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Factors That Influence Multivehicle Rear-End Crashes: Analysis of Crash Propagation and Injury Severity

FACTORS THAT INFLUENCE MULTIVEHICLE REAR-END CRASHES: ANALYSIS OF CRASH PROPAGATION AND INJURY SEVERITY

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EXECUTIVE SUMMARY

Multi-vehicle rear-end crashes constitute a significant portion of the total crashes in the United States. Information and early warning about the vehicle stream ahead can reduce the possibility of such crashes and given a crash the injury severity of occupants. The objective of this study is to examine the effect of information and other factors on rear-end crash propagation and the propensity of driver injury in such crashes. We also explore the implications of our findings for developing early warning systems.

In a platoon of vehicles, the following drivers avoid striking the leading vehicles, by processing the braking and speed information received from the conventional taillights and the Center High Mounted Stoplight (CHMSL) of the directly leading vehicles. Moreover, to receive early warnings, some drivers monitor CHMSL on other leading vehicles. Only if the vehicle directly leading is "transparent," will the driver be able to observe the CHMSL on other leading vehicles. Such monitoring can provide early warning of braking and other events and reduce the chances and severity of collisions. This study examines the effect of CHMSL and transparency or opaqueness of leading vehicles, while controlling for driver, vehicle and roadway/environmental factors. The literature has found a link between the presence of CHMSL and a 4% to 8% reduction in rear-end crashes. This study complements earlier efforts by exploring the effect of driver information on crash propagation from two to three vehicles and directly analyzes information effects on changes in injury severity.

Real-life crash and inventory data on two-vehicle and three-vehicle rear-end crashes are analyzed. The study is based on a 1994-1995 Highway Safety Information System (HSIS) database for North Carolina limited-access roadways (N=3912 crashes; 12.5% three-vehicle rear-end collisions). Only passenger cars, vans, pickup trucks and station wagons (trucks and cars) involved in rear-end crashes are considered. Passenger cars constitute the largest portion of vehicles on these limited-access roadways and they are usually transparent compared with vans, pickup trucks and station wagon trucks that are often larger and opaque. Therefore, vehicle type is also used as a measure of whether a vehicle is transparent or opaque. To measure the presence of CHMSL, an indicator variable for vehicle model year was created. Passenger car and station wagon car models of 1986 or later and van, pickup truck and station wagon truck models of 1994 or later have mandatory CHMSL. While this variable captures the CHMSL effect, it may also contain the effects of other technology improvements that can reduce rear-end crash propagation and injury severity. These crash data provide greater realism (compared with hypothetical or driver reported data, for example), but the measures for driver information also contain other effects.

The analysis indicates that there is no statistical evidence to link the presence of CHMSL with lower crash propagation. That is, CHMSL are not necessarily more effective in rear-end crashes involving three-vehicles compared with two-vehicles. However, we found that passenger cars are less likely to be struck (in position 1) than to strike. Vans, pickup trucks and station wagons are more likely to strike (in positions 2 or 3). This is consistent with the hypothesis that drivers may respond to information from two or more vehicles ahead. The results on injury severity in rear-end crashes show that in a two-vehicle crash, the leading driver is more likely to be injured, whereas, in a three-vehicle crash, the driver in the middle is likely to be more severely injured. Furthermore,

as rear-end crashes propagate from two-vehicle to three-vehicles the last driver is relatively less severely injured. To analyze injury severity on the KABCO scale, ordered probit models were estimated. The CHMSL variable used in three separate models estimated for Driver 1, 2 and 3 injuries is statistically significant. The presence of CHMSL on Vehicle 1 (and other safety improvements in recent years) provides protection in rear-end collisions to Driver 1 (8.7% reduction in injuries); its presence on Vehicle 2 protects Driver 2 (3.5% reduction in injuries). Interestingly, the presence of CHMSL on Vehicle 1 can reduce Driver 2 injuries by as much as 2.6% and Driver 3 injuries by 6.5%. Thus the presence of CHMSL on Vehicle 1 not only protects the Driver of Vehicle 1, but it also reduces Driver 2 and Driver 3 injuries. The drivers of vans, pickup trucks and station wagon cars/trucks that are struck in position 1 have 11.0% lower chances of getting injured compared with passenger car drivers. Drivers of vans, pickup trucks and station wagon cars/trucks that strike (in position 2) have a 4.6% lower chance of injury. Thus, vans, pickup trucks and station wagons provide greater driver protection to drivers when struck compared to when they strike another vehicle (although in both cases they are less likely to be injured than passenger car drivers). This result indicates that the vehicle mass effect exceeds the information blocking effect of larger vehicles. Furthermore, it was found that being struck by a larger vehicle (van, pickup truck or station wagon) is more injurious than striking a larger vehicle. Street lighting mitigated the increased injury severity of nighttime crashes and males were consistently more severely injured in rear-end crashes, despite fewer of them getting involved in such crashes. Finally, the implications of our results for new safety technologies are discussed.

SECTION 1: BACKGROUND

Multi-vehicle rear-end crashes constitute 15%-20% of the total vehicles damaged on roadways in the United States. With increased speed limits, and urban area traffic moving bumper-to-bumper at high speeds (often with less than the recommended headway), rear-end multi-vehicle crashes may increase in the future. Measures that can reduce such crashes include drivers receiving information from existing technologies such as conventional taillights and the Center High Mounted Stoplight (CHMSL) and new Intelligent Transportation systems (ITS) early warning devices. Research on the impact of CHMSL suggests a 17% reduction in rear-end crashes for vehicles equipped with CHMSL (Evans 1991). However, to our knowledge, the literature has not examined the full extent of information impacts as some drivers may also monitor CHMSL on vehicles ahead of the one they are directly following and receive early warnings. Such early warnings can be particularly beneficial for drivers with longer reaction times in terms of reduction in rear-end crash propagation and injury severity, given a crash. The research question is: What role does driver information play in rear-end crash propagation and driver injury severity? Although not directly investigated in this study, the analysis explores how information received through ITS warning devices may reduce crash propagation and injury severity. The unique features of this study are:

- The investigation of information effects on rear-end crash propagation while controlling for other driver, vehicle, roadway and crash factors.
- Analysis of driver information effects on the whole spectrum of driver injury severity measured on the KABCO scale. That is, the study examines how driver information (through shorter response times) can reduce injury crashes to non-injury crashes.

Literature

Typically, driver, vehicle and roadway/environment characteristics influence crash occurrence and injury severity. In rear-end collisions, initial headway between lead and following vehicles and the deceleration rates of lead and following vehicles determine collision propensity. The following driver's decision to decelerate depends on the information regarding conditions and events in front. The important aspects of information received by the driver are its content, medium and accuracy. Two key sources of information are the conventional taillights and CHMSL of the leading vehicles. When red taillights turn on, they convey to the following driver that the leading vehicle is braking. The physical location of the light source and its intensity are important elements. The accuracy of information conveyed by conventional brake lights compared to CHMSL may be different. Specifically, drivers may respond to CHMSL faster than they respond to conventional lower mounted brake lights because it:

(1) is not easily confused with other signal lights,
(2) turns on only when the brake is applied,
(3) is mounted in the line of sight where it is easily observed by the drivers of the directly following vehicle and possibly by other following vehicles as well.

Alternatively, inaccurate information may be received from the conventional brake and turn signal lights when they are working simultaneously. The message received by the following driver(s) can sometimes become ambiguous if the leading driver simultaneously turns on the turn signal and uses the brake.

It is illustrative to review impacts of CHMSL on directly following vehicles. The CHMSL is required on all sedans and station wagon cars manufactured since September 1, 1985 and all light duty trucks, vans and station wagon trucks (e.g., sports utility vehicles) manufactured after September 1, 1993; although they started appearing on some light trucks in model year 1991 (Kahane and Hertz 1998). If pickup trucks have a cap, blocking the view of the CHMSL, then NHTSA (National Highway Traffic Safety Administration) recommends that a supplemental CHMSL be installed. The NHTSA 1996 performance plan reports that CHMSL rule evolved through experimental research, test fleets, regulatory analysis, rule making and evaluation. They state that research conducted between 1974 and 1979, and test fleet experience between 1976 and 1979 with CHMSL equipped passenger cars, demonstrated high levels of effectiveness in reducing rear-end crashes compared to conventional brake lights. The regulatory impact analysis projected benefits of 50% reduction of CHMSL relevant crashes, injury reduction of 40,000 per year, damage reduction of $434 million per year; and costs per vehicle of $4 to $7 (1982 dollars). After the implementation of the standard in new vehicles, a NHTSA evaluation study found that CHMSL equipped passenger cars were 17% less likely to be stuck to the rear while braking than the cars without CHMSL. It was projected that when all the passenger cars on the road have CHMSL, they will prevent 126,000 police-reported crashes, 80,000 nonfatal injuries and $910 million in property damage per year. Data from 1987 showed that the CHMSL was a very cost-effective safety device.

Studies by Farmer (1996) and Kahane and Hertz (1998) have revealed that CHMSL were most effective in the early years, resulting in about 8.5% reduction in rear impact crashes. More recently, the effect seems to have stabilized at 4.0% to 5%, possibly due to the "acclimatization" of drivers with CHMSL. They also discuss the "vehicle age effect" where older vehicles have proportionately fewer rear impacts, side impacts and reported non-injury crashes. However, they note that this effect does not derive from theory or intuition, but from the observation of data.

Kahane and Hertz (1998) report that in passenger cars the reduction in reaction time due to CHMSL is 0.11 seconds. The reaction time for drivers following a truck with CHMSL was 0.09 second shorter than for drivers following a truck without CHMSL.

Kahane (1989) reported that CHMSL is more likely to be effective in crashes involving three or more vehicles than in rear-end crashes involving two vehicles. Thus a relatively greater reduction in three-vehicle crashes can be expected. Kahane and Hertz (1998) report that CHMSL are more effective during daytime, at locations away from traffic signals, in towaway crashes than non-towaway crashes, fewer distractions due to other lights or traffic features. CHMSL effectiveness did not vary significantly across age and gender.

With regards to injury severity, Kahane and Hertz (1998) reports about an equal reduction injury rear impact crashes (4.0%) versus non-injury crashes (4.3%). They conclude that CHMSL are effective across a fairly wide spectrum of crash severity. However, they did not find strong evidence to suggest a reduction in rear-end fatal crashes.

Some studies have been conducted to evaluate the impacts of ITS early warning devices on rear-end collisions. As far back as 1974, Shefer (1974) reports an experimental automobile radar demonstration, designed to avoid rear-end collisions on highways. The idea that a passive reflector, mounted on the back of vehicles, returns the frequency transmitted from the following vehicle, allowing drivers to judge distance (and relative speeds) more accurately. Farber (1995) presents the results of a study of rear-end collision-warning algorithms using REAMACS (Rear-end Accident Model And Countermeasure Simulation). REAMACS is a simulation of rear-end collision situations on freeways and estimates the benefits of collision-avoidance systems. The study identifies significant reduction in rear-end collisions by providing imminent crash warnings, without producing excessive number of nuisance alarms. Beymer and Hochnadel (1994) propose an early warning information system using linear traffic formations to send brake status through traffic streams. The brake status information is sent rearward electronically. A changed information system provides early warnings. Basically, the Look-Ahead Headway Detection (LAHD) technology allows braking, deceleration and turn signal information from the front of the stream of passenger cars to be available "instantly" to the following motorists. This technology will need to be implemented on all vehicles before it can work in real-life traffic streams. Also it is not clear if such information will not cause unnecessary braking and result in secondary crashes that might not have occurred without the information.

To facilitate early warnings, Halogen technologies can reduce the time taken to light up the CHMSL by about 0.2 seconds compared with conventional bulbs. The implication is that a significant reduction in rear-end crash costs is possible through rapid information transferred to the following vehicles. Knipling (1992) describes the application of a seven-step crash problem analysis methodology to rear-end crashes. The discussion focuses on lead-vehicle stationary crashes, the largest sub-class of rear-end crashes. The principal counter measure concept examined is a headway detection system that would detect "threatening" vehicles in a vehicle's forward travel path.

