The Influence of Rear Turn Signal Characteristics on Crash Risk

Note: Agency staff will be performing additional analysis on the safety effectiveness of amber/red turn signals. Once that work is complete, the agency will conclude whether any action may be warranted.

Technical Report Documentation Page

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16. Abstract

The relationship between the relative risk of a rear-end collision involving a turn, merge, or lane change maneuver and the characteristics of the rear turn-signal configuration was examined using rear-end collision crash data pooled from seven States. To perform the analysis, a detailed database of rear signal characteristics was developed for the vehicles most frequently involved in crashes among five of the States. The signal lamp characteristics were combined with other factors contained in the crash record in a stepwise logistic regression that modeled the odds of a rear-end collision while performing a turn-signal-related maneuver as a function of all of these factors. Two contrast groups were used as the denominator of the odds ratio in separate analyses. The first contrast group was comprised of the striking vehicles involved in turn-signal-related rear-end collisions. The second contrast group was comprised of rear-struck vehicles not engaged in turn-signal relevant maneuvers.

The first analysis suggests that there is an association between amber turn signals and a reduction of between 3 and 28 percent in the odds of being the struck (versus striking) vehicle in a turn-signal-relevant maneuver. The second analysis found no association between turn signal color and the odds of being struck in a turn-signal-relevant maneuver. The differences in the two analyses are discussed in terms of how well the respective contrast groups are insulated from potential effects of turn signal configurations.

Additional analyses substituted vehicle series name with body style as a predictor in the model, and examined turn signal characteristics in vehicles that have been produced with both amber and red turn signals at different times.

Although the analysis suggests that there may be a safety benefit associated with amber turn signals, it is unclear that turn signal color itself is completely responsible for the benefit. Further investigation of factors confounded with lamp color seems warranted before drawing a strong conclusion that turn signal color, by itself, is responsible for the observed differences.

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Contents

Executive Summary

Requirements for the color of rear turn signals differ between the standards set by the Economic Commission for Europe (ECE) and the United States standards. In the ECE standards, all rear turn signals are required to be amber, while in the United States, they can be either red or amber. This difference has led to questions about whether there are safety differences associated with each turn signal color. Consistent color coding of functions might facilitate recognition of the meaning of the signal, allowing a driver to respond more efficiently. It is also possible that, apart from color coding, an amber turn signal is also more conspicuous to a following driver amid a field of red tail and stop lamps. This might allow an amber turn signal to be recognized more quickly or confused less often with another rear signal.

The possible effects of turn signal color have been explored in a limited number of laboratory studies and crash analyses, with mixed results. Some laboratory studies suggest no effect on driver responses, while others cite advantages with amber lamps. Crash data analyses are similarly mixed. Examining rear-end collisions into turning vehicles, some reports have found no evidence of an effect of turn signal color on crash rates.

The following analysis revisits this issue with the benefit of a larger pool of crash data than before, and a logistic regression model that include many factors—such as driver age, gender, vehicle model, and vehicle age—that were not considered in previous analyses.

Method

This analysis examines the crash records of seven States to determine if there is an association between rear signal characteristics and the risk of a rear-end collision into a turning vehicle, taking into account a variety of other characteristics associated with the crash. To perform the analysis, detailed rear signal characteristics were determined for the top 50 vehicle models involved in crashes in Kentucky, Maryland, New Jersey, North Carolina, and Pennsylvania during 2003. For each model, the history of the rear signal configuration was examined over a 15-year window beginning with 1990, identifying rear signal color, lamp function configuration (i.e., whether a turn signal is separated from the stop lamp or tail lamp), light source (LED, tungsten filament), and optical characteristics.

The detailed lamp characteristics were combined with several other factors identified in the crash data in a stepwise logistic regression that modeled the odds of a rear-end collision while turning, merging, or changing lanes (i.e., a turn-signal-relevant maneuver), as a function of all of these factors. In a slight departure from previous crash analyses, the contrast group (used as the denominator of the odds ratio) in the first analysis was made of the striking vehicles from the same collisions. In a second analysis, the contrast group was made of rear-struck vehicles engaged in maneuvers that were not turn-signal relevant.

Results and Discussion

The first analysis found a reduction of between 3 and 28 percent in the odds of being the struck (versus striking) vehicle in a turn-signal-relevant maneuver when the

vehicle was equipped with amber versus red turn signals. In addition, an effect of rear signal light source was also observed such that LED turn signals appeared to reduce crash odds between 33 and 92 percent. Although interesting, the latter result is based on a single vehicle model equipped with LED turn signals and cannot be readily generalized to all vehicles equipped with LED turn signals.

The second analysis found no association between turn signal color and the odds of being struck in a turn-signal-relevant maneuver, although turn-signal reflector optics (versus lens optics) were found to reduce the odds by between 5 and 51 percent. However, similar to the previously described LED result, this result is largely based on a few vehicle models equipped with turn signals with reflector optics, and generalization to all such lamps would be premature.

The differences between the two analyses indicate that selection of a contrast group can influence the effects observed. Because the contrast group in the first analysis is better insulated from the influence of rear signals, these results may be more accurate than those from the second analysis, implying that amber turn signals may be associated with lower odds of rear-end collision during turning, merging, or lane change maneuvers.

Conclusions

Although the analysis suggests that there may be a safety benefit associated with amber turn signals, it is unclear that turn signal color itself is completely responsible for the benefit. It is important to recognize that color is likely to be confounded with other factors that could also contribute to this effect. For example, although separation of functions was partly controlled for in this study, amber turn signals are usually separated from red stop and tail lamps. Also, requirements for the minimum and maximum candlepower of amber turn signals are 1.6 to 2.5 times greater than red turn signals. Further investigation of these other factors seems warranted before drawing the strong conclusion that turn signal color, by itself, is responsible for the observed differences.

Part I: The Association of Turn Signal Characteristics With Rear-End Collisions

Overview

As vehicle turn signals evolved and became standardized over the last 100 years, differences arose in the European and United States standards (Moore & Rumar, 1999). One particular difference is that European standards, governed by the Economic Commission for Europe (ECE), require rear turn signals to be exclusively amber (yellow). In the United States, Federal Motor Vehicle Safety Standard (FMVSS) 108 allows rear turn signals to be *either* amber or red. Thus, in Europe all rear turn signals are consistently colored amber, while in the United States, they are colored either amber or red.

One reason for the difference, ironically, stems from subjective tests of amber turn signals and recommendations made in the United States by the Vehicle Lighting Committee (VLC) of the Automobile Manufacturer's Association to the European organization of lighting experts, the Group de Travail-Bruxelles (GTB), at a meeting in 1960. The GTB, in turn, recommended the exclusive use of rear amber turn signals to the Europeans, and in 1967 the ECE made it a requirement. Meanwhile, U.S. manufacturers rejected their use based on unproven cost benefits (Maurer, 1980).

Presumably, the VLC demonstrations suggested that rear amber signals were more conspicuous than red, but detailed accounts of the demonstrations are not available. Based on human factors design principles, a case can easily be made that exclusive use of an amber rear turn signal would be preferred to a condition in which a turn signal could be either red or amber. At the perceptual level, an amber turn signal would be more easily distinguished from other red-colored rear lighting by the difference in color. Moreover, current lamp technology also necessitates the use of separate lamp compartments for differently colored lamps, ensuring that an amber turn signal is likely to be spatially offset from the red tail and brake lamps. Physical lamp separation also results in likely differences in the contrast between the off and on states of a lamp—there is likely to be less contrast between the off and on states of red turn signals that share compartments with red tail or brake lamps than for amber lamps in separate compartments. Photometric differences between amber and red signal intensity might also exist—FMVSS 108, for example, stipulates higher minimum and maximum intensities for yellow (amber) turn signals than for red (see Table 1). Actual intensity differences in the vehicle fleet could affect the relative conspicuity of each lamp (although one reason for the intensity difference was to offset the greater conspicuity of red signals). Unfortunately, there are no surveys available that accurately quantify such differences, but it is likely that differences exist. Finally, consistency in the meaning of the signal's color across the vehicle fleet could also speed recognition. Europeans, for example, might recognize rear-turn signals more quickly than Americans because they may benefit from the redundancy in color-coding the turn function (i.e., amber means turn, red means stop); in contrast, American drivers must recognize that a red signal could indicate a turning or braking vehicle and base their recognition on other signal cues (e.g., flashing lamps, asymmetric lamp illumination, non-energized center high-mounted stop lamp).

Table 1.
Minimum and maximum candlepower values stipulated in FMVSS 108.

Lamp		Lighted sections		
	1	2		3
Red turn signal	80/300	95/360		110/420
Yellow (amber) turn signal	130/750	150/900		175/1050

There have been a few laboratory studies examining the potential consequence of allowing two differently colored turn signals. Luoma, Flannagan, Sivak, Aoki, and Traube (1995) found that reaction time to a braking signal is shorter in the presence of amber turn signals compared to red. However, because this study blocked trials by signal color, it is important to recognize that the result may not be directly applicable to the American driving environment where a mixture of amber and red is always present. In the study, participants may have adopted a strategy whereby a brake detection response was solely dependent on the appearance of a red light within the amber turn-signal block. In the red turn-signal blocks, an alternative strategy that does not rely on color-coding would be necessary. The result suggests that European drivers might enjoy an advantage of color-coded function while American drivers do not. However, it does not suggest that that amber or red signals have a particular advantage in the context of a roadway environment where mixtures of both colors are present.

Post (1975) examined driver reaction time to respond to turn, brake, and hazard signals with a variety of lamp configurations. Although reaction time to amber hazard signals was generally shorter than to red, no difference was found in reaction time to turn signals or brake signals when a configuration employing amber signals was compared to one with red. Similarly, Mortimer and Sturgis (1974) found no significant effect of turn signal color on reaction time, although many of their results suggest shorter reaction times were observed with amber turn signals. Recognizing that as a red stimulus shifts toward the visual periphery it appears less saturated and more yellow, Sivak, Flannagan, Miyokawa, and Traube (2000) questioned the general utility of signal color coding in normal driving, where objects are presumably first detected in the periphery. They found that in daylight conditions, color discrimination declined at viewing angles of 10 degrees or more, suggesting that the usefulness of color might be somewhat limited in hastening detection.

