes, and the resulting model holds promise for revealing insights into consumer risk adjustment. The model was validated using observed market shares from the 2006 market as a benchmark, and simulations were conducted to reveal expected market outcomes if effective active safety features are widely implemented or the frontal NCAP test speed is modified.

Results suggest that incorporating active safety features or reducing the NCAP frontal barrier test speed will have positive impacts on total firm profits, serious occupant injuries, and fuel consumption within the market of individuals who consider purchasing from the new SUV/CUV offerings. The magnitude of the predicted safety benefit is diminished by consumers adjusting their purchasing patterns and choosing lower-mass vehicles, and the reduction in fuel consumption is diminished as more consumers choose to purchase from the SUV/CUV market. These considerations must be accounted for when forecasting the expected outcomes from new technology adoption and regulatory decisions. While the two cases presented in this paper demonstrate benefits to both company profits and societal good, there may be other scenarios where these outcomes trade off; in those situations, a simulation environment such as the one presented here can help decision-makers weigh the costs and benefits of alternatives with a market perspective.

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