While there is literature on the emerging information devices that can prevent rear-end collisions, the factors that influence rear-end crash propagation and injury severity need further exploration. There is a need to understand the impact of information devices vis-a-vis information currently available to drivers. Specifically, we need to know how is information is influencing/will influence rear-end crash propagation and injury severity?

Scope and Data Description

On a roadway with significant traffic, information about events ahead is received by drivers directly from the environment and by observing the taillights of leading vehicles. The information received critically influences the propagation of multi-vehicle rear-end crashes. In this study, the impacts of two critical information sources on rear-end crash propagation is explored: The presence or absence of CHMSL on lead vehicles and opaque versus transparent lead vehicles.

The North Carolina 1994-1995 HSIS crash data were used for analysis. This database includes all injury crashes and those costing more than $1000 in property damage. Counties suffering from high non-reporting (milepost) bias were removed. The counties were: Dare, Graham, Pamlico, Swain and Transylvania with approximately 53%, 21%, 23%, and 27% non-reported cases respectively. A total of 3425 two-vehicle and 487 three-vehicle crashes are analyzed. The following restriction were imposed in this study:

(1) Crashes that occurred on access-controlled divided roadways in order to focus on information effects from vehicles ahead, by removing confounding factors like driveways and intersections.
(2) Two-vehicle and three-vehicle rear-end crashes because of sample size limitations in the data set, i.e., the sample size for four or more vehicle rear-end crashes was very small.
(3) A limited set of vehicle types that include passenger cars, vans, pickup trucks and station wagons (cars and trucks) in order to study the interactions of vehicles of relatively similar performance and size.

These restrictions on the data and the reasoning behind them are further discussed in more detail below. Rear-end crashes that happened on freeways in North Carolina with full access control and a median were retained. We report some descriptive statistics below on all crashes of this type in order to understand the significance of the phenomenon. In our model of the causes of freeway rear-end collisions we restrict our analysis to collisions that involve some combination of station wagon (car and truck), pickup truck, van, or sedan. To properly perform the analysis, we needed two-vehicle and three-vehicle rear-end collisions fitting the above criteria so we could identify the order in which the vehicles struck each other. We retained all two-vehicle rear-end crashes in which exactly one vehicle received rear-end damage without front-end damage (referred to as Vehicle 1) and exactly one vehicle which received front-end damage without rear-end damage (referred to as Vehicle 2). The vehicles may have incurred other types of damage, as long as neither had both front and rear damage. We retained all three-vehicle crashes in which exactly one vehicle had front-end damage without rear-end damage, exactly one had rear-end damage without front-end damage, and exactly one had both front-end and rear-end damage. This allowed us to determine the order of the vehicles in the collision: Vehicle 1 had rear-end damage without front-end, Vehicle 2 had both rear- and front-end damage, and Vehicle 3 had front-end damage without rear-end damage. In addition, we deleted any observations that contained incomplete or inconsistent information, e.g., some collisions were labeled as involving three vehicles, but included data on just two vehicles.

SECTION 2: REAR-END CRASH PROPAGATION

To understand crash propagation, we need to understand the mechanics of rear-end crashes. We begin by analyzing the interactions between three successive vehicles and their drivers on a freeway. From this we develop hypotheses that are testable with HSIS data.

Dynamics of Rear-End Collisions

The following model shows the location, $x_{i,t}$, speed, $s_{i,t}$, and acceleration, $a_{i,t}$, for consecutive vehicles in a lane on a highway. The subscript i indicates the vehicle number, with 1 the lead vehicle and 3 the last vehicle. The model can be applied to a platoon of arbitrarily many vehicles. The subscript t indicates time. Let t indicate the time at which Vehicle 1 begins to brake (making acceleration negative), and let $t+1$ indicate some time Δt later. For ease of explication, assume that acceleration is constant and lane changing is not permitted. Then the location of Vehicle 1 at time $t+1$ can be expressed

$$x_{1,t+1} = x_{1,t} + s_{1,t}\Delta t + .5\, a_{1,t}(\Delta t)^2 \qquad (1)$$

The driver of Vehicle 2 (following Vehicle 1) responds to the braking of Vehicle 1 with a lag of r_{12}, which can be considered the reaction time of driver 2 to a change in the speed of Vehicle 1. Then the position of Vehicle 2 at time $t+1$ can be expressed

$$x_{2,t+1} = x_{2,t} + s_{2,t}\Delta t + .5\, a_{2,t}(\Delta t - r_{12})^2 \qquad (2)$$

The difference between the locations of the two vehicles at time $t+1$ can be expressed by subtracting (2) from (1). Call the separation between Vehicles 1 and 2 d_{12}:

$$d_{12,t+1} = x_{1,t} - x_{2,t} = d_{12,t} + s_{1,t}\Delta t - s_{2,t}\Delta t + .5\, a_{1,t}(\Delta t)^2 - .5\, a_{2,t}(\Delta t - r_{12})^2 \qquad (3)$$

A rear-end collision with Vehicle 1 will be avoided if $d_{12,\,t+1} > 0$. Assuming that the two vehicles were going the same speed at time t, then $d_{12,\,t+1} > 0$ if

$$d_{12,t} > -.5\, a_{1,t}(\Delta t)^2 + .5\, a_{2,t}(\Delta t - r_{12})^2 \qquad (4)$$

In order to identify the location of Vehicle 3 at time $t+1$, the reaction time of driver 3 to a change in speed by Vehicle 2 (which happened in response to the change in speed by Vehicle 1), must be added in. Thus, the location of Vehicle 3 at time $t+1$ is

$$x_{3,t+1} = x_{3,t} + s_{3,t}\Delta t + .5\, a_{3,t}(\Delta t - r_{12} - r_{23})^2 \qquad (5)$$

And Vehicle 3 will avoid a collision with Vehicle 2 if $d_{23,\,t+1} > 0$. Applying a similar analysis as in (4), this will be true if

$$d_{23,t} > -.5\, a_{2,t}(\Delta t - r_{12})^2 + .5\, a_{3,t}(\Delta t - r_{12} - r_{23})^2 \qquad (6)$$

If the driver of Vehicle 3 is able to see the center high mounted stop light on Vehicle 1 (or judge the deceleration of Vehicle 1 through another information source) at the same time as the driver of Vehicle 2 does, then both Drivers 2 and 3 will respond to the same stimulus; and the reaction time of Driver 3 to the acceleration by Driver 1 will be reduced. In the limiting case, this would reduce r_{23} to 0. In this case, (6) reduces to the condition that $d_{23,t+1} > 0$ if

$$d_{23,t} > .5(-a_{2,t} + a_{3,t})(\Delta t - r_{12})^2 \tag{7}$$

If Vehicle 2 hits Vehicle 1, then the speed of the collision is given by

$$s_{2,t+1} = s_{2,t} + a_{2,t}(\Delta t - r_{12}) \tag{8}$$

Value of Driver Information

In general, deceleration rates will vary between vehicles, depending on the vehicle and roadway characteristics and how hard the driver brakes. But, to illustrate the value of driver information, assume that the deceleration parameters are equal for all three vehicles in this example. Then the right hand side of (7) becomes 0, and guarantees that $d_{23,t+1} > 0$, assuming that Vehicle 2 is able to stop without hitting Vehicle 1. If Vehicle 2 hits Vehicle 1, then Vehicle 3 has braking time for deceleration of $(D_t - r_{12} - r_{23})$, and braking time is increased as r_{23} is decreased. In the limiting case where $r_{23} = 0$, Vehicle 3 has braking time of $(D_t - r_{12})$ and separation of $(d_{12,t} + d_{23,t})$ to keep it from becoming part of the wreck.

There is an additional benefit of this information. Even if Vehicle 3 is unable to stop in time to avoid hitting Vehicle 2, the extra braking time may still reduce the speed at which Vehicle 3 strikes Vehicle 2. This would tend to reduce the severity of injuries to the passengers in these two Vehicles.

Implications for Existing and Future Safety Enhancement Devices

Systems that influence the information that Driver 3 has about Vehicle 1 include:

- The center high mounted stoplight. Regular brake lights (mounted on the sides) of Vehicle 1 would generally not be visible to Driver 3 (during daytime), since Vehicle 2 would block the view. However, the third light, located in the center and at a greater height, is often visible to Driver 3, either over or through the windows of Vehicle 2. This might already be serving as an early warning device for Vehicle 3, reducing r_{23}. (Note that Driver 3 will also have a reaction time r_{13} after observing the Vehicle 1 third light as it turns on; this effect will be incorporated into our analysis). In this study we include an evaluation of the effect of the third brake light.
- Sight barriers from Vehicle 2. Most passenger cars and some mini-vans and pickup trucks with transparent rear windows (and no cargo or passengers blocking the line of sight), for example, would allow Driver 3 to see the third brake light on Vehicle 1. Vans without transparent rear windows, many pickup trucks, and most commercial trucks would block this view. This effect will be specific to the particular make of the vehicle. We hypothesize that the presence of "opaque" vehicles will increase the probability of multi-vehicle crashes and injury severity, all else being equal. However, opaque vehicles are typically larger and following drivers may drive with longer headways mitigating this effect.
- ITS driver warning devices. If Vehicle 2 has a warning device that cautions Driver 2 of the deceleration of Vehicle 1 and getting too close to it, then r_{12} can be reduced (but not eliminated). Importantly, if the Vehicle 2 device also warns Driver 3 either through a dedicated light on the rear of Vehicle 2 or through flashing the brake lights

of Vehicle 2, then it would have alerted Driver 3 at the same time it alerted Driver 2. This would thus reduce or eliminate r_{23} and reduce the risk of collision and injury.

- ITS vision enhancing systems. Reduced visibility due to fog and precipitation significantly contributes to multi-vehicle crashes (Evans 1991). ITS vision devices allow the drivers of Vehicles 2 and 3 to sense the speed of Vehicles 1 and 2 respectively by observing their brake lights (which would otherwise be obscured by fog or rain). This then translates to reduced reaction times (r_{12}, r_{23}) and collision risk in adverse weather situations. Note that precipitation also increases the stopping distance.
- Advanced Weather Systems (AWS) are being developed separately for localized network weather monitoring and forecasting. They consist of roadside sensors that monitor road surface temperature, whether the surface is wet or dry, and the presence of snow and ice. And there are visibility sensors that can monitor fog, smog, drizzle, heavy rain, sleet and snow. Processed data from the roadside sensors can be disseminated through the ITS devices to warn drivers of the increased stopping distance and the possibility of skidding.

Data Analysis

Descriptive Statistics

The data set was restricted to two- and three-vehicle rear-end collisions on North Carolina freeways involving passenger cars, station wagon cars and trucks, vans, and pickup trucks. To explore differences between our sample and all freeway crashes, Table 1 shows comparisons of the vehicle compositions of all North Carolina freeway collisions and of collisions in our data set. The first column of Table 1 shows the distribution of vehicles in all freeway crashes during 1994-95. Column 2 shows the distribution of passenger cars, station wagon cars and trucks, pickup trucks, and vans in crashes that involved only those types of vehicles. Column 3 shows the distribution of vehicle types for all freeway rear-end crashes, and Column 4 shows the distribution of vehicle types for all freeway rear-end crashes involving only vehicles of the type passenger car, station wagon, pickup truck, or van. Passenger cars constitute a relatively higher percentage of the vehicles in the types of crashes retained for analysis (Column 4) than they do for freeway crashes in general, while the other types of vehicles constitute more constant proportions across the different cases.