As mentioned earlier, use of amber rear turn signals necessitates separation from the red stop lamps, resulting in both a spatial offset from the other rear signal lamps, and a likely boost in contrast between the off and on state of the signal. Relevant to the issue of lamp separation, a recent study reported by (Luoma, Sivak, & Flannagan, 2006) examined whether rear-end collisions were influenced by separation of the brake lamp function from the other rear signal functions. They reasoned that braking activity for

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vehicles equipped with separated (dedicated) brake lamps would be easier to distinguish from other signal functions, especially at night when tail lamps are normally energized, reducing the contrast between the off and on states for combined lamps. The results suggest that dedicated stop lamps reduce rear-end collisions, although the authors caution that further examination of the data are warranted.

Beyond laboratory investigations, there has been just one analysis of crash data that investigated whether any differences in turn signal characteristics might be reflected in the crash record. Taylor and Ng (1981) examined insurance claim records involving rear-end collisions. They compared the proportion of turning crashes involving struck lead vehicles equipped with red turn signals to those equipped with amber turn signals. To account for exposure differences, the proportions were compared to rear-end collisions that did not involve turning vehicles. The analysis found no difference in rear-end crash rates between vehicles equipped with amber and red turn signals. Although the study attempted to analyze factors like driver age, gender, vehicle size, model year, light conditions, and at-fault driver status, the sample size of 1440 vehicles (386 amber; 1053 red) may have been insufficient to observe a clear effect. A power analysis that assumes a 6-percent difference in proportions of red lamps involved in turning versus non-turning crashes (with proportionally similar crash distribution) suggests that nearly 3,000 crashes would be needed to detect such a difference.

All of the vehicles compared in the preceding crash study pre-date the introduction of center high-mounted stop lamps (CHMSL), introduced in the 1986 model year. One effect of the introduction of CHMSL was an estimated reduction of rear-end collisions by about 4.3 percent (Kahane & Hertz, 1998). One might argue that, in the years prior to the introduction of CHMSL, red rear turn signals might have been more confusable with rear brake signals and possibly led to more rear-end collisions during turning. Once the CHMSL was introduced, the difference between a turning and a braking vehicle may have become clearer to following drivers. It seems that now, there is perhaps even less chance that a difference between turn signal color might lead to a rear-end collision.

It is important to keep in mind that the experimental studies cited above do not present subjects with conditions that are directly comparable to the circumstances in which a crash occurs. For example, studies that address questions about unique color-coding of rear signal function (e.g., Luoma, Flannagan, Sivak, Aoki, & Traube, 1995; Mortimer & Sturgis, 1974) do not resemble the existing U.S. and Canadian crash environments where there is a mixture of both red and amber turn signals—red could signal either a turn or braking, a turn could be signaled with either an amber or red flashing lamp, however amber would mean a turn. While there may be some benefit for all vehicles to use amber rear turn signals, domestic crash data cannot directly assess this benefit. Instead, any differences found in crash rates between the two colors are most likely attributable to differences that make one more conspicuous than another.

Signal characteristics related to crash risk

In the few crash analyses that attempt to address the potential differences between red and amber turn signals there is little discussion about what mechanisms might lead a driver to be more likely to strike a vehicle equipped with a red turn signal and less likely to strike a vehicle equipped with an amber turn signal. Indeed, it is often implied that

amber turn signals are more conspicuous than red. Perhaps amber turn signals are noticed earlier than red turn signals and provide drivers with more time to anticipate the movements of a forward vehicle.

On the other hand, perhaps drivers mistake a red turn signal for a brake signal. Unfortunately, this would not explain how confusion between a turn and a brake signal would lead to a rear-end collision. That is, if a driver sees a turn signal and mistakes it for a brake signal, it is reasonable to assume that the normal response would be to brake, perhaps inappropriately. If a driver sees a brake signal, and mistakes it for a turn signal, it is conceivable that the driver might fail to brake and strike the forward vehicle. However this failure could easily occur for *either* amber or red turn signal equipped vehicles. Unless there is a scenario in which (from the following driver's perspective) a turn signal indicates that a rapid deceleration is imminent, and in which a brake signal does *not* indicate an imminent deceleration, it is difficult to see how the confusion of one signal for another would lead to a rear-end collision.

There are a few scenarios in which something like this is plausible. As vehicles approach a lane closure on a limited access highway, there may be both braking and signaling of a merge into an adjacent lane. If a driver following behind another vehicle in an adjacent lane, mistakes the forward vehicle's signal as braking instead of merging, a rear-end collision could result when the forward vehicle encroaches into the following driver's lane (shown in Figure 1). In another scenario, it is plausible that as a vehicle transitions from a high speed to a lower speed, braking may occur over an extended duration in order to decelerate in a smooth fashion. From the perspective of a following vehicle, in this context the forward vehicle's brake lamp does not signal an imminent deceleration. However, if a turn signal is energized, a following vehicle may well anticipate that a stronger deceleration is about to happen (in order to make a turn at a comfortable speed). In this scenario, a failure to detect the turn signal may impede the following driver's ability to anticipate the deceleration, resulting in a rear-end collision (shown in Figure 2).
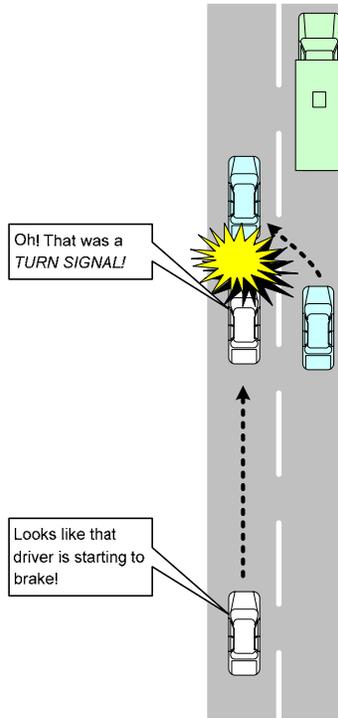
Figure 1. A crash scenario in which a turn signal is mistaken for a brake signal and leads to a rear-end collision.
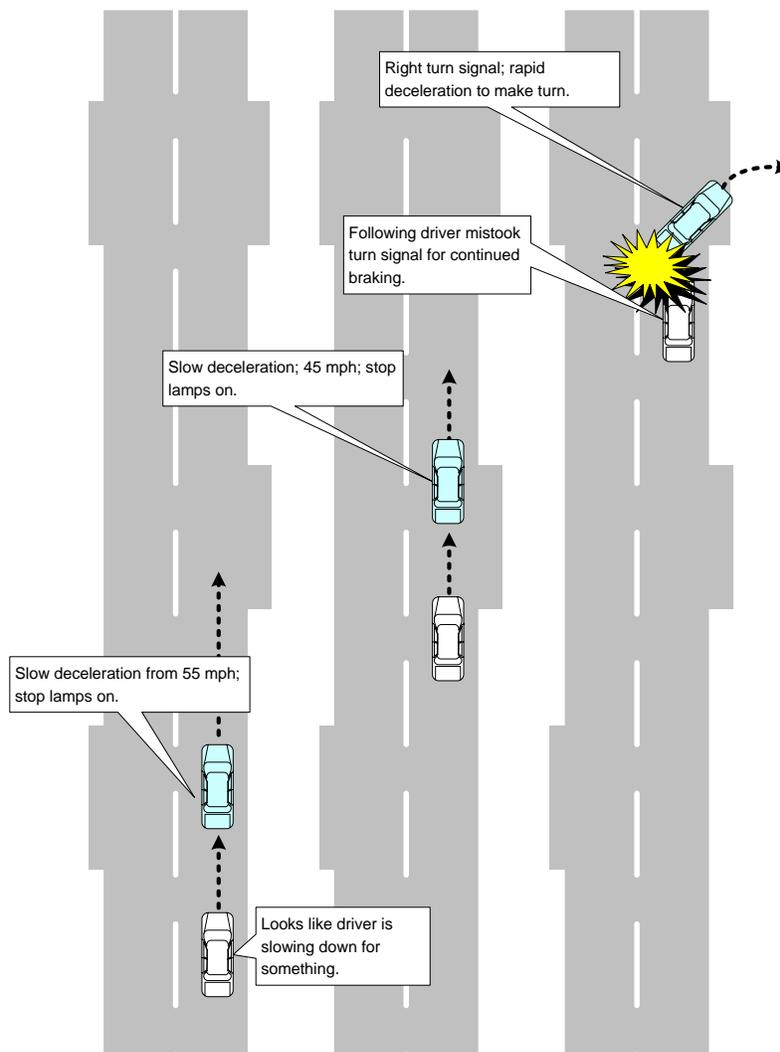
Figure 2. Crash scenario in which a forward vehicle initiates a gentle deceleration before turning. In this example, the turn signal could help a following driver identify where the forward vehicle will initiate a sharp deceleration in order to execute a turn.

General analysis approach

Throughout this report, data were analyzed using stepwise logistic regression procedures (the LOGISTIC procedure, in SAS). In this approach, the odds of a crash are modeled using various characteristics of a driver-vehicle configuration (independent factors). In this analysis, there is particular interest in turn-signal lamp characteristics, but, as will be seen, other factors may also influence the odds of a crash. The stepwise analysis proceeds by adding factors to a regression model one-by-one. Each factor is drawn from the pool of candidate factors until no factors remain in the pool that can improve the predictive power of the model. The resulting model contains only those factors that significantly improve prediction of the dependent variable.

For this analysis, the dependent variable is the odds of a crash likely to be associated to a driver's response to a rear turn signal—that is, a relevant crash. To obtain the odds of a relevant crash, non-relevant crashes are also required. The resulting odds are given by:

$$odds = \left(\frac{frequency\ of\ relevant\ crashes}{frequency\ of\ non\text{-}relevant\ crashes} \right)$$

Logistic regressions actually model the natural log of the odds of an event as a function of multiple independent factors, providing estimates of the influence each factor has on the resulting odds. The "event" in this analysis is the odds of a rear-end collision into a vehicle that is either turning or changing lanes (and, presumably, influenced by turn signal characteristics). The question addressed in the analysis is whether these odds are smaller for lead vehicles equipped with amber turn signals than they are for lead vehicles equipped with red turn signals.