If passenger cars are easier to see over, through, or around than other vehicles, then, other things equal, they should be less likely to be rear-ended by other vehicles. A driver following a passenger car would more readily see the behavior of vehicles ahead of the car, and be able to react to changes in speeds of those vehicles. The driver following the passenger car would also be able to see other types of road conditions and react to them more quickly as well. A driver following another type of vehicle, such as a van, would have greater difficulty seeing the road conditions and events ahead and would not know that he/she needed to brake until the van ahead begins braking. This difference in information increases reaction times for drivers following large opaque vehicles. Thus cars are less likely to be rear-ended in position 1. We should be able to test this hypothesis using the crash data set.

The data set contains two-vehicle and three-vehicle rear-end crashes. We number the lead Vehicle as 1, the vehicle that strikes it as 2, and, should another vehicle rear-end the second, it is labeled 3. Vehicles that are less likely to be rear-ended (passenger cars) should appear in relatively lower numbers in position 1 and relatively greater numbers in positions 2 and 3. Table

2 tests this hypothesis.

The first column of Table 2 shows the relative percentages of the four vehicle types in this data set. The second column shows the relative percentages of the vehicle types in position 1. The third column shows the relative frequencies for each vehicle type in position 2, and the fourth column the relative frequencies for each vehicle type in position 3. So, for example, cars comprise 69.1% of the vehicles found in position 1 while comprising 73.1% of the vehicles found in position 2. The difference in means is presented in Column 5, the standard error of the difference in means is presented in Column 6, and a t-test on the difference in means is presented in Column 7. As expected, passenger cars appear significantly less frequently in position 1 than they do in position 2. Wagons and vans appear significantly less often in position 2 than they do in position 1. This result suggests that drivers may be responding to information from two (or more) vehicles ahead. This finding, while consistent with our expectation, does not control for many other factors that can contribute to rear-end crashes.

To capture information effects, variables called CHMSL were created. They equal 1 if a passenger car or station wagon car involved in the collision was manufactured in model year 1986 or later and a van, pickup truck and station wagon truck was manufactured in 1994 or later. Approximately 68.3% and 67.8% of the vehicles in positions 1 and 2 respectively had CHMSL. Table 3 suggests that the presence of CHMSL on Vehicle 1 or Vehicle 2 or both does not reduce crash propagation. This result is somewhat surprising and it is not consistent with the literature or our expectations. We also explored the relationship between model year and number of vehicles involved (Figures 1 and 2). The graphs do not suggest a significant reduction in three-vehicle crashes compared with two-vehicle rear-end crashes. (Kahane (1989) suggested that CHMSL are likely to be more effective in crashes that involve three or more vehicles compared with two-vehicle crashes.) A model is developed below to include other factors, and other information measures, in addition to CHMSL and vehicle type.

Modeling Crash Propagation

A number of factors besides driver information influence the probability of a vehicle being rear-ended by another. These factors would include variables that could affect the (1) initial separation between vehicles, (2) vehicle deceleration rates, and (3) and driver response time. Any factor that decreases the first two items or increases the third would reduce the final separation between two successive vehicles and thus make rear-end collisions more likely.

To study the effects of driver information on crash propagation, we need to specify a model of factors that contribute to rear-end collisions. Consider a given two-vehicle collision i, and whether the crash is propagated by a third vehicle rear-ending the first two.

Let the categorical variable w_i indicate whether vehicle j is rear-ended $(w_i = 1)$ or not $(w_i = 0)$. In this data set vehicle j is the second vehicle in crash i. Whether or not vehicle j is rear-ended will depend on several categories of factors, which can be represented:

$$w_i = \beta'\mathbf{x} + \varepsilon \tag{9}$$

w_i is the dependent variable (crash propagation),
β' is the vector of estimated parameters,
$\mathbf{x}$ are the explanatory variables.

These factors can include:

- Information about the vehicles already involved in the crash i and other information such as warning notices of bottlenecks or a crash ahead.
- Vehicle characteristics for the two vehicles already involved in collision i.
- Roadway characteristics, such as road geometry and traffic volumes on the highway segment where collision i occurred.
- Environmental factors, such as day/night, visibility, weather conditions, pertaining to the time that collision i occurs.
- Driver characteristics for the drivers of the vehicles that initiated collision i.

The unit of observation is the initial rear-end collision. Since we only observe vehicles and drivers involved in collisions rather than the population of all vehicles and drivers that passed a given freeway segment, we must restrict our analysis to vehicles involved in collisions and examine whether they were subsequently rear-ended. Each observation is at least a two-vehicle rear-end collision that occurs on a freeway. The dependent variable takes on the value of 1 if the initial two-vehicle collision is subsequently struck by a third vehicle. The dependent variable takes a value of 0 if the rear-end crash does not propagate (from two to three vehicles).

In each observation, Vehicle 2 has already rear-ended Vehicle 1. If present, the drivers of other vehicles approaching the collision (or who are immediately behind the collision at the time that it occurs) receive information from the wreck. The driver of a third vehicle present at the time of the wreck would also receive information from the vehicles ahead before the first collision occurs. Thus the model includes factors from Vehicle 1 and Vehicle 2 that may provide information to the drivers of succeeding vehicles. If the information makes crash propagation less likely, then the dependent variable is more likely to take on a value of 0. Likewise, characteristics of the first two vehicles and the behavior of the drivers of the first two vehicles may affect the crash in such a way as to make it more or less likely to be struck by a third vehicle. Environmental and roadway characteristics will also affect the likelihood of crash propagation.

Binary logit and probit regression models were estimated. No significant differences were found in the results, so the binary logit model, measuring the propensity to propagate rear-end collision, is reported. It examines the effects of information, vehicle characteristics, and driver behavior from two vehicles ahead as well as environmental variables and the roadway geometry. These factors are listed in Tables 4 and 5. Again, the dependent categorical variable identifies whether the crash continues beyond Vehicle 2 in collision i. About 12.5% of the rear-end crashes in the data set involve three vehicles and the rest involve two vehicles. We present the estimated model and note that several of the explanatory variables are statistically insignificant. We discuss below the implications of these results for understanding rear-end crash propagation.

Information Effects

Several of the variables listed in Table 5 also encompass information effects, both in the quantity and quality of information received by the drivers of approaching vehicles. These are the lighting variables, road geometry variables, vehicle type variables (passenger cars, vans, pickups and wagons), and the variables concerning CHMSLs, proxied by the year of vehicle manufacture. Table 4 shows that a majority of vehicles in position 1 (68.3%) had CHMSL, and about the same number of vehicles in position 2 had CHMSL (67.8%).

Neither of the two variables for CHMSL were negative and significant in the logit model.

In fact, the presence of CHMSL on the second vehicle was significantly associated with a higher propensity for rear-end crash propagation (5% level). We also estimated separate logit models with vehicle model year in position 1 and position 2 and CHMSL1 and CHMSL2 as explanatory variables. However, the results showed that only CHMSL1 was positive and statistically significant at the 5% level.

Vehicle Characteristics

To capture vehicle type we included variables for the larger vehicles (vans, pickup trucks and station wagon trucks and cars), that are more likely to be opaque. Positive signs on these variables would be consistent with the information hypothesis. Approximately 30.9 percent of the vehicles in position one and 26.9 percent in position two were larger/opaque. We found little evidence in the model to suggest that crashes involving larger opaque vehicles are more likely to propagate.

Driver characteristics

The application of driver attributes here differs from the usual application in the safety literature, since we have characteristics of the vehicles that could potentially be rear-ended. The censored nature of the data does not allow us to identify the characteristics of drivers who approach the crash, but stop in time. Thus, the driver characteristics here may say something about the behavior of the drivers already involved in the two-vehicle crash, and whether that behavior makes the crash more difficult for approaching drivers to avoid. We include driver gender and age, but do not have a-priori hypotheses about the direction of these variables. The model indicates that if Driver 2 is female, then the crash is more likely to propagate. None of these variables proved interesting in the logit model.

Roadway Factors

Heavier traffic flow would make it more likely for a collision to propagate, by making it more likely for another vehicle to be immediately behind the first two vehicles. Thus the probability of propagation should be increasing with increasing average traffic flow (AADT—Average Annual Daily Traffic) and the probability of propagation should be highest at peak commuting times (7:00 AM—9:00 AM and 3:00 PM—6:00 PM, PEAKTIME), leading us to expect positive signs on both of these variables. A greater number of lanes can mean more vehicles approaching the collision, but could also mean more room to avoid the initial wreck if adjoining lanes are open. These opposing effects make the a priori expectation for the effect of the number of lanes indeterminate. As can be seen in the descriptive statistics there is a wide range of AADT in the data set (2,100 to 123,400). The variable for AADT and for traveling during peak time were both positive and highly significant in the logit model.

The road geometry could affect lines-of-sight and allow drivers to better see around or over the vehicles immediately ahead. Thus curves and grades could offer drivers more information about the traffic ahead and give them more reaction time, reducing the likelihood of a chain reaction. Drivers further compensate by driving slower and more carefully. The omitted category in the model was a straight-level road, which means information effects would make the coefficients on these variables negative. The greatest information would come from a curve on a grade. All the collisions in the data set happened on freeways, so the curves indicated are generally long and gradual that would allow an opportunity to see around the vehicles immediately ahead; and the curves would not be so sharp as to be blind curves. It is also possible that the geometry could affect vehicle performance: stopping is more difficult on descents and less difficult on ascents; braking in a curve requires drivers to turn while braking. The data set does not allow us to distinguish between uphill and downhill grades. The performance effects and slower/more careful driving would tend to make the signs of these variables positive. Thus, the signs of these variables, a-priori, are indeterminate. Negative signs here would say that information is important, and that information effects exceed the countervailing effects. The results for the road geometry variables show that traveling on a graded curve and on a straight hill crest or bottom both significantly decreased the likelihood of being involved in a rear-end crash. The other road geometry variables were statistically insignificant (5% level).

Environmental Factors

The presence of snow and ice or wet roads could induce two effects. Braking is more difficult which would give positive coefficients, i.e., increase crash propagation propensity. But drivers also compensate, either by not driving, putting fewer vehicles on the road and reducing the likelihood of a chain reaction, and drivers may also drive more slowly with longer headways. Both effects would tend to reduce propagation. Thus, a priori, the sign of the coefficient is indeterminate. Neither the variable for snow and ice nor for wet roads was significant in the logit model.

Poor light could reduce visibility and increase the likelihood of a chain reaction collision. Daylight is the base (omitted) category, so reduced visibility would tend to increase crash propagation. Drivers could also compensate, reducing the magnitude of this effect. Night is also the time of lowest traffic, and without hourly traffic counts, the night variables (and dusk/dawn) would also be picking up the effects of lighter traffic. The latter effect would tend reduce crash propagation, leaving the expected signs on these variables indeterminate. Positive signs would be consistent with the information hypothesis: poorer visibility gives approaching drivers poorer information about the vehicles ahead. None of these variables were significant in the logit model. Overall, the model seems to suggest that after accounting for exposures (through AADT and peak times), CHMSL and vehicle type variables do not explain much of the crash propagation phenomena. However, road geometry variables that capture information effects and driver behavior explain a significant portion of the variation.

Another way of looking at the question of crash propagation and vehicle type is presented in Table 6. This table can best be summarized as suggesting that vehicle types on the roadway are not uniformly distributed across space and/or time. In Table 6, the vehicle type for the first vehicle is shown across the top, and down the left is shown the vehicle type for the second vehicle in each collision. The numbers under the column "Car" show that, when a passenger car is the first vehicle, 75% of the second vehicles are passenger cars, 7% are wagons, etc. Reading across the row that is labeled "Car," we see that a passenger car is the second vehicle 75% of the time when a passenger car is the first vehicle, 68% of the time when a station wagon is the first vehicle, and so on. Overall, a passenger car is the second vehicle 73% of the time. The highlighted cell shows that passenger cars constitute the greatest percentage of second vehicles when a passenger car is the first vehicle. Indeed, this is the only cell in the row with a percentage higher than the 73% for the overall share of cars as second vehicle in all crashes in the data set. The highest value in each row is highlighted, and, as can be seen, the greatest values occur along the diagonal, suggesting correlation. To help see this effect better, Table 6 also shows the same data scaled by a different metric. The numbers in parentheses in Table 6 show the relative frequency of a given vehicle type as a second vehicle behind a particular type of first vehicle, divided by its overall relative frequency as second vehicle in all crashes in the data set. If vehicle types were randomly distributed, then every entry in this table would equal one. If a vehicle of a given type is positively correlated with the lead vehicle's type, then the cell has a value greater than one. If the vehicle type is negatively correlated with the lead vehicle's type, then the cell will have a value less than one. So passenger cars as second vehicle have their highest relative frequency behind cars, wagons have their highest relative frequency behind other station wagons, pickups behind pickups, and vans behind vans. In fact, vans appear with more than double their average relative frequency behind other vans.

This suggests that there are probably some roadways or some times of day when vans are more likely to be on the road, others when passenger cars are more likely to be on the road, and so on. If vehicle types tend to cluster this way, then a vehicle of a given type is likely to be followed relatively more frequently by a vehicle of the same type. This means that the exposure rate, for example, of vans to other vans that could possibly rear-end it, can be greater than the exposure rate of vans to passenger cars that could rear-end it. Since we are unable to control for differential exposure rates in our data set, we are unable to separate out this exposure effect from the information effects that we would like to measure.

SECTION 3: INJURY ANALYSIS IN REAR-END CRASHES

As indicated earlier, the concern over rear-end crashes is largely due to their higher frequency. More collisions often imply more injuries. This portion of the study examines injuries in two-vehicle and three-vehicle rear-end crashes. We are particularly interested in exploring the impacts of information on the intensity of injuries incurred by drivers in rear-end collisions. Rear-end collisions occur when the relative speed of the following vehicle exceeds that of the leading vehicle. An important reason for rear-end collisions is the lack of information and early warning about the speed of the leading vehicle.

To understand injury severity, the 1994-1995 North Carolina Highway Safety Information System (HSIS) crash and inventory data for limited-access roadways are analyzed. The data does not have direct measures of driver information, but there are variables that serve as proxies for driver information. The two variables used as proxies for information are:

(1) The presence of Center-High Mounted Stoplight (CHMSL) that were mandated in passenger cars and station wagon cars after 1985 (1986 models) and in vans, pickup trucks and station wagon trucks after 1993 (1994 models). The center high mounted stoplight, being in the line of sight and relatively unambiguous (compared with the side taillights), helps following drivers detect and respond to the braking of the leading vehicle more quickly.
(2) A "transparent" leading vehicle. If drivers can see over, around and through the vehicle in front, then they can receive early warnings from leading vehicles that are braking. For example, in a platoon of three passenger cars, the driver of the third passenger car can usually see the CHMSL of the first vehicle indirectly through the windows of the second passenger car (if passengers and cargo do not block the view). But if the second vehicle is opaque, e.g., large pickup trucks, vans and station wagon trucks then the information regarding vehicle one will be blocked by vehicle 2. Transparent vehicles can provide more information to following drivers that can hasten the following driver(s)' evasive maneuvers, reducing the collision speed and the consequent injuries.

The effect of these two "information variables" on injury severity is analyzed using simple statistical analysis and modeling. Three separate ordered probit models of injury severity for Drivers 1, 2, and 3 involved in rear-end crashes were estimated. Injury is measured on the KABCO scale. In addition to the effect of CHMSL, the vehicle year variable used in the models also contains the effect of vehicle technology improvements. The vehicle type variable used in the analysis contains the effects of information and vehicle size (vans, pickup trucks and station wagon trucks are usually larger). This is a limitation of using real-life crash data for analyzing information effects.

In this North Carolina HSIS data, restricted to limited-access roadways and passenger vehicle, van, pickup truck and station wagon truck collisions only, there were 3425 two-vehicle and 487 three-vehicle rear-end crashes. While exploring the effects of driver information, the ordered probit models control for the driver, vehicle, roadway, environment, and crash variables. The marginal effects of each factor on the likelihood of each injury severity class are reported. Policy implications and possible countermeasures are then discussed.

Factors That Influence Driver Injury

Rear-end crashes analyzed in this study occur when the leading vehicle decelerates. The injury occurrence process in a two-vehicle rear-end crash is likely to be different than a three vehicle rear-end crash. In a two-vehicle collision, the leading driver (referred to as Driver 1) is likely to be pushed backward into the seat, when struck by the following vehicle. The headrest can provide support for the head and the seat can provide "body protection." But there is a chance of whiplash or neck injuries, caused mainly by the continuation of neck moving back at a different speed than the head and the rest of the body. Upon striking, the following driver (referred to as Driver 2) is likely to be jolted forward, possibly hitting objects in the front of the vehicle, e.g., the front window, steering wheel and the dash board. In rear-end crashes that occur at high relative speeds, seat belt (if present and worn) and airbag (if deployed) can provide protection to Driver 2 during a crash, reducing injury severity.

In a three-vehicle rear-end collision, Driver 1 may be pushed back twice—once when Vehicle 2 strikes it and another time when Vehicle 3 strikes Vehicle 2. However, the injury effect on Driver 1 of Vehicle 3 striking Vehicle 2 is likely to be relatively small, owing to the dampening effect of Vehicle 2. Furthermore, in a three-vehicle collision, the driver of Vehicle 2 is first jolted forward (when it strikes Vehicle 1) and then jolted backward, when Vehicle 3 strikes the rear of Vehicle 2. Two direct jolts in the opposite directions are likely to induce relatively severe Driver 2 injuries. Driver 3, when involved in a rear-end collision, is jolted forward and might strike the objects in front of him/her. However, the striking speed is likely to reduce as the crash propagates (partly due to the presence of driver information), and reduce Driver 3 injury severity.

The focus of this portion of the study is to understand the effect of information on injury severity. In rear-end crashes, the following drivers receive their information by observing the side-mounted taillights of the leading vehicle. Moreover, due to its central location, CHMSL can provide important information to the immediately following driver. This can either prevent collisions or lower the impact speeds, reducing injury severity.

A driver following a "transparent" vehicle (e.g., a passenger car) can receive early warnings about potential deceleration by observing the Center High Mounted stoplight (CHMSL) of the vehicle ahead of the one being directly followed and/or get an earlier sense of why the vehicle in front might decelerate. This can reduce the relative speed of impact. However, if traveling behind an opaque vehicle (e.g., a van, station wagon truck), passenger car drivers experience information blockage. This can potentially increase impact speeds and the resulting injury severity. Although, the following drivers possibly compensate for the lack of information by driving at a longer headways. Longer headways by vehicles following opaque vehicles may reduce collision intensity and injury severity.

The CHMSL concept is captured by creating "year" indicator variables that equals 1 if a passenger car and station wagon car model is 1986 or later and a van, pickup truck, station wagon truck involved in collisions is model year 1994 or later. Larger vehicles considered in this study are usually opaque to the following drivers. Using vehicle type variable in model specifications captures the transparent/opaque concept. The variable captures the following compensating effects:

- Larger vehicle size implies that the driver of the vehicle will sustain relatively less severe injuries compared with passenger car driver.
- If a larger (opaque) vehicle is struck, the injuries of the large vehicle driver can be more severe owing to its information blocking effect on the rear vehicle. However, the driver of the following vehicle might compensate for the information blocking effect of the larger vehicle by traveling at a larger headway behind. This gives more time to the following driver to react and therefore reduce the impact force.
- Higher seating position in a larger striking vehicle implies that the driver is not restricted to observing the vehicle immediately in front. This can then allow the driver of the larger striking vehicle to brake in advance and reduce the severity of the collision.
- Performance-wise, larger vehicles are relatively more sluggish, increasing striking speeds and injury severity. However, the larger vehicles considered in this study (vans, pickup trucks and station wagon trucks) may be only slightly more sluggish that passenger cars, if at all.
- Larger vehicles are also subject to overturning more than passenger vehicles, increasing injury severity. However, crashes involving overturned vehicles were not analyzed in this study.

In addition to information factors discussed above, driver, vehicle, roadway, environmental and crash factors are likely to influence the injury outcome in rear-end crashes. A summary of our a-priori expectations regarding injury severity is presented in Table 7.

Injury Severity Analysis

The variable of interest is the injury propensity for each driver. Table 8 provides an overview of driver injuries in the data. Separate cross-tablulations for two-vehicle and three-vehicle crashes indicate that there is a statistically significant relationship between driver sequence in a rear-end crash and the severity of injuries ($p>0.05$). The important points are:

- There are substantially more two-vehicle collisions (87.6% are two-vehicle collisions) than three-vehicle collisions, as expected. Non-injured drivers exceed injured drivers (70-85% of the involved drivers are not injured). As expected, there are relatively few severe injuries in these rear-end collisions (only one fatality occurred among 8311 vehicle involvements).
- Given rear-end collisions, Driver 1 is more likely to be injured (31.2% received injuries) in a

two-vehicle crash compared with Driver 2 in the same crash (12.0% were injured). In a three-vehicle crash, Driver 2 is more likely to be injured (37.8% received injuries) compared with Driver 1 in the same crash (23.6% were injured).

- Surprisingly, Driver 1 is less likely to get injured in a three-vehicle crash compared with a two-vehicle rear-end crash (31.2% vs. 23.6% of Vehicle 1 drivers were injured in two-vehicle and three-vehicle crashes respectively). Furthermore, Driver 2 is more likely to get injured in a three-vehicle crash compared with a two-vehicle rear-end crash (12.0% vs. 37.8% of Vehicle 2 drivers were injured in two-vehicle and three-vehicle crashes respectively).
- In three-vehicle rear-end collisions, relatively fewer injuries were received by drivers of Vehicle 3 (17.2% of the drivers were not injured) compared with Drivers 1 and 2 (23.6% and 37.8% respectively were injured).
- Examining the injury spectrum, in two-vehicle rear-end collisions, Driver 1 injuries (except for B type injury) are statistically more than expected. In three-vehicle crashes, B and C injuries are more than expected for Driver 2, and A and B injuries for Dirver 3.

The crosstabulations do not explore information effects on injury severity and cannot control for the effects of driver, vehicle and roadway factors on injury severity. Therefore, to understand the effect of information and other factors on injury severity in rear-end crashes, we need to estimate multivariate models.

Modeling Methodology

The ordered probit model is suitable for analysis of five-point KABCO injury severity (ordinal and categorical) scale. As a multivariate model, ordered probit accounts for interdependencies among explanatory variables and the marginal effects of significant variables can be used to examine the degree to which different factors influence the severity class of injury. Importantly, this model can represent unequal differences between categories in the dependent variable for each significant factor. In other words, it does not assume that the difference between the first and second injury class is the same as the difference between the fourth and fifth class. For a detailed discussion of the model, see O'Donnell and Conner (1996) or Duncan et al. (1998). In this analysis, the K and A injury categories are combined due to only one fatality in these data. Injury severity is coded as 0—no injury, 1—C type injury, 2—B type injury and 3—A type injury or K type, fatal injury.