As mentioned above, calculation of odds also requires counting the target vehicle's involvement in non-relevant crashes. Non-relevant crashes are crashes that are not affected by the variable of interest (i.e., turn signal color) that can serve as a kind of measure of general vehicle exposure. The crash analyses cited earlier determined non-relevant crash frequency using rear-end crashes between vehicles in which turning or lane change maneuvers were not involved (shown in Figure 3). More importantly, these non-relevant crashes were classified as either red or amber, based on the rear signal configuration of the *lead* (i.e., struck) vehicle. One critique of using the lead vehicle is that it is possible that a rear signal configuration that reduces rear-end collisions in lane change, merge, and turning scenarios might also produce side-benefits that reduce rear-end collisions in other circumstances (i.e., non-relevant) as well. If lamp characteristics influence both relevant and non-relevant crash characteristics in the same way, the resulting odds ratio (relevant/non-relevant) may not show any influence. In this report, an alternative calculation of the non-relevant crash is provided in which non-relevant crashes are based on the rear-signal configuration of the *striking* vehicle. Presumably, the drivers in striking vehicles are not influenced by the rear signal characteristics of their own vehicles.
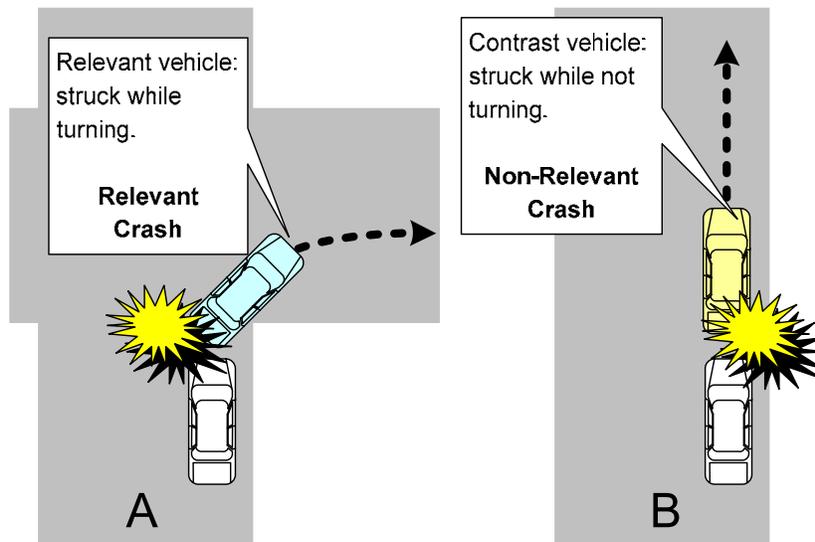
Figure 3. Crash scenarios in which the turn signal characteristics are relevant are illustrated in A; crash scenarios in which turn signal characteristics are non-relevant are illustrated in B.
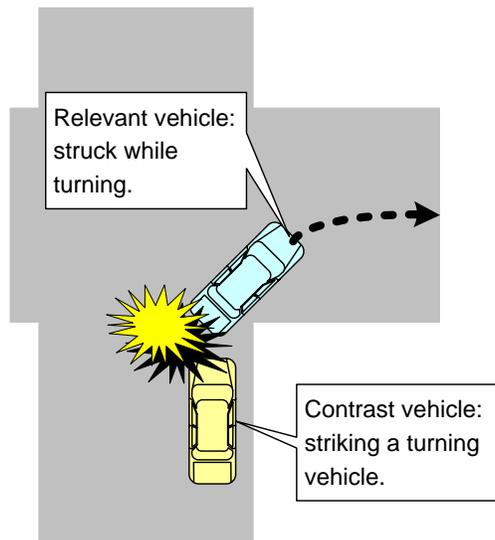

Figure 4. As an alternative to B in Figure 3, odds ratios were based on the signal characteristics of the struck versus striking vehicle in rear-end collisions involving turning vehicles.

Method

Vehicle Selection and Rear Signal Database Development

As described in the analysis approach, an important component of the logistic regression analysis is the association of rear signal lamp characteristics to the odds of a crash. In the ideal situation, a complete set of rear signal characteristics would be determined for each vehicle involved in a rear-end collision and factored into the regression. Unfortunately, there are no available reference sources that describe a vehicle's rear signal configuration throughout its production history.

Alternative vehicle selection strategies were considered with the aim of producing a sufficiently large vehicle sample to ensure sufficient power in the crash analysis so that even modest influences of signal lamp characteristics could be determined. In prior crash analyses (for example, Luoma et al., 2006; Taylor & Ng, 1981), researchers selected companion vehicle pairs with known differences in signal color (or other attributes) and made direct comparisons between them. These vehicle selections appear to have been made in an ad hoc fashion—no reference sources exist that provide sufficient description of vehicle rear signal configurations to support selection. Without such a reference, determination of the rear signal characteristics of a vehicle requires individually researching the signal characteristics of each vehicle model that might be included in a crash analysis. Because rear signal characteristics are also an element of vehicle styling, they change as a vehicle's body style evolves over time. Thus it is necessary to trace the rear signal production history of each vehicle. To compile this information, it was necessary to gather data from several sources. These included dealerships, parts catalogs, promotional brochures, owners groups, and contacts from within the auto companies. Since it was not feasible to conduct an exhaustive survey of all vehicle makes and models, limits were placed on the models and model-years included in the survey.

Model years were selected to span the years 1990 to 2005, and models were selected to include only the top 50 models found in an initial survey of five State crash datasets from the calendar year (CY) 2003. Each dataset included the vehicle identification number (VIN) for each vehicle involved in a collision. The VIN was used to determine the make, series name (model), and model year of each vehicle by decoding it using VINDICATOR 2005 software, developed by the Highway Loss Data Institute. Differences were found among the selected State crash datasets in the proportion of involved vehicles that were successfully decoded (shown in Table 2). The North Carolina datasets have the fewest decoding errors (around 8%); while Florida, Maryland, and New Jersey have the most (around 40%).

Table 2.
Proportion of the total number of vehicles in each State dataset that could not be
successfully decoded by VINDICATOR software.

State	Year	Total Crashes	Total Vehicles	Total Decoding Errors	Percent
Florida	2003	243,294	478,182	192,236	40.2%
Kentucky	2003	154,075	278,531	48,316	17.4%
Maryland	2003	109,098	202,808	78,200	38.6%
Michigan	2004	374,446	637,539	194,044	30.4%
New Jersey	2002	324,053	606,502	252,981	41.7%
New Jersey	2003	319,980	609,439	246,656	40.5%
North Carolina	2002	285,135	448,162	33,702	7.5%
North Carolina	2003	270,224	470,561	41,197	8.8%
Pennsylvania	2003	139,402	230,413	25,742	11.2%

State crash datasets were selected based on the volume of crashes reported, geographical distribution, inclusion of VIN data, and use of coding conventions that would allow sufficient distinction of crash scenario details to enable determination of relevant and non-relevant crashes, vehicle roles (striking/struck), and other factors detailed in the crash section of this report. The resulting compilation of crash frequency of vehicle models is shown in Table 3, sorted in descending order by frequency.

Table 3.
Counts of the most frequently occurring vehicle models in five State crash datasets from
CY 2003 collapsed over model years.

KY	MD	NC	NJ	PA	Make	Series	Totals
4,127	6,251	17,864	12,027	3,793	HONDA	ACCORD 4D	51,958
7,981	6,980	12,850	11,053	3,423	TOYOTA	CAMRY 4D 2WD	51,173
4,677	5,515	7,311	7,817	2,506	TOYOTA	COROLLA SEDAN 2WD	35,649
5,882	3,453	9,234	7,340	4,462	FORD	TAURUS 4D	35,206
1,698	2,514	6,185	6,567	2,189	HONDA	CIVIC 4D	23,096
2,603	2,898	5,975	5,058	1,859	NISSAN	ALTIMA 4D	22,477
2,852	2,505	5,291	5,972	3,240	FORD TRUCK	EXPLORER 4D 4X4	20,770
3,106	3,521	5,213	2,738	1,474	FORD	LTD/CROWN VICTORIA 4D	19,954
1,860	2,218	4,771	5,242	1,678	NISSAN	810/MAXIMA SEDAN	18,392
3,655	2,566	3,695	2,594	3,788	CHEVROLET	CAVALIER 2D	18,354
2,310	1,988	4,612	5,835	2,595	JEEP	GRAND CHEROKEE 4D 4X4	18,191
1,733	2,174	4,821	3,650	1,231	NISSAN	SENTRA 4D	16,895
1,711	1,826	4,071	3,717	2,184	SATURN	SL 4D	16,504
2,722	1,255	5,530	1,925	1,186	FORD	MUSTANG 2D	16,187
2,569	2,610	3,721	2,161	2,586	CHEVROLET	CAVALIER 4D	16,095
1,182	1,894	4,173	4,179	1,443	HONDA	CIVIC 2D COUPE	15,827
3,510	1,090	5,069	1,460	1,093	FORD TRUCK	RANGER PICKUP 4X2	15,380
2,614	1,112	4,727	1,772	1,020	FORD TRUCK	F150 PICKUP 4X2	14,457
2,550	1,022	4,032	2,133	2,062	PONTIAC	GRAND AM 4D	13,484
3,730	834	4,569	1,088	1,011	CHEVY TRUCK	S10 PICKUP 4X2	13,285
1,545	1,336	3,666	2,865	1,583	DODGE TRUCK	GRAND CARAVAN 2WD	12,985
1,886	1,556	3,461	2,053	1,810	FORD	ESCORT 4D	12,952
1,648	1,073	3,389	3,464	1,602	FORD TRUCK	WINDSTAR VAN	12,823
2,170	909	3,973	2,141	1,481	BUICK	LESABRE 4D	12,646
2,644	1,174	3,373	1,797	1,829	CHEVROLET	LUMINA 4D	12,464
1,556	1,626	2,940	2,255	1,997	DODGE	NEON 4D	12,181
2,868	1,343	2,950	2,240	2,150	CHEVY TRUCK	T10 BLAZER 4D 4X4	12,029
1,218	1,517	4,381	2,119	866	MAZDA	626 SEDAN	11,950
1,467	999	2,685	3,428	732	LINCOLN	TOWN CAR/CONT. 4D	11,822
1,757	819	3,245	2,226	1,673	BUICK	CENTURY 4D	11,550
740	1,076	3,581	3,209	855	HONDA	ACCORD 2D	11,481
1,667	1,244	2,906	2,994	2,000	JEEP	CHEROKEE 4D 4X4	11,398
1,808	1,581	2,776	2,227	1,371	CHEVROLET	MALIBU 4D	11,389
1,280	1,208	2,554	2,491	1,606	DODGE TRUCK	CARAVAN VAN 2WD	11,313
1,356	934	2,264	2,648	867	MERCURY	MARQUIS/G. MARQ. 4D	11,282
1,897	877	3,302	1,910	796	CADILLAC	DEVILLE 4D FWD	10,870
697	1,156	3,121	2,662	955	MITSUBISHI	GALANT 4D 2WD	10,730
1,739	805	3,020	1,821	1,428	DODGE	INTREPID 4D	10,266
1,291	777	2,154	2,605	1,304	MERCURY	SABLE 4D	9,536
1,289	477	3,215	978	308	FORD TRUCK	F150 SUPER PU 4X2	9,439
910	1,117	2,346	1,967	1,185	FORD	FOCUS 4D	9,094
2,316	430	3,557	541	515	CHEVY TRUCK	10/1500 PU 1/2T	8,852
1,818	540	3,187	914	668	CHEVROLET	CAMARO 2D	8,826
1,406	566	3,164	805	409	FORD TRUCK	RANGER SUPER PU 4X2	8,638
1,448	732	2,471	1,334	1,395	FORD	ESCORT 2D	8,631
388	187	3,275	268	87	FORD TRUCK	EXPLORER 4D 4X2	8,024
1,521	715	2,354	1,416	952	FORD	CONTOUR 4D	7,936
906	628	2,372	1,589	767	MITSUBISHI	ECLIPSE 2D 2WD	7,871
825	896	1,215	2,423	1,210	HYUNDAI	ELANTRA 4D	7,853
1,801	503	2,116	1,240	1,022	PONTIAC	GRAND PRIX 4D	7,720
1,078	861	2,319	1,237	1,114	DODGE	STRATUS 4D	7,669