The ordered probit model has the following form:

$$y^* = \beta'\mathbf{x} + \varepsilon \qquad (10)$$

Where:

y^* is the dependent variable (injury severity that is unobserved),
β' is the vector of estimated parameters,
$\mathbf{x}$ are the explanatory variables, and
ε is the normally distributed error term

Parameter estimates (β) represent the effect of explanatory variables on the underlying injury scale. Only the signs, relative magnitudes and significance of the parameter estimates can be interpreted directly; separate computation of the marginal effects for each independent variable is needed to understand the effect of a unit change in the independent variable. Based upon this specification, the probability of the dependent variable falling in any ordered category is:

$$\text{Prob } (y=n) = \phi(\mu_n - \beta'\mathbf{x}) - \phi(\mu_{n-1} - \beta'\mathbf{x}) \tag{11}$$

ε has a cumulative distribution denoted by $\Phi(\cdot)$ and density function denoted by $\phi(\cdot)$. An individual falls in category n if $\mu_{n-1} < y^* < \mu_n$; the injury data, y, are related to the underlying latent variable, y*, through thresholds μ_n, where n = 1...3. We have the following probabilities:

$$\text{Prob } (y = n) = \Phi(\mu_n - \beta'\mathbf{x}) - \Phi(\mu_{n-1} - \beta'\mathbf{x}), \qquad n = 1...3 \tag{12}$$

Where, $\mu_0 = 0$ and $\mu_3 = +\infty$ and where $\mu_1 < \mu_2$ are defined as two thresholds between which categorical responses are estimated. The estimation of this model is relatively simple; the likelihood function is derived in Greene (1997). Ordered probit estimation will give the thresholds μ and parameters β.

The thresholds, μ, show the range of the normal distribution associated with the specific values of the response variable. The remaining parameters, β, represent the effect of changes in explanatory variables on the underlying scale. The marginal impacts of factors **x** on the underlying injury propensity can be evaluated as:

$$\partial \text{ Prob } (y = n)/ \partial \text{ x } = -[\phi(\mu_n - \beta'\mathbf{x}) - \phi(\mu_{n-1} - \beta'\mathbf{x})]\beta, \ \ n=1...3. \tag{13}$$

Computation of marginal effects is particularly meaningful for the ordered probit model where the effect of variables **x** on the intermediate categories is ambiguous if only the parameter estimates are available. Formal goodness of fit measures for the ordered probit model are not available in the literature.

Model Specification

Three separate ordered probit models for Driver 1, 2 and 3 injury severity were estimated. The variables tested in the models included:

- Crash factors: Number of vehicles involved (THREEVEH) and sequence of vehicle types.
- Vehicle and information factors: Vehicle type (CAR, VAN, PICKUP, WAGON) and vehicle model year.
- Roadway factors: Traffic volume (AADT), roadway geometry (STRTGRD, SRTOTH, CURVLEV, CURVGRD, CURVOTH), number of lanes, peak time indicator, speed limit (SPD_LIMIT), collision locations (e.g., bridge, underpass, railroad crossing) and terrain (FLAT, ROLLING, MOUNTAIN).
- Environmental factors: Road surface condition (DRY, WET, SNOWICE), and light condition along the roads (NIGHTLITE, NIGHTDARK, DUSKDAWN).
- Driver factors: Age and gender (AGE, DRV_SEX) and driver restraints (e.g., shoulder and lap belt usage).

The two vehicle factors reported above are likely to contain the effect of traffic information. Vans, pickup trucks and station wagon trucks are likely to be opaque and hence block information to the following vehicles, increasing injury severity, given a collision. The model year indicator of involved vehicles captures the effect of center high mounted stop light along with technology improvements over the years.

The relevant variable definitions and their means appeared in Table 4. About 12.5% of the crashes were three-vehicle collisions and the rest were two-vehicle rear-end collisions. A majority of Vehicles 1 and 2 involved in these crashes had center high mounted stop lights (68.3% and 67.8% respectively). The proportion of vans, pickup trucks and station wagon cars/trucks involved was 30.9% for Vehicle 1 and 26.9% for Vehicle 2, compared with passenger cars. The average annual daily traffic on roads where these crashes occurred was 61,280 with an average of 4.5 lanes and mean speed limit of 56 mph. About 24.8% of the crashes occurred on straight-grade roadways. A majority of the crashes (54.5%) occurred during the peak times 7:00 AM—9:00 AM and 3:00 PM—6:00 PM. A small proportion (10.8%) of the crashes occurred at night on unlit streets and a smaller proportion (4.9%) occurred at night on lighted streets. Wet roadway crashes were 21.8% and crashes in snowy/icy conditions were 1.7%. The average age of the involved drivers was 36 years. Relatively larger proportions of females were involved in these rear-end crashes than males. Interestingly, the proportion of females seems to increase as the crash propagates: 54% female drivers were rear-ended, 61% female drivers in Vehicle 2 rear-ended Vehicle 1, and 64% of female drivers in Vehicle 3 rear-ended Vehicle 2. Very few drivers in position 1 were charged with a violation (5.3%) compared with those in positions 2 and 3 (87.3% and 98.4% respectively).

Model Results

Tables 9, 10, and 11 show the modeling results for each driver (in Vehicles 1, 2 and 3) involved in either a two-vehicle or three-vehicle rear-end crashes. Estimation of these separate unrestricted models (one for each driver) is justified compared with using a restricted pooled model on theoretical and empirical grounds. The impact of information is expected to vary across the sequence of vehicles involved in a rear-end collision. Moreover, the model results indicate that the impacts of important variables are different across struck and striking vehicles.

The effect of a variable is relatively strong when the significance level is above 95%, and the effect is marginal when the significance level is between 90% and 95%. A positive sign for a parameter estimate indicates increasing injury severity with increase in the magnitude of the explanatory variable.

Interactions among variables were explored in the models. The important interactions tested included (1) the sequence of vehicle involvement (e.g., Car-Car, Car-Large vehicle, Large vehicle-Car, Large vehicle-Large vehicle; Car-Car-Car, Car-Car-Large vehicle,...Large vehicle-Large vehicle-Large vehicle), (2) the number of vehicles involved in rear-end collisions with vehicle type and vehicle year and (3) vehicle type with vehicle year. However, none of the interactions were statistically significant. Some variables were removed from the model because if they were found to be statistically insignificant and dropped from the model. However, certain statistically insignificant variables (at 10% level) were retained in the model either for theoretical reasons or because they were part of a larger variable set.

Driver 1—Struck Vehicle

Table 9 shows the results for Driver 1 injuries. To capture the effect of center high mounted stoplights, variables called CHMSL1 and CHMSL2 were created. These variables equal to 1 if the passenger car involved in the crash was manufactured after 1985 or in the case of vans, pickup trucks and station wagon truck it was manufactured after 1993 when the center high mounted stop lights were mandated. As expected, the sign of CHMSL1 is negative (significant at 99.9%), suggesting that the presence of center high mounted stoplight is associated with less severe Driver 1 injuries. This is partly because the center high mounted stoplight, being in the line of sight and relatively unambiguous (compared with the side taillights), helps Driver 2 detect and respond to the braking of the front vehicle more quickly. Moreover, this variable captures the effects of other vehicle technology improvements over the years. While it may be argued that the "year" effect is solely attributable to the safety improvements in vehicle design over the years (e.g., shatter-resistant windshields and crash cages), the literature on CHMSL indicates that center stop lights reduce the propensity of collisions (Evans 1991, Kahane 1989). Therefore, we believe that this variable partly captures the information effect. CHMSL2 is statistically insignificant, indicating that the presence of center high mounted stop light on the first striking vehicle and safety improvements over time do not reduce Driver 1 injury severity.

The variable THREEVEH denotes whether the crash involves three vehicles (coded as 1) or two vehicles (coded as 0). In three-vehicle crashes, Driver 1 is expected a-priori to be more severely injured than in two-vehicle crashes. Contrary to our expectations, the sign of THREEVEH is negative, indicating that more vehicles involved in rear-end collisions do not necessarily increase the injury severity for Driver 1. This result might be reflective of three-vehicle collisions more likely occurring on higher AADT roadways, where congestion is higher and relative speeds lower (although the AADT variable included in the model to control for its effect is statistically insignificant). Furthermore, the peak period (especially in urban areas) slows down traffic, reducing the injury severity in rear-end collisions. The peak time indicator variable shows that collisions occurring between 7:00 AM—9:00 AM and 3:00 PM—6:00 PM are likely to be less injurious for Driver 1 than during other times.

A set of vehicle type variables (vans, pickup trucks and station wagon cars/trucks) were included in the model to capture the effect of differences in the information received by drivers involved in rear-end crashes. Large vehicle variable (BIG_VEH1) is negative and statistically significant, indicating that the injuries of struck drivers in large vehicles are less severe compared with car driver injuries. This implies that the effects of larger vehicle size, and possibly longer following distance by the striking vehicle exceed the information blocking effect of the larger/opaque vehicle on the rear vehicle. (Note that crashes involving overturned vehicles were excluded from the data.)

The coefficient for BIG_VEH2 is positive and significant indicating that getting struck by a larger vehicle (van, pickup or wagon) significantly increases Driver 1 injury. This implies that the effect of larger striking mass (and associated inertia) exceeds the compensating effect of Driver 2's higher seating position in larger vehicles which can facilitate observation beyond the vehicle immediately in front and therefore reduce the impact speed.

For Driver 1, darkness with no road lighting significantly increases rear-end crash severity. However, no significant relationship was found between drivers' injury and dark with lighting (NIGHTLITE). This means that street lighting enhances visibility and provides information to reduce the effect of darkness on injury severity. Also, it is possible that emergency response to crashes that occur in unlit and dark areas (at night) is slower than in other conditions, exacerbating unattended injuries.

Concerning road geometry, Driver 1 involved in rear-end collisions is more likely to be injured when traveling on straight-grade roads, compared with other roadway geometry including straight level roads. Grades can reduce vehicle control and increase speed variability resulting in more severe rear-end collisions.

The positive sign for AGE1 reflects that older drivers are significantly (1% level) more likely to be severely injured in rear-end collisions compared with younger drivers, as expected. An additional variable AGE1_SQ is created by squaring age, with the expectation that older individuals are likely to be more severely injured. This effect is negative and statistically significant, indicating that while older drivers are more likely to be injured this effect reduces with older age. The injuries of male drivers in rear-end crashes are significantly more severe than female drivers (female coded as 1). On the one hand, males are relatively less fragile than females, but on the other hand, they may drive more aggressively. The more severe injuries might reflect the more aggressive driving behaviors of male drivers.

To control for their effects AADT, speed limit and number of lanes are included in the model, despite their statistical insignificance.

The reported marginal effects show the changes in probability (or chance) of injury severity with a unit change in the explanatory variable, when all other variables are held at their means. Given a collision, a relatively large injury severity advantage (8.7% reduction in Driver 1 injuries) is provided by driving in a vehicle with CHMSL1. As stated earlier, this advantage might also reflect other vehicle safety improvements. Furthermore, driving a larger vehicle that is struck (compared with driving a passenger car that is struck) is associated with 11% increase in non-injuries, 9.2% reduction in C injuries, 1.3% reduction in B injuries and 0.5% reduction in K and A injuries. On the other hand, being struck by a larger vehicle increases the chances of injuries: 4.8% increase in C injuries, 0.7% increase in B injuries and 0.3% increase in K and A injuries (there is a 5.8% reduction in uninjured drivers). Thus the injury protection advantage of driving a larger vehicle is much greater (an 11% reduction in driver injuries) than the disadvantage of being struck by a larger vehicle (a 5.8% increase in driver injuries).

Driver 2—First Striking Vehicle

The ordered probit model describing Driver 2 injuries is shown in Table 10. As expected, if the second vehicle in a rear-end collision is struck by a third vehicle, then Driver 2 injuries are more severe. Multiple points of contact (front and rear for Vehicle 2) means greater energy transfer to Driver 2, in at least two (possibly) opposite directions, increasing the severity of injuries.

Importantly, the information effect of CHMSL, captured through the "year" indicator variable on Vehicle 1, decreases Driver 2 injury severity. That is, if Vehicle 1 has a center stoplight, then the following driver may be able to slow down considerably before a rear-end collision, reducing the energy transfer during the collision. The same reasoning applies to the striking Vehicle 2 having a mandatory center high mounted stoplight. The results show that Driver 2 is less severely injured if Vehicle 2 was built in a year when center high mounted stoplight was mandatory. Overall, this variable captures the dual effects of driver information and improvements in vehicle safety over time.

Driving a large vehicle (van, pickup truck or station wagon truck) that strikes a vehicle is less injurious than being in a passenger car that strikes a leading vehicle. This effect can be attributed to the larger Vehicle 2 size and higher seating position in Vehicles 2, facilitating observation beyond the vehicle immediately in front. Although a larger Vehicle 2 can block Driver 3 from observing Vehicle 1 resulting in more severe Driver 2 injuries, this effect seems to be subsumed in the mass protection effect.

Consistent with the results for Driver 1, dark without lighting significantly increases Driver 2 injury severity. However, the presence of lighting at night neutralizes the increased effect of darkness on Driver 2 injury severity.

Higher traffic volume is associated with lower injury severity of Driver 2, possibly due to reduced travel speeds. Also, the more cars there are to hit, the more cautious drivers may become. Additionally, peak time traffic plays a similar role in Driver 2 injury as in Driver 1, i.e., Driver 2 injuries are less severe during peak periods. Overall, rear-end crashes occurring during peak times seem less severe. Interestingly, more highway lanes are associated with higher injury propensity for Driver 2 in rear-end collisions.

Snowy or icy road surface is associated with higher Driver 2 injury severity. Snowy or icy conditions can impair drivers' ability to control a vehicle longitudinally and this can lead to more severe Driver 2 injuries. Although drivers may use more caution in adverse weather situations. The data shows that drivers do not compensate sufficiently to neutralize the higher injury risk in snowy/icy conditions. (The snow/ice effect was not statistically significant for Driver 1.)

Driver 2, when male is more likely to be injured. This result is consistent with the earlier result regarding gender. Finally, the following variables were not statistically significant (10% level): Speed limit, wet road surface, grade, dusk or dawn and driver age.

Comparing the marginal effects of variables across the two models can provide further insights. The presence of CHMSL on a vehicle (and other safety improvements) provides protection in rear-end collisions to Driver 1 (8.7% reduction in injuries) as well as Driver 2 (3.5% reduction in injuries). Moreover, the presence of CHMSL on Vehicle 1 can reduce Driver 2 injuries by as much as 2.6%. Earlier analysis showed that given a rear-end collision, the presence of CHMSL on Vehicle 2 did not necessarily prevent the propagation of collision. The drivers of vans, pickup trucks and station wagon cars/trucks that are struck in position 1 experience a reduction in injury severity of 11.0% compared with passenger car drivers. Drivers of vans, pickup trucks and station wagon trucks that strike (in position 2) experience reduced injury severity by 4.6%. Overall, vans, pickup trucks and station wagon trucks provide greater driver protection when struck compared to when they strike another vehicle.

Driver 3—Second Striking Vehicle

Many of the explanatory variables tested are not significant in explaining Driver 3 injuries (Table 11). This can be partly due to the relatively small sample size for Driver 3 (N=487). Model 3 indicates that the signs of statistically significant variables are consistent with earlier models. CHMSL1 is marginally significant (10% level) suggesting that it reduces Driver 3 injury severity. This provides (weak) evidence that information can reduce the injury severity of following drivers. However, CHMSL2 is not statistically significant. Other significant variables associated with Driver 3 injuries are more lanes, the collision occurring at off-peak hours and the driver being male. Although not a main focus of this analysis, females are consistently less likely to be injured in rear-end crashes, despite their greater involvement in such collisions.

The marginal effects for CHMSL on Vehicle 1 indicate a 6.5% reduction in the chance of injury to Driver 3. This means that the presence of CHMSL on Vehicle 1 not only protects the Driver of Vehicle 1, but it also reduces Driver 2 and Driver 3 injuries. The effect of CHMSL on Vehicle 2 is not statistically significant, but the marginal effect shows a 3.3% reduction in injuries.

Potential Biases

Two possible biases are non-mileposting of the crash location (either by police officer or the computerized locating algorithm) and non-reporting of crash by driver(s). Five North Carolina counties with high non-location bias were excluded from the data set. While non-reporting is always a concern in a crash study, it is perhaps less of a concern on access-controlled roadways, that are relatively heavily patrolled by police and where higher AADT levels mean that noninvolved drivers may report the crash. Moreover, the presence of an "innocent" driver who is struck should reduce non-reporting.

In rear-end crashes non-reporting could bias the results if all vehicles in a collision are older and therefore do not meet the $1000 property damage requirement (and there are no injuries). If such bias exists and could be corrected for, then the results of the injury severity study will be more pronounced. That is, there will be more non-injury crashes of older vehicles that are now unreported.

Another potential bias can be due to 10% of the passenger cars of model years 1980 to 1985 having retrofitted CHMSL by 1987 (Kahane and Hertz 1998). In light trucks, CHMSL installation began as early as 1991. This means that the CHMSL variables in this data set may not be capturing all vehicles with CHMSL. This will make the CHMSL findings on injury severity more conservative (CHMSL may have an even greater positive effect on injury reduction than observed).

SECTION 4: CONCLUSIONS AND RECOMMENDATIONS

This study develops a conceptual structure for rear-end crash propagation and the resulting injury severity and it explores the effects of information while controlling for other factors. Real-life crash and inventory data on two-vehicle and three-vehicle rear-end crashes are analyzed. The study is based on a 1994-1995 Highway Safety Information System (HSIS) database for North Carolina limited-access roadways (N=3912 crashes; 12.5% three-vehicle rear-end collisions). Only passenger cars, vans, pickup trucks and station wagons (trucks and cars) involved in rear-end crashes are considered. Passenger cars constitute the largest portion of vehicles on these limited-access roadways and they are usually transparent compared with vans, pickup trucks and station wagon trucks that are often larger and opaque. Therefore, vehicle type is also used as a measure of whether a vehicle is transparent or opaque. To measure the presence of CHMSL, an indicator variable for vehicle model year was created. Passenger car and station wagon car models of 1986 or later and van, pickup truck and station wagon truck models of 1994 or later have mandatory CHMSL. While this variable captures the CHMSL effect, it may also contain the effects of other technology improvements that can reduce rear-end crash propagation and injury severity. These crash data provide greater realism (compared with hypothetical or driver reported data, for example), but the measures for driver information also contain other effects.

The analysis indicates that there is no statistical evidence to link the presence of CHMSL with lower crash propagation. That is, CHMSL are not necessarily more effective in rear-end crashes involving three-vehicles compared with two-vehicles. However, we found that passenger cars are less likely to be struck (in position 1) than to strike. Vans, pickup trucks and station wagons are more likely to strike (in positions 2 or 3). This is consistent with the hypothesis that drivers may respond to information from two or more vehicles ahead. The results on injury severity in rear-end crashes show that in a two-vehicle crash, the leading driver is more likely to be injured, whereas, in a three-vehicle crash, the driver in the middle is likely to be more severely injured. Furthermore, as rear-end crashes propagate from two-vehicle to three-vehicles the last driver is relatively less severely injured. To analyze injury severity on the KABCO scale, ordered probit models were estimated. The CHMSL variable used in three separate models estimated for Driver 1, 2 and 3 injuries is statistically significant. The presence of CHMSL on Vehicle 1 (and other safety improvements in recent years) provides protection in rear-end collisions to Driver 1 (8.7% reduction in injuries); its presence on Vehicle 2 protects Driver 2 (3.5% reduction in injuries). Interestingly, the presence of CHMSL on Vehicle 1 can reduce Driver 2 injuries by as much as 2.6% and Driver 3 injuries by 6.5%. Thus the presence of CHMSL on Vehicle 1 not only protects the Driver of Vehicle 1, but it also reduces Driver 2 and Driver 3 injuries. The drivers of vans, pickup trucks and station wagon cars/trucks that are struck in position 1 have 11.0% lower chances of getting injured compared with passenger car drivers. Drivers of vans, pickup trucks and station wagon cars/trucks that strike (in position 2) have a 4.6% lower chance of injury. Thus, vans, pickup trucks and station wagons provide greater driver protection to drivers when struck compared to when they strike another vehicle (although in both cases they are less likely to be injured than passenger car drivers). This result indicates that the vehicle mass effect exceeds the information blocking effect of larger vehicles. Furthermore, it was found that being struck by a larger vehicle (van, pickup truck or station wagon) is more injurious than striking a larger vehicle. Street-lighting mitigated the increased injury severity of nighttime crashes and males were consistently more severely injured in rear-end crashes, despite fewer of them getting involved in such crashes.

The results have the following implications for new safety technologies:

- The presence of CHMSL did not affect the propagation of rear-end collision. This means that there is a need and potential for early warning devices in preventing collision propagation. Furthermore, CHMSL seems to serve as an early warning device that reduces crash injury severity (given a collision) for all drivers involved in two-vehicle and three-vehicle rear-end crashes. Therefore CHMSL benefits are already accruing in collision situations and the additional injury reductions (given collisions) from driver information and warning technologies may be limited. To further reduce reaction times and reduce the risk of injuries in collision it might be valuable to have a Vehicle 2 information dissemination device that warns Driver 3 early (e.g., through dedicated displays on the rear of Vehicle 2 or through flashing the brake lights of Vehicle 2).
- The sight barriers from Vehicle 2 being opaque did not indicate higher crash propagation or injury risk. Instead we found that opaque vehicles, which in this data set are typically larger than passenger cars, provide greater protection to drivers of such vehicles.
- Reduced visibility at nighttime significantly contributes to injury severity in rear-end crashes. ITS vision enhancing and night vision devices that can allow the drivers of Vehicles 2 and 3 to sense the speed of Vehicles 1 and 2 respectively and any other events such as the presence of people can translate to reduced reaction times and injury risk in nighttime crash situations.

- The presence of snow/ice is associated with higher Driver 2 injury severity. Vehicle- and roadway-based advanced weather systems that can monitor the presence of snow and ice can provide useful information/warnings to drivers.

This research points towards important future research areas:

- Better quality data. Further research into information effects on crash propagation with better crash data is needed. Due to data limitations, we were not able to fully distinguish between the effects of CHMSL and other safety improvements such as shatter-resistant windshields and crash cages.
- Analysis of other roadway classifications and locations. There is a need to examine the effects of driver information on partial access control and no access control roadways. Furthermore, there is a need to examine injuries in rear-end crashes across states.

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References

(1) Beymer, B., and R. Hochnadel. Chained information systems: An aid to prevent rear-end collisions. Paper no. 940763, *Transportation Research Board,* National Research Council, Washington, D.C. 1994.

(2) Duncan, C., Khattak, A., Council, F. Applying the ordered probit model to injury severity in truck-passenger car rear-end collisions. *Transportation Research Record* 1635, TRB, Washington, D. C., National Research Council, pp. 63-71, 1998.

(3) Evans, L. Traffic Safety and the Driver, Van-Nostrand Reinhold, New York, 1991.

(4) Farber, E., *Modelling rear-end collisions and countermeasures.* International Conference on Application of New Technology to Transport Systems, Melbourne, Australia, May 1995 Vol. 1. ITS Australia, Parkville, Victoria, pp. 327-340, 1995.

(5) Farmer, C. Effectiveness Estimates for Center High Mounted Stop Lamps: A Six-Year Study, *Accident Analysis and Prevention*, Vol. 28, February 1996.

(6) Greene, W. *Econometric Analysis,* New York, NY: Macmillan Publishing Co., Third Edition, 1997.

(7) Kahane, C. *An Evaluation of Center High Mounted Stop Lamps Based on 1987 Data*, NHTSA, Report DOT HS 807 442, Washington, D.C., 1989.

(8) Kahane, C. and E. Hertz. *The Long-Term Effectiveness of Center High Mounted Stop Lamps in Passenger Cars and Light Trucks.* NHTSA Technical Report, US DOT, Washington, D.C., March 1998.