Using this list as a basis, data on each vehicle's rear signal lighting configuration were compiled in a supplemental database that could be cross-referenced using decoded VIN information from the crash tables. For each vehicle make and series name, the rear signal lamp configuration was described using the following principal data fields (summarized in Table 4:

- **Start/End Model Years (1990-2005).** Within a model's lifetime, styling changes occur that frequently result in changes in a rear signal lamp's configuration. This data field identifies the spanning years for a given lamp configuration.
- **Turn Signal Color (Red, Amber).** This field identifies the color of the energized turn signal.
- **Turn Signal Lens Color (Clear/Tinted).** Clear signal lenses admit more light than tinted lenses potentially affecting daytime visibility.
- **Turn Signal Source (Tungsten/LED).** Although most vehicles are equipped with tungsten-filament bulbs, some newer vehicles are beginning to appear equipped with LED turn signal sources. There is some evidence that the rapid rise time of an LED lamp enhances a driver's response (Sivak, Flannagan, Sato, Traube, & Aoki, 1994).
- **Turn Signal Optics (Lens/Reflector).** A signal lamp can distribute light using a faceted lens or using a smooth lens and faceted reflector combination.
- **Rear Signal Separation Code.** This code identified how the stop, turn, and tail (presence) lamps were distributed among the separate lamp compartments on the rear of the vehicle. In the code, separate compartments were indicated by comma separations; combined functions within a compartment were indicated using slashes to separate the codes.

The lens color, source, and optics of brake and tail lamps were also identified during this process, although these attributes were not specifically investigated in the turn-signal analyses. Additional fields were used to flag exceptions, record notes, identify vehicles equipped with rear fog lamps, and reference photographs of sample lamps. An example data-entry screen is shown in Figure 5.

Table 4.
Definition of supplemental database fields used to describe rear signal configuration.

Grouping	Field Name	Values	Description
Model Year Span	Start Year	4-digit year	Many vehicles change signal lamp characteristics along with other styling changes.
	End Year	4-digit year > start year	
Turn Signal	Color	Red, Amber	
	Lens Color	Clear, Tinted	
	Source	Tungsten, LED	
	Optics	Lens, Reflector	
Brake Signal	Lens Color	Clear, Tinted	
	Source	Tungsten, LED	
	Optics	Lens, Reflector	
Tail Signal	Lens Color	Clear, Tinted	
	Source	Tungsten, LED	
	Optics	Lens, Reflector	
Rear Signal Separation	Configuration	e.g., S/T/TS, T	In the example, S = Stop Lamp, T = tail lamp (presence), and TS = Turn Signal. Separate lamp compartments are separated by commas. The example code identifies a rear-signal in which one compartment has combined stop, tail, and turn signal functions, and a separate compartment containing only the tail lamp.
		S,T,TS	All lamp functions separate.
		S/T/TS	All lamp functions combined.
		S/T, TS	Stop and Tail combined, Turn Signal separate.
		S/T, T, TS	Stop and Tail combined, Tail and Turn Signal separate.
		S/T, T/TS	Tail combined with separated Stop and Turn Signal.
		S/T/TS, T	All functions combined in one compartment, separate compartment for Tail.
		S/TS, T	Stop and Turn Signal combined, Tail lamp separate.
		S/T, S/T, TS	Two compartments with Stop and Tail combined; Turn Signal separate.
		S/T/TS, S/T	Stop, Tail, and Turn Signal combined, Stop and Tail combined.

Figure 5. Microsoft Access data entry form used to compile lamp characteristics of rear signal lamps.

Crash Scenario Selection and Data Processing

Crash records were initially obtained for Florida, Kentucky, Maryland, North Carolina, New Jersey, and Pennsylvania for CY2003 and Michigan CY2004. The analysis was later expanded to include data from CY2002 for New Jersey and North Carolina based on a power analysis that estimated the number of cases required to observe risk differences as small as 9 percent.

The VIN data from each State dataset was initially linked to the VINDICATOR 2005 dataset to produce a standard labeling for vehicle makes and series names. Each of the resulting State datasets was then examined to determine the extent of data loss that occurred as a consequence of VIN-decoding errors. Datasets varied in the accuracy with which the VIN is transcribed. Common reasons for a decoding error include: the recorded VIN is missing, is invalid, or has failed to match a series/model key in the VINDICATOR dataset. As shown in Table 2, the Florida and New Jersey datasets had the largest proportion of vehicle identification errors (about 40%); the North Carolina datasets had the fewest identification errors (8 to 9%).

Relevant and Non-Relevant Crashes. As described earlier, the key dependent measure in the logistic regression is an odds ratio that relates the odds of a *relevant* crash with respect to a *non-relevant* crash. In this analysis, *relevant* crashes used the following selection criteria:

- The crash was identified as a rear-end collision.
- Only two vehicles were involved in the collision. This was done to simplify the crash configuration so that each vehicle's role could be unambiguously determined.
- The lead (i.e., struck) vehicle was either described as changing lanes, merging, or turning. It is plausible to assume that the lead vehicle may have been using a turn signal prior to the maneuver, although it is clear that drivers often omit use of turn signals.
- One vehicle's impact location was identified as in the rear (struck); and the other vehicle's impact location was identified as in the front (striking). This restriction served to exclude crashes where both crash participants are identified as occurring in the same location. For this analysis, the characteristics of the lead vehicle's rear signals served as the basis of the relevant dataset.

In the logistic regression, the *non-relevant* dataset serves as a kind of exposure control helping to normalize the relevant crash data to the varying concentrations of vehicles on the roadway. Selection of a suitable basis for this control sample can introduce artifacts into an analysis that can obscure or even bias an outcome. For example, suppose the relationship between driver age (young/old) and risk of involvement in rear-end collisions were evaluated using another collision type—for example, single-vehicle road departure (SVRD)—as an exposure control. Systematic differences in the SVRD crash sample—especially related to a factor of interest, driver age—could lead to an erroneous conclusion.

In this analysis, two *non-relevant* datasets were developed. The first dataset used the same crash criteria employed in the *relevant* crash selections with the exception that the rear-signal characteristics were determined for the *striking* vehicle. It is thus assumed

that the rear signal characteristics of a striking vehicle play little role in these crashes and can serve as a reasonable measure of exposure. While there may be significant demographic differences between striking and struck drivers in this scenario, it is assumed that such differences are not systematically related to a driver's signal lamp characteristics.

The second *non-relevant* dataset was developed based on the analyses reported by Taylor and Ng (1981). In their analyses, *non-relevant* crashes were identified as rear-end collisions that did not involve turns, merges, or lane change maneuvers. Importantly, the authors identified the characteristics of the lead (struck) vehicle in these crashes. One potential difficulty with this approach is that if the turn signal characteristic of interest— amber versus red—somehow influences the salience of other rear signals, we might find that other rear-end collision types (i.e., those *not* necessarily involving turns, merges, or lane changes) are also affected. In this case, there is a chance that an amber turn signal might reduce both the *relevant* **and** *non-relevant* crashes. This would diminish the likelihood of observing an effect. The selection criteria for this dataset, referred to as *non-turning* crashes, applied the same selection criteria as described for the *Relevant* crash selection except that the lead vehicle maneuver was *not* described as turning, merging, or changing lanes.

Table 5 provides a breakdown of the rear-end crash scenarios and their distribution within each State dataset. For most of the States, *non-turning* crashes make up between 13 and 18 percent of all reported crashes; the *relevant* crashes make up between 1 and 2 percent of all crashes. Notably, Florida appears to be an outlier with proportionally less than half of the crash percentages found in the other State datasets. It is currently unclear what the basis of this difference is.

Table 5.
Frequency of all crashes and rear-end crashes involving two vehicles in which the struck vehicle was not turning, merging, or changing lanes, and two vehicles in which the struck vehicle was turning, merging, or changing lanes.