(9) Knipling, R., *A Front-end analysis of rear-end crashes. Surface transportation and the information age.* Proceedings of the IVHS America 1992 Annual Meeting,

Newport Beach, California, May 17-20, 1992. Vol. 2. IVHS America, Washington, D.C., pp. 733-745, 1992.
(10) O'Donnell, C., and Connor, D. Predicting the severity of motor vehicle accident injuries using models of ordered multiple choice, *Accident Analysis and Prevention*, 28:6, pp. 739-753, 1996.
(11) Shefer, J., *A New Kind of Radar for Collision Avoidance.* SAE Automotive Engineering Congress, Detroit, Michigan, SAE Technical Paper 740096, February 25- March 1 pp. 481-493, 1974.

Table 1. Vehicle Types in the 1994-1995 North Carolina HSIS Collisions Data Set.

Vehicle Type	All Freeway Crashes	Rescaled All Freeway Crashes	All Freeway Rear-end Crashes	Rescaled All Freeway Rear-end Crashes
Passenger Car	62%	76%	66%	78%
Station Wagon	8%	10%	8%	10%
Pickup Truck	8%	10%	7%	8%
Van	4%	5%	3%	4%
Other Vehicles	19%	*	17%	*
TOTAL	100%	100%	100%	100%

Note: Passenger Car = Two or four door sedan. Station Wagon = Station wagon car or truck. Other vehicles include large trucks, bus, recreational vehicles, farm equipment, motorcycles and ambulances.

Table 2. Vehicle Types by Position in 1994-1995 North Carolina Rear-end Collisions Data Set.

Vehicle Type	Selected Crashes Pos. #1	Selected Crashes Pos. #2	Selected Crashes Pos. #3	Difference in means #1 - #2	Standard error of difference in means #1-#2	t-test #1 - #2
Passenger Car	69.1%	73.1%	71.5%	-4	0.0102	-3.91*
Station Wagon	10.8%	8.3%	8.4%	2.5	0.0066	3.77*
Pickup Truck	13.4%	13.9%	15.6%	-0.5	0.0078	-0.64
Van	6.8%	4.8%	4.5%	2	0.0053	3.79*
TOTAL	100%	100%	100%			

*Difference is significant at the 5% level. Passenger Car = Two or four door sedan. Station Wagon = Station wagon car or truck. Other vehicles include large trucks, bus, recreational vehicles, farm equipment, motorcycles and ambulances.

Table 3. Center High Mounted Stoplight (CHMSL) by Number of Vehicles Involved in North Carolina Rear-end Collisions.

Center High Mounted Stoplight		**Two-Vehicle Crash Count**	**Two-Vehicle Crash Percent**	**Three-Vehicle Crash Count**	**Three-Vehicle Crash Percent**	**Total**
CHMSL ON VEH 1	**Not present**	1115	90.0%	124	10.0%	1239
	Present	2310	86.4	363	13.6	2673
CHMSL ON VEH 2	**Not present**	1133	89.8	128	10.2	1261
	Present	2292	86.5	359	13.5	2651
CHMSL1 & CHMSL2	**Not present**	1833	89.5	216	10.5	2049
	Present	1592	85.5	271	14.5	1863

Table 4. Summary statistics of relevant variables for rear-end crash propagation

Variable	Description	Mean	Std. Dev.	Minimum/ Maximum
THREEVEH	1 if crash involves three vehicles, 0 else	0.1245	*	0/1
SPEED_LIMT	Speed limit	56.49	4.08	35/65
WET	1 if wet conditions, 0 else	0.2178	*	0/1
SNOWICE	1 if snow or ice, 0 else	0.01738	*	0/1
CURVGRD	1 if curve and grade, 0 else	0.05803	*	0/1
CURVLVL	1 if curve and level, 0 else	0.02658	*	0/1
CURVOTR	1 if curve & hill crest or bottom, 0 else	0.01713	*	0/1
STRTGRD	1 if straight and grade, 0 else	0.2408	*	0/1
STRTOTR	1 if straight & hill crest or bottom, 0 else	0.04857	*	0/1
AADT*1000	Average annual daily traffic volume	61.280	27.428	2.1/123.4
PEAKTIME	1 if weekday commute time, 0 else	0.5488	*	0/1
NIGHTLITE	1 if dark, street lit, 0 else	0.0491	*	0/1
NIGHTDARK	1 if dark, not lit, 0 else	0.1076	*	0/1
DUSKDAWN	1 if dusk or dawn, 0 else	0.0478	*	0/1
CHMSL1	1 if vehicle 1 has CHMSL, 0 else	0.6833	*	0/1
CHMSL2	1 if vehicle 2 has CHMSL, 0 else	0.6777	*	0/1
VAN1	1 if vehicle 1 is a van, 0 else	0.0677	*	0/1
VAN2	1 if vehicle 2 is a van, 0 else	0.0481	*	0/1
WAGON1	1 if vehicle 1 is a station wagon, 0 else	0.1076	*	0/1
WAGON2	1 if vehicle 2 is a station wagon, 0 else	0.0826	*	0/1
PICKUP1	1 if vehicle 1 is a pickup truck, 0 else	0.1339	*	0/1
PICKUP2	1 if vehicle 2 is a pickup truck, 0 else	0.1385	*	0/1
DRV_SEX1	1 if vehicle 1 driver is female, 0 if male	0.5404	*	0/1
DRV_SEX2	1 if vehicle 2 driver is female, 0 if male	0.6071	*	0/1
DRV_AGE 1	Age of driver of vehicle 1	37.88	13.93	15/97
DRV_AGE2	Age of driver of vehicle 2	34.20	14.22	6/97
NO_LANES	Number of lanes	4.483	0.96	4/8
VIOL1	1 if vehicle 1 driver charged with violation, 0 else	0.0532	*	0/1
VIOL2	1 if vehicle 2 driver charged with violation, 0 else	0.8727	*	0/1
VEHYR1	Vehicle 1 model year	1989	4.78	31/96

VEHYR2	Vehicle 2 model year	1989	4.57	52/96
Vehicle 3 Statistics N=487				
AADT	Average annual daily traffic volume	71.076	26.094	2.1/123.4
CHMSL3	1 if vehicle 3 has CHMSL, 0 else	0.6940	*	0/1
DRV_SEX3	1 if vehicle 3 driver is female, 0 if male	0.6407	*	0/1
VIOL3	1 if vehicle 3 driver charged with violation, 0 else	0.9836	*	0/1
VEHYR3	Vehicle 3 model year	1989	4.44	68/96

The mean values of the variables for Driver 3 are based on N=487, mean values for Drivers 1 and 2 are based on N=3425, otherwise statistics are based on full sample N=3912.

Table 5. Results of Binary Logit Regression Model of Propagation Probability

Variable	B	P (Sig.)	Mean	Marginal Effect
AADT	0.0000114	0.0000*	61280	1.24524E-06
PEAKTIME	0.6055	0.0000*	0.5488	0.066139605
CHMSL1	0.2271	0.0818	0.6833	0.024806448
CHMSL2	0.3021	0.0181*	0.6777	0.032998802
CURVGRD	-0.9536	0.0018*	0.058	-0.104163051
CURVLEV	-0.3468	0.3115	0.0266	-0.037881445
CURVOTH	-0.8897	0.0895	0.0171	-0.097183165
STRTGRD	-0.1349	0.2608	0.2408	-0.014735314
STRTOTH	-0.8947	0.0074*	0.0486	-0.097729322
SPEED_LIMT	0.0009	0.9523	56.49	9.83082E-05
NIGHTDARK	-0.0385	0.8275	0.1076	-0.004205408
NIGHTLIGHT	0.1686	0.4385	0.0491	0.018416412
DUSKDAWN	-0.0286	0.9004	0.0478	-0.003124018
AGE1	0.0084	0.6719	37.8755	9.17544E-04
AGE2	0.0143	0.4046	34.2037	0.001562009
AGE1 SQ	-0.0001	0.6262	1628.659	-1.09231E-05
AGE2 SQ	-0.0001	0.4543	1371.945	-1.09231E-05
VAN1	-0.2796	0.2532	0.0677	-0.030541096
VAN2	-0.0279	0.9178	0.0481	-0.003047556
WAGON1	0.0838	0.5973	0.1076	0.00915359
WAGON2	-0.2017	0.3029	0.0826	-0.022031971
PICKUP1	-0.1472	0.4115	0.1339	-0.01607886
PICKUP2	0.0003	0.9988	0.1385	3.27694E-05
DRV_SEX1	0.1223	0.243	0.5404	0.013358999
DRV_SEX2	0.223	0.0374*	0.6071	0.024358599
SNOWICE	0.0121	0.9782	0.0174	0.0013217
WET	-0.0117	0.9247	0.2178	-0.001278007
Constant	-3.9628	0.0002*		

N = 3912, dof=27, *=Significant at 5% level, Model Significance = 0.0000

Table 6. Sequence Of Vehicle Types in Rear-End Collisions (relative frequencies in parentheses)

Vehicle 2	Vehicle 1				
	Passenger Car	**Station Wagon**	**Van**	**Pickup Truck**	**TOTAL**
Passenger Car	75% (1.03)	68% (0.94)	71% (0.97)	67% (0.92)	73% (1.00)
Station Wagon	7% (0.90)	14% (1.70)	5% (0.64)	9% (1.13)	8% (1.00)
Van	4% (0.83)	4% (0.84)	11% (2.36)	6% (1.31)	5% (1.00)
Pickup Truck	13% (0.96)	14% (0.98)	13% (0.93)	17% (1.25)	14% (1.00)
TOTAL	100%	100%	100%	100%	100%

Table 7. Expectations Regarding Effects of Various Factors (When Present or Higher) on Injury Severity in Rear-End Collisions.

Increase or Presence of Variable	A-Priori Expectations		
	Driver 1 (Leading)	**Driver 2 (Following)**	**Driver 3 (Following)**
CHMSL ON VEHICLE 1	Reduce injury severity due to info & lower impact speed	Reduce injury severity due to info & lower impact speed	Some effect especially if Vehicle 2 is transparent (else no effect)
CHMSL ON VEHICLE 2	No/minor effect	Reduce injury due to info & lower impact speed	Reduce injury due to info & lower impact speed
LARGER VEHICLE 1	Reduce injury due to larger mass; increase injury due to opaqueness (lack of Vehicle 2 info)	Increase injury severity due to opaqueness (lack of info) and striking larger mass	No/minor effect
LARGER VEHICLE 2	Increase injury due to larger striking mass	Reduce injury severity due to larger mass; increase injury due to opaqueness (lack of Vehicle 3 info)	Increase injury severity due to opaqueness (lack of info) and striking larger mass
LARGER VEHICLE 3	No/minor increase	Increase injury severity due to larger striking mass	Reduce injury severity due to larger mass
THREE-VEH. COLLISION	Increase injury severity due to two jolts	Increase injury severity due to two jolts	Not relevant
SPEED_LIMT	Higher speed collisions increase injury severity	Higher speed collisions increase injury severity	Higher speed collisions increase injury severity
NO. OF LANES	Unknown	Unknown	Unknown
AVERAGE DAILY TRAFFIC	More traffic reduces speeds and injury severity	More traffic reduces speeds and injury severity	More traffic reduces speeds and injury severity
DARK	Lower visibility increases injury severity	Lower visibility increases injury severity	Lower visibility increases injury severity
DARK LIT	Lighted roads neutralizes the effect of darkness	Lighted roads neutralizes the effect of darkness	Lighted roads neutralizes the effect of darkness
DUSK OR DAWN	Lower visibility increases injury severity	Lower visibility increases injury severity	Lower visibility increases injury severitybhgfjuuujikkkkii u6t6t
PEAK TIME	Reduce injury severity due to slower moving traffic	Reduce injury severity due to slower moving	Reduce injury severity due to slower moving
GRADE	Increase injury severity due to less control	Increase injury severity due to less control	Increase injury severity due to less control
WET SURFACE	Increase injury due to slippery surface/ Reduce injury due to cautious driving	Increase injury due to slippery surface/ Reduce injury due to cautious driving	Increase injury due to slippery surface/ Reduce injury due to cautious driving
SNOW OR ICE	Increase injury due to	Increase injury due to	Increase injury due to

	slippery surface/ Reduce injury due to cautious driving	slippery surface/ Reduce injury due to cautious driving	slippery surface/ Reduce injury due to cautious driving
DRIVER 1 AGE	Older drivers more prone to injury	No effect	No effect
DRIVER 2 AGE	No effect	Older drivers more prone to injury	No effect
DRIVER 3 AGE	No effect	No effect	Older drivers more prone to injury
DRIVER 1 FEMALE	Females physiologically more prone to injuries; but less aggressive drivers	No effect	No effect
DRIVER 2 FEMALE	No effect	Females physiologically more prone to injuries; but less aggressive drivers	No effect
DRIVER 3 FEMALE	No effect	No effect	Females physiologically more prone to injuries; but less aggressive drivers

Note: CHMSL = Center-High Mounted Stop Light

Table 8. Overview of Driver Injuries—Observed and (Expected) Injuries in Two-vehicle and Three-vehicle Rear-end Collisions.