State	Year	Total Crashes	Two-Vehicle Rear-End Non-Turning (Non-Relevant Crashes)	Percent	Two-Vehicle Rear-End Turn, Merge, Lane Change (Relevant Crashes)	Percent
Florida	2003	243,294	17,991	7.4%	1,287	0.5%
Kentucky	2003	154,075	27,517	17.9%	2,219	1.4%
Maryland	2003	109,098	17,148	15.7%	1,131	1.0%
Michigan	2004	374,446	62,433	16.7%	4,552	1.2%
North Carolina	2002	285,135	50,346	17.7%	4,408	1.6%
North Carolina	2003	270,224	47,674	17.6%	4,427	1.6%
New Jersey	2002	324,053	59,017	18.2%	6,243	1.9%
New Jersey	2003	319,980	58,872	18.4%	6,514	2.0%
Pennsylvania	2003	139,402	18,279	13.1%	1,144	0.8%

Once the crash records of the two rear-end scenarios were selected (relevant and non-relevant), the VIN data of both the striking and struck vehicles in the turning/merging/lane changing rear-end collisions were matched to vehicles contained in the Rear Signal Database. Note that the Rear Signal Database contains only the most frequently occurring 50 vehicles among five CY 2003 State crash datasets (shown in Table 3). With this restriction, the overall vehicle sample size becomes smaller. The resulting breakdown by State is shown in the first two data columns of Table 6. The total vehicle count used in this analysis is approximately 13 times greater than included in the Taylor and Ng study (1981). The first two data columns of Table 7 shows the same data, collapsing over States and showing the breakdown by turn signal color and driver role in the collision.

A similar selection procedure was used to create a dataset comprised of rear-end crashes *not* involving turning, merging, or lane change maneuvers. This dataset served as a second *non-relevant* crash reference, similar to the striking drivers previously described. The resulting crash breakdown by state is shown in the third data column of Table 6, and the crash breakdown by turn signal color is shown in the third column of Table 7. An overview of the data processing steps is shown in Figure 6.

Table 6.
Crash counts by State and driver role in collision for each rear-end collision type.

State		Rear-end collisions while turning, merging, or changing lanes			Rear-end collisions not involving turning, merging, or changing lanes
		Struck (Rear Impact)		Striking (Front Impact)	Struck (Rear Impact)
Florida		361		285	4,904
Kentucky		812		676	10,525
Maryland		496		421	7,047
Michigan		1,478		1,276	19,900
North Carolina		3,163		2,756	36,289
New Jersey		3,398		2,839	31,098
Pennsylvania		382		336	5,972
Total		10,090		8,589	115,735

Table 7.
Breakdown of crash frequencies by signal lamp color, role in crash, and for each rear-end collision type.

| Signal Lamp Color		Rear-end collisions while turning, merging, or changing lanes			Rear-end collisions not involving turning, merging, or changing lanes
		Struck (Rear Impact)		Striking (Front Impact)	Struck (Rear Impact)
Amber		4,975		4,417	58,964
Red		5,115		4,172	56,771
Total		10,090		8,589	115,735
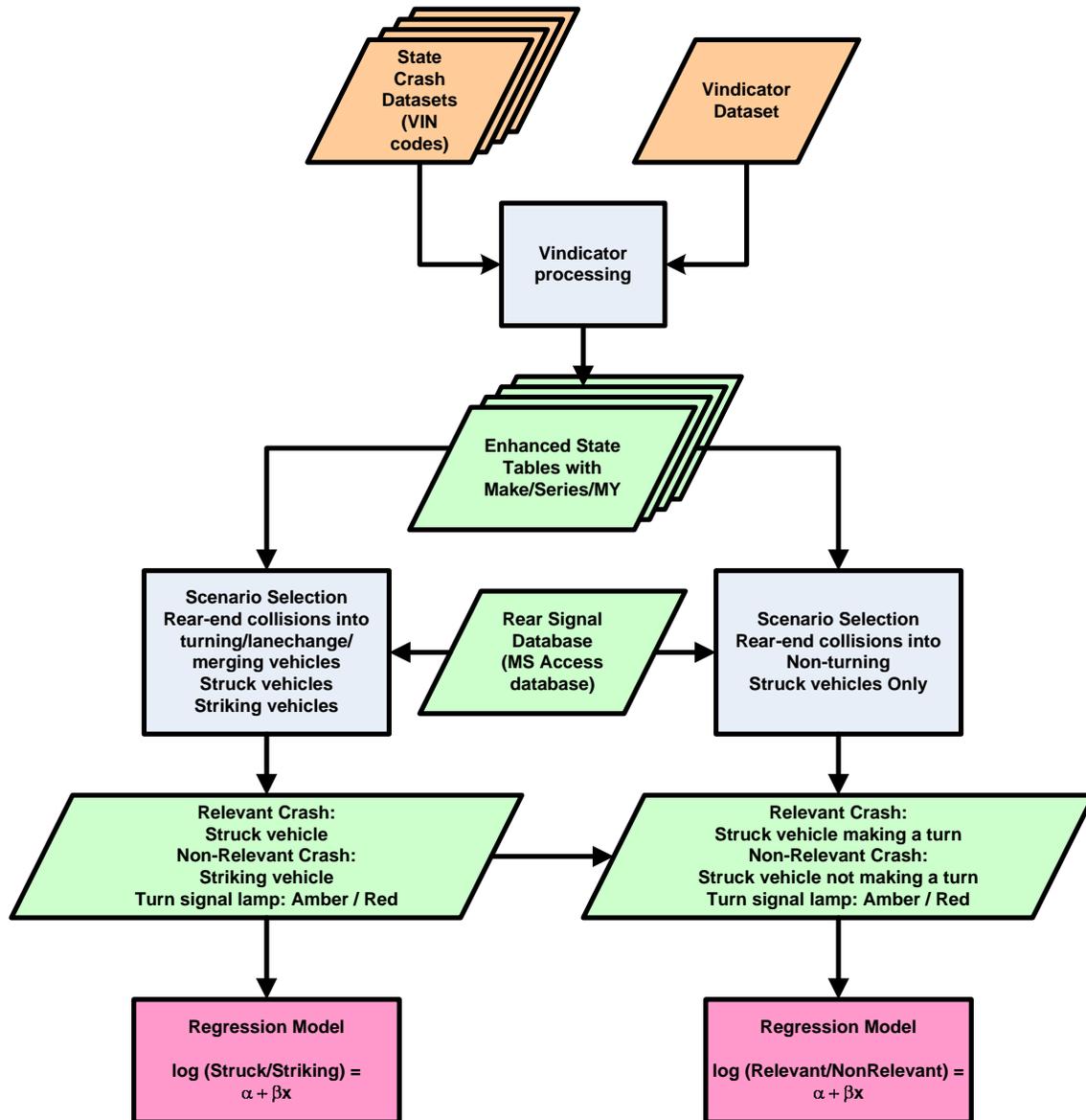
Figure 6. Overview of the data-processing steps that produced the datasets used in the regression analysis. Processes are drawn as rectangles; datasets are drawn as parallelograms. Orange datasets were supplied from external sources; green datasets were generated as part of this project.

Logistic Regression Models

Two response variables are defined in separate regression models. The first is the odds of being the struck vehicle versus the striking vehicle in a rear-end collision involving a vehicle turning, merging, or changing lanes (a *relevant* collision). The second response variable is the odds of being the struck vehicle in a *relevant* collision (as before) versus a *non-relevant* collision—a struck vehicle in a rear-end collision involving maneuvers that do not include turning, merging, or changing lanes. For each model, several variables in the datasets were identified as a potential influence on the odds of a crash. Each of these variables was identified and included in a logistic regression in which a stepwise selection procedure was employed which evaluated each variable with respect to its contribution to the predictive power of the model. Each variable was added to the model only if it produced a significantly better predictive model. As variables were added to the model, those already contained in the model were reevaluated and removed if they no longer contributed to the model's predictive power. Table 8 describes individual candidate variables included in the stepwise regression analysis and provides a rationale for their inclusion. Table 9 describes candidate interactions between variables that were also added to the same regression models. Interactions considered in each model included driver age with gender, light condition, and State; light conditions with each of the turn-signal lamp characteristics, and vehicle age with series name.

One reason so many variables were included in this analysis was that, as with any correlational analysis, many variables are likely to be indirectly related to each other. For example, younger drivers are more likely to drive older or less expensive vehicles; older drivers are more likely to drive luxury models. Amber turn signals are always physically separated from red stop lamps, but red turn signals may or may not be separated. In this latter example, to assess the importance of stop and turn signal separation, the model will only evaluate this variable using the red turn signal cases because there are no differences among the amber turn signals.

Table 8.
Main effect variables included in the logistic regression model.

Variable	Description
State	This is the State in which the crash occurred.
Light Condition	Because the conspicuity of signal lighting may interact with lighting conditions, light condition (light, dark) was included in the model. Conditions were classified as dark if the reported light conditions were "dark" or "dark with lights." Dawn, dusk, and unknown conditions were excluded from the analysis.
Gender	Reported gender of the driver.
Driver Age Group	This is a classification of the driver's age as either young (<30 years), middle (30-64 years), and old (>64 years).
Vehicle Age	This is a continuous variable computed as the calendar year of the crash minus the model year of the vehicle plus 1 (to avoid negative numbers from new vehicles with model numbers greater than the calendar year). Vehicle age at time of crash has been reported to have an inverse relationship to risk of rear end collision (e.g., Kahane & Hertz, 1998).
Series Name	This is the model name of the vehicle. It is used to account for factors that may influence crash risk within select populations of vehicle owners (e.g., Camaro owners are likely different from Civic owners).
Body Style	This variable is correlated with Series Name. It groups vehicles into the following broad body style categories: Luxury, Sports, Utility, 4-Door, 2-Door, Passenger Van, and Pickup. It was used as an alternate analysis level.
Turn Signal Color	Amber or Red. This is the signal lamp characteristic that identifies the color of the illuminated turn signal. It is the primary variable of interest in most prior studies.
Turn Signal/Stop Signal Separation	Yes / No. This variable identifies whether the turn signal shared a compartment with a brake signal. It is plausible that turn signal color may be less important than signal separation and only appears to be important because amber turn signals are by necessity separate from the stop signal.
Turn Signal/Tail Lamp Separation	Yes / No. This variable identifies whether the turn signal shared a compartment with a tail lamp. The rationale for this variable is similar to the rationale presented for the preceding variable.
Turn Signal Separation from All	Yes / No. This variable identifies whether a turn signal share any compartments with other lamps. If either of the two preceding variables is 'yes,' this variable will be 'yes.'
Turn Signal Source	LED / Tungsten. This variable identifies the illumination source of the lamp. Differences in the rise time of different signal sources could influence the conspicuity of a signal lamp.
Turn Signal Optics	Lens / Reflector. This variable identifies whether the light distribution from a signal lamp is controlled by a faceted lens, or by a silver reflector. A signal lamp that employs reflector optics passes light through a smooth lens.
Turn Signal Lens Color	Clear / Tinted. This variable identifies whether the turn signal lens is clear or tinted. In the case of a clear lens, the lamp color is produced by a tinted bulb. In daylight, the non-energized clear-lens lamp appears silver and can reflect ambient sunlight. This can reduce the contrast between off and on states.

Table 9
Interaction terms included in the logistic regression model.

Interactions Between	Secondary variables	Description
Driver Age Group	Gender	Young male drivers are often identified as an especially aggressive group. The rationale for including this interaction is that crash risk may be affected by gender differences more among younger drivers than older drivers.
	Light Condition	Crash risk may interact with driver age and light conditions if, for example, older drivers disproportionately avoid driving in darkness.
	State	Driver age distribution among states may not be homogeneous. For example, there may be an observed higher crash risk among older drivers in Florida than in New Jersey.
Light Condition	Turn Signal Color	The rationale for modeling the interaction between light conditions and each of the lamp characteristics is that it is plausible that the influence of any lamp attribute on crash odds could differ under different ambient light conditions.
	Turn Signal/Stop Signal Separation	
	Turn Signal/Tail Lamp Separation	
	Turn Signal Separation from All	
	Turn Signal Source	
	Turn Signal Optics	
	Turn Signal Lens Color	
Vehicle Age	Series Name	The rationale for this interaction is that as a vehicle ages, changes in vehicle function and ownership demographics may influence crash odds.

Results

Analysis 1: Log Odds of Struck/Striking Role

The results of each logistic regression will be presented in a tabular form in which the selected effects will be presented along with parameter estimates of each variable. In the interest of clarity, estimates are not reported for variables in which many levels are identified—e.g., vehicle series name (50 levels), vehicle body style (8 levels), and State (7 levels). Such variables have been included in this analysis to effectively account for the influence these factors have on the resulting odds ratio so that the effects of interest—turn signal lamp characteristics—can be clearly observed. The results of the analysis are shown in Table 10. The part of the regression model related to the lighting configuration fits into the regression as follows:

Predicted logit of Struck =	**Parameter**
0.0496	(Intercept)
+(0.2976)(FEMALE)	(Gender)
+(.5962)(MIDDLE) or (0.6733)(OLD)	(Age)
+(0.1105)(DARK)	(Light Condition)
+(0.0475)(Middle-aged and Female) or (-0.3399)(Old and Female)	(Age x Gender)
+(-0.0434)(Vehicle Age)	(Vehicle Age)
+(0.3308)(Accord 4D) or (-0.2248)(Altima 4D) or (β estimate for Series Name)(presence of Series Name)	(Series Name)
+(-0.0259)(VehicleAge)(Accord 4D) or (0.0370)(Vehicle Age)(Altima 4D) or (β estimate for Series Name x Age interaction)(Vehicle Age)(Series Name)	(Vehicle Age x Series Name)
+(-0.1786)(AMBER)	(Signal Color)
+(-1.4431)(LED)	(Signal Source)

Thus it appears that amber rear turn signals are associated with a smaller odds of a being struck in a rear-end turning crash than red turn signals; likewise it also appears the LED-based turn signals are associated with a even greater reduction in odds of being struck compared with the odds found with tungsten light sources. The 95 percent confidence interval on the odds ratio associated with turn signal color is 0.72 to 0.97. Reinterpreted as the estimated percent crash reduction effect of amber versus red (reported in previous analyses), this is equivalent to an estimated reduction of between 3 and 28 percent.

The observed effect of turn signal light source is substantially larger than observed for turn signal color. The 95 percent confidence interval on the odds ratio associated with source is 0.083 and 0.673. Interpreted as an estimated percent crash reduction associated with using LED versus tungsten turn signals, this is equivalent to an estimated reduction of between 33 and 92 percent. While the size of the effect appears to be dramatically large, the confidence interval is also wide, suggesting that the result is based on a small portion of the sample data. On further examination of the sample of vehicles contributing to this analysis, it was found that virtually all the samples of LED turn signals were from the 2000-2005 Cadillac DeVille. Essentially, the analysis compared the rear-end collision odds of the 2000-2005 Cadillac DeVille (equipped with LED turn signals) to the same odds for 1991 to 1999 version of the DeVille (equipped with tungsten turn signals). Despite the general trend for older model vehicles to decline

in their rate of being struck in rear-end collisions, it appears that the newer model DeVilles, equipped with LEDs, buck this trend. Given that the LED effect is based on the implementation in one vehicle model line, it would be inappropriate to generalize this result to all LED turn signal implementations.

Also found was an association between gender and crash odds—female drivers have a greater odds of being struck than male drivers (conversely, male drivers have a greater odds of playing a striking role). Similarly, older and middle aged drivers have greater odds of being struck than younger drivers. There is also an interaction between age and gender—middle-aged female drivers demonstrated an especially greater risk of being struck (or conversely, they demonstrate an especially low risk of striking).

Table 10

Logistic regression analysis of the odds of struck role in a rear-end collision involving a lead vehicle turning, merging, or changing lanes. Series name and series name by vehicle age interactions were omitted from the table.

Predictor	β	SE β	Wald's χ^2	df	p	e^β Odds Ratio
Constant (intercept)	0.0496	0.34	0.02	1	0.88	1.05
Gender (Male = 0, Female = 1)	0.2976	0.05	34.77	1	< .0001	1.35
Age Group (Young = 0)						
Middle	0.5962	0.05	167.77	1	< .0001	1.82
Old	0.6733	0.08	70.90	1	< .0001	1.96
Light Condition (Light = 0, Dark = 1)	0.1105	0.04	7.25	1	0.01	1.12
Gender x Age Group (Young, Male = 0)						
Middle, Female	0.0475	0.07	0.51	1	0.48	1.05
Old, Female	-0.3399	0.12	8.13	1	0.00	0.71
Vehicle Age	-0.0435	0.05	0.83	1	0.36	0.96
Turn Signals						
Color (Red = 0, Amber = 1)	-0.1786	0.08	5.61	1	0.02	0.84
Source (Tungsten = 0, Led = 1)	-1.4431	0.53	7.30	1	0.01	0.24
			χ^2	df	p	
Model evaluation						
Likelihood ratio test			792.12	117	< .0001	
Score test			778.93	117	< .0001	
Wald test			749.78	117	< .0001	
Goodness of fit test						
Hosmer and Lemeshow			4.25	8	0.834	
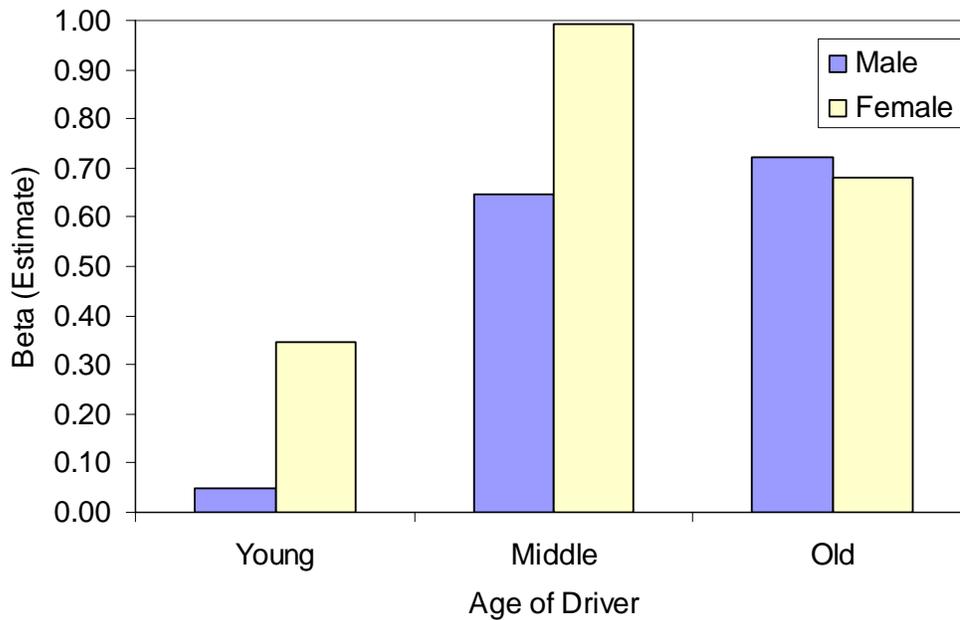
Figure 7. Interaction effect between gender and driver age. The estimate reflects the sum of the estimates for each condition; the larger the estimate, the greater the odds of being the struck driver in a rear-end collision; the lower the estimate, the greater to odds of being the striking driver.

The Influence of Other Turn Signal Characteristics. While an effect of lamp color was observed in the preceding analysis, this does not necessarily preclude the influence of lamp separation on crash odds, although it suggests that lamp color is a better predictor of the observed odds ratio. If lamp color is excluded from the analysis, then separation of the turn signal from the tail lamp becomes a significant predictor, albeit weaker (see Table 11).

The color/separation issue was further explored in a separate analysis of the effect of turn signal separation among vehicles equipped with red turn signals; and in an analysis of the effect of color among vehicles equipped with separated signal lamps. Lamp separation was a poor predictor of crash odds among vehicles equipped with red turn signals (Wald $\chi^2 = 0.93$, $df=1$, $p = .33$); and turn-signal color was a poor predictor among vehicles equipped with separated lamps (Wald $\chi^2 = 2.07$, $df=1$, $p = .15$). The odds ratio estimates, although unreliable, suggest that color might be more influential on the crash odds than lamp separation—the observed reduction for amber is about 18 percent, for separated lamps it is 11 percent.