Driver Injury	Two-Vehicle			Three-Vehicle				Grand Total
	Driver 1	**Driver 2**	Total	**Driver 1**	**Driver 2**	**Driver 3**	Total	
No Injury	2355 (2685.0) 68.8%	3015 (2685.0) 88.0%	5370	372 (359.3) 76.4%	303 (359.3) 62.2%	403 (359.3) 82.8%	1078	6448
C Injury	963 (628.5) 28.1%	294 (628.5) 8.6%	1257	109 (108.7) 22.4%	160 (108.7) 32.9%	57 (108.7) 11.7%	326	1583
B Injury	81 (89.5) 2.4%	98 (89.5) 2.9%	179	5 (17.0) 1.0%	22 (17.0) 4.5%	24 (17.0) 4.9%	51	230
A Injury	25 (21.5) 0.7%	18 (21.5) 0.5%	43	1 (2.0) 0.2%	2 (2.0) 0.4%	3 (2.0) 0.6%	6	49
Killed	1 (0.5) 0.0%	0 (0.5) 0%	1	0 (0) 0.0%	0 (0) 0.0%	0 (0) 0.0%	0	1
TOTAL	**3425**	**3425**	6850	**487**	**487**	**487**	1461	**8311**

Two-Vehicle: Chi-square = 440.926, $p = 0.000$
Three-Vehicle: Chi-square = 77.224, $p = 0.000$

Notes:
1. Column percentages reported.
2. The expected values for two-vehicle and three-vehicle collisions are computed separately.

Table 9. Modeling Results and Marginal Effects for Driver 1 Injury Analysis

Variables	Coefficient And Test Statistic			Marginal Effects			
	B	P	Mean	Inj.=0	Inj.=1	Inj.=2	Inj.=3
Constant	-1.0614	0.00889		0.3667	-0.3060	-0.0447	-0.0161
THREEVEH	-0.21657	0.00148	0.1245	0.0748	-0.0624	-0.0091	-0.0033
AADT/10000	0.00233	0.78918	6.128	-0.0008	0.0007	0.0001	0.0000
SPD_LIMT	0.00493	0.38812	56.49	-0.0017	0.0014	0.0002	0.0001
NO_LANES	0.00340	0.88577	4.489	-0.0012	0.0010	0.0001	0.0001
STRTGRD	0.09281	0.04983	0.2408	-0.0321	0.0268	0.0039	0.0014
DRV_AGE1	0.03396	0.00002	37.88	-0.0117	0.0098	0.0014	0.0005
AGE1_SQ	-0.00036	0.00005	1629.	0.0001	-0.0001	0.0000	0.0000
BIG_VEH1	-0.31872	0.00000	0.3093	0.1101	-0.0919	-0.0134	-0.0048
BIG_VEH2	0.16730	0.00096	0.2692	-0.0578	0.0482	0.0070	0.0025
DRV_SEX1	-0.33463	0.00000	0.5404	0.1156	-0.0965	-0.0141	-0.0051
CHMSL1	-0.25155	0.00000	0.6833	0.0869	-0.0725	-0.0106	-0.0038
CHMSL2	-0.04446	0.36196	0.6777	0.0154	-0.0128	-0.0019	-0.0007
NIGHTLITE	0.11986	0.20925	0.0491	-0.0414	0.0346	0.0051	0.0018
NIGHTDARK	0.11800	0.08059	0.1076	-0.0408	0.0340	0.0050	0.0018
DUSKDAWN	-0.10419	0.30606	0.0478	0.0360	-0.0300	-0.0044	-0.0016
PEAKTIME	-0.09578	0.03631	0.5445	0.0331	-0.0276	-0.0040	-0.0014
μ_1	1.4341	0.00000	--	--	--	--	--
μ_2	2.0219	0.00000	--	--	--	--	--

N=3912 Chi-squared = 181.3856 Degree of freedom = 16 Sig.=0.0000
Log likelihood function =-2743.717 Restricted log likelihood = -2834.410

Table 10. Modeling Results and Marginal Effects for Driver 2 Injury Analysis

Variables	Coefficient And Test Statistic			Marginal Effects			
	B	**P**	**Mean**	**Inj.=0**	**Inj.=1**	**Inj.=2**	**Inj.=3**
Constant	-1.3703	0.00292		0.2951	-0.2116	-0.0699	-0.0136
THREEVEH	0.83297	0.00000	0.1245	-0.1794	0.1286	0.0425	0.0082
AADT/10000	-0.03897	0.00017	6.128	0.0084	-0.0060	-0.0020	-0.0004
SPD_LIMT	0.00492	0.46738	56.49	-0.0011	0.0008	0.0003	0.0000
NO_LANES	0.06629	0.01819	4.489	-0.0143	0.0102	0.0034	0.0007
WET	0.05459	0.37273	0.2178	-0.0118	0.0084	0.0028	0.0005
SNOWICE	0.33660	0.03999	0.0174	-0.0725	0.0520	0.0172	0.0033
STRTGRD	0.03798	0.51216	0.2408	-0.0082	0.0059	0.0019	0.0004
DRV_AGE2	0.01240	0.13995	34.20	-0.0027	0.0019	0.0006	0.0001
AGE2_SQ	-0.00010	0.29412	1372.	0.0000	0.0000	0.0000	0.0000
BIG_VEH1	0.02147	0.71201	0.3093	-0.0046	0.0033	0.0011	0.0002
BIG_VEH2	-0.21261	0.00150	0.2692	0.0458	-0.0328	-0.0108	-0.0021
DRV_SEX2	-0.35230	0.00000	0.6071	0.0759	-0.0544	-0.0180	-0.0035
CHMSL1	-0.12046	0.03606	0.6833	0.0259	-0.0186	-0.0061	-0.0012
CHMSL2	-0.16029	0.00821	0.6777	0.0345	-0.0248	-0.0082	-0.0016
NIGHTLITE	0.14235	0.22440	0.0491	-0.0306	0.0220	0.0073	0.0014
NIGHTDARK	0.34285	0.00000	0.1076	-0.0738	0.0529	0.0175	0.0034
DUSKDAWN	-0.22939	0.10436	0.0478	0.0494	-0.0354	-0.0117	-0.0023
PEAKTIME	-0.13212	0.01841	0.5445	0.0284	-0.0204	-0.0067	-0.0013
μ_1	0.82835	0.00000	--	--	--	--	--
μ_2	1.6082	0.00000	--	--	--	--	--

N=3912 Chi-squared = 274.8048 Degree of freedom = 18 Sig.=0.0000
Log likelihood function = -1910.449 Restricted log likelihood = -2047.852

Table 11. Modeling Results and Marginal Effects for Driver 3 Injury Analysis

Variables	Coefficient And Test Statistic			Marginal Effects			
	B	**P**	**Mean**	**Inj.=0**	**Inj.=1**	**Inj.=2**	**Inj.=3**
Constant	0.61595	0.64819		-0.1460	0.0903	0.0493	0.0065
AADT/10000	-0.03495	0.24976	7.108	0.0083	-0.0051	-0.0028	-0.0004
SPD_LIMT	-0.01649	0.46063	55.97	0.0039	-0.0024	-0.0013	-0.0002
NO_LANES	0.12671	0.08591	4.618	-0.0300	0.0186	0.0101	0.0013
STRTGRD	0.12891	0.46218	0.2279	-0.0306	0.0189	0.0103	0.0014
DRV_AGE3	-0.02133	0.30055	34.85	0.0051	-0.0031	-0.0017	-0.0002
AGE3_SQ	0.00032	0.14955	1437.	-0.0001	0.0000	0.0000	0.0000
BIG_VEH2	0.21602	0.26707	0.2320	-0.0512	0.0317	0.0173	0.0023
BIG_VEH3	-0.17035	0.37223	0.2854	0.0404	-0.0250	-0.0136	-0.0018
DRV_SEX3	-0.42226	0.00735	0.6407	0.1001	-0.0619	-0.0338	-0.0045
CHMSL1	-0.27211	0.09145	0.7454	0.0645	-0.0399	-0.0218	-0.0029
CHMSL2	-0.13921	0.45991	0.7372	0.0330	-0.0204	-0.0111	-0.0015
NIGHTLITE	-0.00241	0.99421	0.0616	0.0006	-0.0004	-0.0002	0.0000
NIGHTDARK	0.03307	0.89441	0.0883	-0.0078	0.0048	0.0026	0.0003
DUSKDAWN	0.47871	0.09228	0.0513	-0.1135	0.0702	0.0383	0.0051
PEAKTIME	-0.38025	0.01339	0.6571	0.0902	-0.0557	-0.0304	-0.0040
μ_1	0.70200	0.00000	--	--	--	--	--
μ_2	1.6746	0.00000	--	--	--	--	--

N=487 Chi-squared = 37.76027 Degree of freedom = 15 Sig.= 0.0001
Log likelihood function = -267.2100 Restricted log likelihood = -286.0901

Figure 1. Vehicle 1 Model Year by Number of Vehicles Involved

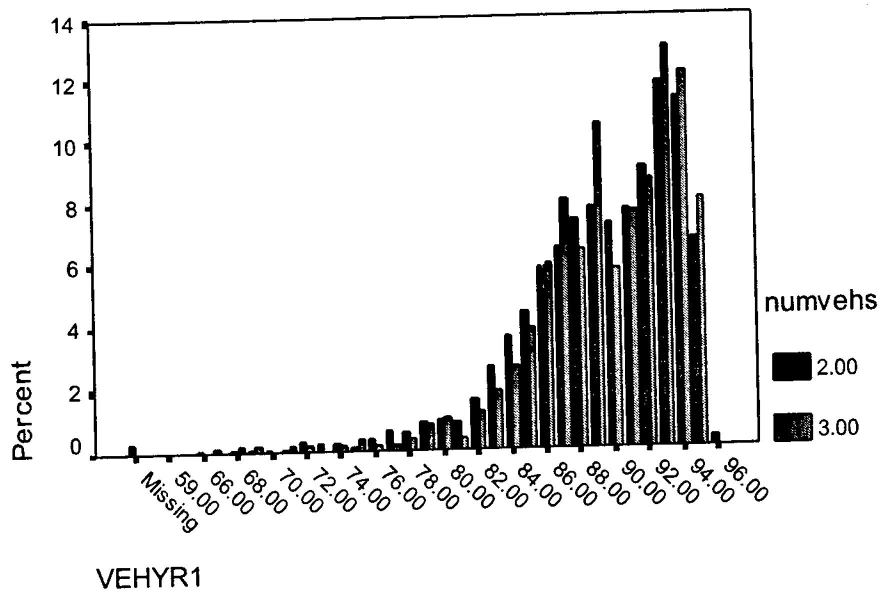

Figure 2. Vehicle 2 Model Year by Number of Vehicles Involved