Table 11
Logistic regression analysis of the odds of struck role in a rear-end collision involving a lead vehicle turning, merging, or changing lanes, excluding lamp color as a predictor. Note that turn signal separation, a factor correlated with lamp color, becomes a predictor of the odds ratio. (As in Table 10, series name and series name by vehicle age interactions are omitted from this table).

Predictor	β	SE β	Wald's χ^2	df	p	e^{β} Odds Ratio
Constant (intercept)	0.0696	0.34	0.04	1	0.84	1.07
Gender (Male = 0, Female = 1)	0.2980	0.05	34.85	1	< .0001	1.35
Age Group (Young = 0)						
Middle	0.5951	0.05	167.24	1	< .0001	1.81
Old	0.6733	0.08	70.90	1	< .0001	1.96
Light Condition (Light = 0, Dark = 1)	0.1107	0.04	7.28	1	0.01	1.12
Gender x Age Group (Young, Male = 0)						
Middle, Female	0.0491	0.07	0.54	1	0.46	1.05
Old, Female	-0.3402	0.12	8.14	1	0.00	0.71
Vehicle Age	-0.0479	0.05	1.06	1	0.32	0.95
Turn Signals Separation						
Tail Lamp (No = 0, Yes = 1)	-0.1480	0.08	3.89	1	0.05	0.86
Source (Tungsten = 0, Led = 1)	-1.4431	0.53	7.30	1	0.01	0.24
			χ^2	df	p	
Model evaluation						
Likelihood ratio test			790.41	117	< .0001	
Score test			777.20	117	< .0001	
Wald test			748.04	117	< .0001	
Goodness of fit test						
Hosmer and Lemeshow			3.76	8	0.878	

Table 12
Cases identifying turn signal separation from stop lamp and tail lamps. Note that combined signals are not possible with amber turn signals.

			Tail Separate From Turn Signal			Stop Lamp Separate From Turn Signal	
			Yes	No		Yes	No
Lamp Color	Amber		9,392	0		9,392	0
	Red		2,389	6,898		2,633	6,654

Analysis 2: Log Odds of Relevant/Non-Relevant Collisions

In this model, instead of employing striking vehicles as the contrast group to computing odds, vehicles struck in non-turning (*non-relevant*) collisions were employed. That is, the odds are the number of vehicles stuck while attempting to turn, merge, or change lanes (a *relevant* crash) divided by the number vehicles involved in *non-relevant* collisions. As mentioned earlier, this duplicates the analysis approach taken in previously published reports. For this measure, no relationship between the odds of a *relevant* crash and turn signal color or source was found. Perhaps turn-signal color and source influence many kinds of rear-end collision types—both *relevant* and *non-relevant* crashes alike—effectively obscuring the influence. Indeed, in the case of the 2000-2005 Cadillac DeVille, both the brake lamp *and* turn-signal sources are LEDs. It is probable that on any given vehicle, the characteristics of a rear turn-signal are related to the characteristics of other rear signals. Use of the *relevant/non-relevant* odds ratio seems to assume the effect of turn signal is independent of the effect of brake signal. Consequently, the remaining analyses in this report will resume use of the logit of the odds of playing the struck role in a relevant rear-end collision as the response variable for each model.

The odds of a *relevant* crash were associated with turn signal optics. Vehicles with reflector optics appear less likely to be involved in *relevant* collisions with lens optics. This translates to an approximately 32-percent reduction in the odds of involvement in *relevant* crashes with reflector optics compared to lens optics (95% CI = 5 to 51%). It is unclear why this happens, although the sample of vehicles equipped with reflector optics is small (0.8% of the sample) and seems to be dominated by late-model (1999-2004) Ford Mustangs, driven by young drivers (58%—18% female, 40% male). As discussed earlier with respect to the LED finding in the first analysis, it seems inappropriate to generalize this particular result to all rear turn signals equipped with reflector optics.

The difference between this analysis and the first one suggests that selection of a contrast group can influence the observed effects. In this case, an influence of turn signal color is present in the first analysis and absent in the second. One reason for its absence in the second analysis might be that both the crash-relevant group (rear-end collisions into vehicles making turn-signal-relevant maneuvers) and the contrast group (rear-end collisions into vehicles *not* making turn-signal relevant maneuvers) are similarly affected by the rear turn signal configuration. Rear signals are visible for both crash groups, and this allows the possibility that rear signal characteristics might both enhance turn-signal conspicuity as well as stop-lamp conspicuity. Thus, if both the relevant crash group and the contrast group are similarly affected by rear signal characteristics, no effect would be observed in the logistic regression. On the other hand, the first analysis using the striking driver's vehicle as a contrast group seems to remove the possibility that the striking crash could be influenced by the rear signals—they are completely out of the striking driver's direct sight. Consequently, the first analysis is preferred to the second analysis.

Table 13.
Logistic regression analysis of the odds that a vehicle is making a tuning, merging, or lane change maneuver in a rear-end collision. Series name effects (50 total) were omitted from the table.

Predictor	β	SE β	Wald's χ^2	df	p	e^{β} Odds Ratio
Constant (intercept)	-2.9646	0.102	847.99	1	< .0001	0.052
State (PA = 1)						
Florida	0.1447	0.078	3.41	1	0.065	1.156
Kentucky	0.1856	0.066	7.95	1	0.005	1.204
Maryland	0.1288	0.072	3.23	1	0.072	1.137
Michigan	0.2019	0.061	10.95	1	0.001	1.224
North Carolina	0.336	0.058	33.43	1	< .0001	1.399
New Jersey	0.5947	0.058	107.13	1	< .0001	1.812
Gender (Male = 0, Female = 1)	0.1338	0.022	34.45	1	< .0001	1.143
Age Group (Young = 0)						
Middle	-0.0406	0.025	2.71	1	0.0998	0.96
Old	0.2129	0.043	24.75	1	< .0001	1.237
Vehicle Age	0.0335	0.004	94.32	1	< .0001	1.034
Turn Signals						
Optics (Lens = 0, Reflector = 1)	-0.3868	0.17	5.13	1	0.024	0.679
			χ^2	df	p	
Model evaluation						
Likelihood ratio test			639.86	65	< .0001	
Score test			641.90	65	< .0001	
Wald test			634.22	65	< .0001	
Goodness of fit test						
Hosmer and Lemeshow			13.73	8	0.089	

Analysis 3: Vehicles grouped by body style

In this analysis, vehicle body style was substituted for vehicle series name using VINDICATOR's vehicle body style field. The grouping generally collected together similar vehicles (e.g., passenger vans: Dodge Caravan and Ford Windstar; utility vehicles: Ford Explorer, Jeep Grand Cherokee, Chevy Blazer), although the 2- and 4-door vehicle categories did not distinguish differences in vehicle size (e.g., a Ford Escort and Pontiac Grand Am were classified together as 2-door vehicles). Vehicle groupings are shown in Table 14 along with turn signal color breakdowns.

The analysis (shown in Table 15) suggests that the 4-door vehicles and passenger vans are not particularly different from the 2-door comparison group with respect to the odds of being the struck vehicle in *relevant* rear-end collisions. Luxury vehicles appear to be more likely to play the struck role; while pickup trucks, sports cars, and utility vehicles are less likely to be the struck vehicle.

The pattern of association between the rear turn-signal characteristics and the odds of being struck in *relevant* rear-end collisions is similar to the pattern reported for Model 1. That is, there is an effect of lamp color such that amber turn signals appear to be associated with reduced odds of rear-end collision. The 95-percent confidence interval on the odds ratio associated with turn signal color is 0.87 to 0.99—a weaker influence than previously seen. The equivalent percent crash reduction associated with amber lamps would be between 1 and 13 percent.

The observed effect of turn signal light source is, like before, larger than turn signal color. The 95-percent confidence interval on the odds ratio associated with LED (versus tungsten) light sources is 0.25 to 0.81. Interpreted as an estimated percent crash reduction associated with LED turn signal sources, this would be equivalent to an estimated reduction of between 19 to 75 percent.

Overall, the body style variable produced a less powerful model (indicated by the higher goodness-of-fit score χ^2 in the Hosmer and Lemeshow test), and possibly absorbed some of the predictive power formerly attributed to turn signal characteristics.

Table 14
Breakdown of the vehicle sample by body style and turn signal color.

Body style	Series Name	Turn Signal Color		Total
		Amber	Red	
2-Door	ACCORD 2D	93	127	220
	CAVALIER 2D		369	369
	CIVIC 2D COUPE	295	120	415
	ECLIPSE 2D 2WD		171	171
	ESCORT 2D	69	108	177
	GRAND AM 2D	40	105	145
	THUNDERBIRD 2D		136	136
2-Door Total		497	1,136	1,633
4-Door	626 SEDAN	265		265
	810/MAXIMA SEDAN	356	5	361
	ACCORD 4D	1,308		1,308
	ALTIMA 4D	444	102	546
	CAMRY 4D 2WD	997		997
	CAVALIER 4D		372	372
	CENTURY 4D		325	325
	CIERA 4D		127	127
	CIVIC 4D	350	155	505
	CONTOUR 4D		238	238
	COROLLA SEDAN 2WD	727		727
	ELANTRA 4D	164		164
	ESCORT 4D	103	224	327
	FOCUS 4D		252	252
	GALANT 4D 2WD	82	146	228
	GRAND AM 4D	83	325	408
	GRAND PRIX 4D	64	182	246
	INTREPID 4D	133	136	269
	JETTA SEDAN	130		130
	LESABRE 4D		258	258
	LTD/CROWN VICTORIA 4D	97	161	258
	LUMINA 4D		331	331
	MALIBU 4D	295	4	299
	MARQUIS/G. MARQ. 4D		185	185
	NEON 4D		316	316
	SABLE 4D	4	291	295
	SENTRA 4D	374	3	377
	SL 4D	446		446
	STRATUS 4D	132	81	213
	TAURUS 4D	131	783	914
4-Door Total		6,685	5,002	11,687

Table 14. (continued)
Breakdown of the vehicle sample by body style and turn signal color.

| Body Style | Series Name | Turn Signal Color | | |
		Amber	Red	Total
LUXURY	DEVILLE 4D FWD		237	237
	TOWN CAR/CONT. 4D		203	203
LUXURY Total			440	440
PASSENGER VAN	CARAVAN VAN 2WD		322	322
	GRAND CARAVAN 2WD		397	397
	WINDSTAR VAN	351		351
PASSENGER VAN Total		351	719	1,070
PICKUP	10/1500 PU 1/2T	2	127	129
	F150 PICKUP 4X2		252	252
	F150 SUPER PU 4X2		52	52
	RANGER PICKUP 4X2	233	77	310
	RANGER SUPER PU 4X2	146	70	216
	S10 PICKUP 4X2		290	290
PICKUP Total		381	868	1,249
SPORTS	CAMARO 2D		97	97
	MUSTANG 2D	84	264	348
SPORTS Total		84	361	445
UTILITY	CHEROKEE 4D 4X4	332		332
	EXPLORER 4D 4X2	92	70	162
	EXPLORER 4D 4X4	328	306	634
	GRAND CHEROKEE 4D 4X4	642		642
	T10 BLAZER 4D 4X4		368	368
UTILITY Total		1,394	744	2,138
Grand Total		9,392	9,287	18,662

Table 15

Logistic regression analysis of the odds of struck role in a rear-end collision involving a lead vehicle turning, merging, or changing lanes.

Predictor	β	SE β	Wald's χ^2	df	p	e^{β} Odds Ratio
Constant (intercept)	-0.0702	0.068	1.08	1	0.30	0.93
Gender (Male = 0, Female = 1)	0.3074	0.05	38.02	1	< .0001	1.36
Age Group (Young = 0)						
Middle	0.5781	0.05	164.50	1	< .0001	1.78
Old	0.6544	0.08	71.87	1	< .0001	1.92
Light Condition (Light = 0, Dark = 1)	0.1059	0.04	6.78	1	0.009	1.11
Gender x Age Group (Young, Male = 0)						
Middle, Female	0.06	0.07	0.82	1	0.364	1.06
Old, Female	-0.3305	0.12	7.83	1	0.005	0.72
Vehicle Age	-0.0289	0.004	39.87	1	< 0.0001	0.97
Vehicle Body style (2-Door = 0)						
4-Door	-0.0194	0.058	0.1133	1	0.7365	0.981
Luxury	0.3803	0.126	9.0717	1	0.0026	1.463
Passenger Van	-0.0436	0.086	0.2593	1	0.6106	0.957
Pickup	-0.2629	0.081	10.4646	1	0.0012	0.769
Sports (versus 2-Door)	-0.2701	0.115	5.5095	1	0.0189	0.763
Utility (versus 2-Door)	-0.1968	0.071	7.5903	1	0.0059	0.821
Turn Signals						
Color (Red = 0, Amber = 1)	-0.0734	0.033	5.0078	1	0.0252	0.929
Source (Tungsten = 0, Led = 1)	-0.7979	0.302	6.9642	1	0.0083	0.45
			χ^2	df	p	
Model evaluation						
Likelihood ratio test			604.430	15	< .0001	
Score test			597.663	15	< .0001	
Wald test			581.789	15	< .0001	
Goodness of fit test						
Hosmer and Lemeshow			7.359	8	0.4984	

Analysis 4: Turn-signal color changes within models

This analysis included vehicle models in which amber and red turn signals appeared on the same model in different model years spanning 1990 to 2005. Models that have had exclusively amber turn signals or exclusively red turn signals throughout their model history were excluded from this analysis. For example, in 1996, the styling on the Ford Taurus was redesigned to use amber turn signals in anticipation of marketing the vehicle to European customers. The styling was given a minor revision in 1998—the amber lens was replaced by a red lens. The next major styling change occurred in the 2000 model year. This evolution is shown in Figure 8. An analysis of within-model signal lamp change may help control factors related to driver demographics that may differ between models. That is, there are likely to be greater similarities between two drivers of the same vehicle model with differently colored turn signals, than there are between two drivers of different models with differently colored turn signals. Use of the series name variable helps account for such differences, allowing the variables associated with lamp characteristics to shine through.

As before, the results suggest that the odds of being the struck vehicle in a *relevant* rear-end collision are smaller with amber turn signals than with red turn signals. The odds ratio of amber versus red turn signals is 0.785. Reinterpreting this effect estimate as a percent crash reduction, the use of amber turn signals may reduce the risk of rear end collision by about 22 percent. A 95-percent confidence interval places the lower and upper bound of this estimate between 12 and 30 percent. Driver age and gender were also strongly associated with the odds of being struck. The odds ratio of female to male drivers was 1.35; the odds ratio of middle to younger-aged drivers is 1.83, and older to younger-aged drivers is 1.84. Finally, a relationship was also observed between the vehicle series name and the odds of being struck, suggesting that vehicle series contributed some predictive power to the model.

Figure 8. Changes in turn signal color within the Ford Taurus from 1990 to 2003.

Table 16.
Logistic regression analysis of the odds of struck role in a rear-end collision involving a
lead vehicle turning, merging, or changing lanes examining only vehicle models in which
the turn signal color was changed within the model's lifespan.

Predictor	β	SE β	Wald's χ^2	Df	p	e^β Odds Ratio
Constant (intercept)	-0.2058	0.123	2.802	1	0.094	0.814
Gender (Male = 0, Female = 1)	0.2968	0.050	35.791	1	< .0001	1.350
Age Group (Young = 0)						
Middle	0.6042	0.051	140.037	1	< .0001	1.830
Old	0.6111	0.102	36.080	1	< .0001	1.842
Vehicle Series (Escort 4D = 0)						
10/1500 PU 1/2T	-0.3948	0.221	3.1944	1	0.0739	0.674
810/MAXIMA SEDAN	0.0107	0.166	0.0042	1	0.9484	1.011
ACCORD 2D	0.1836	0.186	0.9747	1	0.3235	1.202
ALTIMA 4D	0.0729	0.151	0.235	1	0.6279	1.076
CIVIC 2D COUPE	0.1474	0.159	0.856	1	0.3548	1.159
CIVIC 4D	0.3636	0.153	5.6567	1	0.0174	1.439
ESCORT 2D	-0.0767	0.195	0.1551	1	0.6937	0.926
EXPLORER 4D 4X2	-0.0673	0.203	0.1102	1	0.7399	0.935
EXPLORER 4D 4X4	-0.4114	0.145	8.0957	1	0.0044	0.663
GALANT 4D 2WD	0.1635	0.185	0.7843	1	0.3758	1.178
GRAND AM 2D	-0.0957	0.210	0.2081	1	0.6483	0.909
GRAND AM 4D	0.0040	0.157	0.0007	1	0.9795	1.004
GRAND PRIX 4D	-0.1015	0.178	0.3244	1	0.5689	0.904
INTREPID 4D	-0.062	0.175	0.1259	1	0.7228	0.94
LTD/CROWN VICTORIA 4D	-0.336	0.178	3.5507	1	0.0595	0.715
MALIBU 4D	0.3181	0.175	3.2936	1	0.0695	1.375
MUSTANG 2D	-0.3669	0.165	4.9639	1	0.0259	0.693
RANGER PICKUP 4X2	-0.2173	0.171	1.6231	1	0.2027	0.805
RANGER SUPER PU 4X2	0.1513	0.187	0.6526	1	0.4192	1.163
SABLE 4D	0.0379	0.172	0.0486	1	0.8256	1.039
SENTRA 4D	0.138	0.165	0.6961	1	0.4041	1.148
STRATUS 4D	0.0079	0.189	0.0017	1	0.9668	1.008
TAURUS 4D	0.032	0.137	0.0548	1	0.8149	1.032
Turn Signals						
Color (Red = 0, Amber = 1)	-0.2425	0.059	16.961	1	< .0001	0.785
			χ^2	Df	p	
Model evaluation						
Likelihood ratio test			290.278	27	<.0001	
Score test			286.235	27	<.0001	
Wald test			277.546	27	<.0001	
Goodness of fit test						
Hosmer and Lemeshow			9.9706	8	0.2671	

Conclusions

With any regression analysis, one should remember that merely finding a relationship between a variable and a response measure does not demonstrate that the variable caused the response. In the preceding analysis, a relationship seems to exist between turn signal color and the odds of involvement as the struck vehicle in rear-end collisions. Changing the color of a turn signal from red to amber appears to reduce the odds of being struck by 3 to 28 percent. The exact mechanism responsible for this, however, is unclear.

Although rear turn-signal color is implicated, it is important to recognize that signal color is also confounded with other factors that may contribute to this relationship. For example, if signal lamp color is dropped from the regression model, turn-signal/tail-lamp separation becomes a predictor, albeit weaker. It is also important to recognize that the lamp characteristics included in the logistic regressions are incomplete. It is plausible that characteristics of the light output of amber and red signal lamps differ in systematic ways. Perhaps an amber turn signal appears brighter than a red one. Although prior evidence (Mortimer & Sturgis, 1974) suggests that a red lamp is more conspicuous than an amber one, this evidence was collected under static viewing conditions that are quite different from the conditions drivers typically face on a roadway where the signal lamps are likely first detected in the peripheral visual field. Does a red lamp still look more conspicuous than an amber lamp when offset 10 degrees from the direction of gaze? If this is true, then the differences observed between red and amber may not be so much related to differences in color as it is to differences in lamp brightness.

The results also show that the choice of comparative data can also influence the observed results. Using lead vehicles involved in *non-relevant* rear-end collisions (with respect to turn-signal operations) as comparative data, Analysis 2 did *not* find any relationship between color and the odds of involvement in a relevant crash. This suggests that the *non-relevant* crash data may have not been as non-relevant as previous researchers believed. Whatever influences a specific turn signal characteristic may have had on a driver's ability to detect and react to a turning or merging lead vehicle, that same characteristic could have also influenced the detectability of other (perhaps non-relevant) maneuvers of a lead vehicle. This *influence crosstalk* between the target and reference datasets could diminish the chance of observing an influence of a rear signal characteristic on the odds of a particular crash. Instead, the reference group should share as many similarities as possible with the target group except that the variables of specific interest—the rear signal lamp characteristics—should play no conceivable role in the reference group crashes.

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