Exploring Driver Error at Intersections

Key Contributors and Solutions

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A large portion of crashes occur at intersections, and most such crashes are associated with driver mistakes. Severe mistakes may lead to serious injuries; therefore, it is necessary to investigate the factors that contribute to driver error and how those factors influence driver behavior. More information on these contributing factors can help researchers develop cost-effective countermeasures that might help mitigate driver error. The primary objective of this study was to examine key contributors to driver error that took place at uncontrolled, sign-controlled, and signalized intersections. An ordered-probit statistical model and a data-mining technique called "association rules" were implemented to explore these relationships. The results of both approaches were consistent. Association rules were found to be capable of discovering patterns in the data that could not be found in the ordered-probit statistical model. The secondary objective of this study was to provide new insights on how to improve intersection safety by adding to the knowledge regarding the contributing factors of those driver errors. Most, if not all, errors are related to human factors; thus, they can effectively be corrected through a holistic approach that involves engineering, enforcement, and education.

An intersection is where two or more roads meet. Traffic control devices make it possible for vehicles, bicyclists, and pedestrians to move through an intersection in a safe, orderly, and efficient manner. The safety of vehicles, pedestrians, or cyclists can be compromised when an intersection is inappropriately designed, when traffic control devices are not working efficiently, or when drivers make errors. In the past decade, FHWA, ITE, AASHTO, and other private and public institutions have made a strong commitment to improving intersection safety. As a result, the number of fatal crashes taking place at intersections declined by 20% between 1998 and 2012. Still, 6,962 crashes occurring at intersections in 2012 were fatal, which is 23% of total highway fatalities (*1*). The effort to minimize the negative impacts of intersection crashes continues to be a top priority of transportation agencies and professionals.

Despite different study results, it is well acknowledged that driver error is a key contributor to crashes and fatalities, including intersection crashes (*2*). According to police records, driver errors can range from a traffic infraction in which the driver is not paying attention to an intentional traffic violation such as failure to yield or significantly exceeding the speed limit. Relating driver error to other revealed factors can substantiate the knowledge regarding how human factors guide roadway design and traffic control. Since driver error can depend on the type of traffic control present at an intersection (e.g., disregard for traffic control will not occur at uncontrolled intersections), the analysis should distinguish between signalized, sign-controlled, and uncontrolled intersections. Grouping driver errors by intersection control type also provides a view of the driver's reaction to traffic control devices (e.g., signals, signage, pavement marking), traffic density, speed, and turning movements. Turning movements include left- and right-turning vehicles and are closely related to the type of control warranted for an intersection.

It is imperative to identify and understand the factors that could increase the likelihood of these driver errors, since this knowledge could lead to development of cost-effective enforcement strategies, driver education and training programs, and engineering solutions that would help reduce driver error at intersections. The objectives of this study are to examine the common driver errors leading to crashes, explore the critical factors affecting different types of driver error and identify the effects of these factors by intersection type, and recommend cost-effective countermeasures to mitigate driver error.

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LITERATURE REVIEW

Human factors are a critical component of any traffic safety–related study. In recent years, a number of studies have investigated how driver error affects intersection-related crashes (*3–11*). Researchers in Australia found that the majority of intersection crashes occurred at sign-controlled intersections, mainly in rural areas (*3*). The common errors at this type of intersection are failing to stop (*4, 5*) and failing to yield to the approaching vehicle in a conflicting road (*6*). At signalized intersections, crashes usually occur because of errors made by the driver (*3*). Common errors in this scenario include driving at too high a speed, selecting an inappropriate gap, running a red light, and choice in the dilemma zone (*3*). The most common errors at uncontrolled intersections are failing to yield the right-of-way and incorrectly judging the speed of an approaching vehicle during a turn (*12*). Failure to see and then colliding with cyclists is another error frequently made at uncontrolled intersections. Drivers in these instances are more focused on watching approaching vehicles, and therefore may fail to notice the cyclists (*3*).

Crash type is often associated with specific driver errors. Wang and Abdel-Aty showed that angle crashes at signal-controlled intersections are mainly associated with the driver's failure to stop at a red light or turning at an inappropriate time during the red signal (*7*). Bao and Boyle and Preusser et al. found that angle crashes at sign-controlled intersections are mostly due to the driver's poor visualization and failure to yield the right-of-way (*4, 8*). Researchers have also found that most rear-end crashes are associated with the driver's lack of attention (e.g., disregarding the brake light of the leading vehicle) (*7, 9, 10*) or by vehicle operation errors (e.g., failure to stop while braking during poor weather conditions) (*11*). Since crash type and injury severity are closely related (e.g., head-on or angle crashes are more severe than rear-end crashes), studying driver errors can help identify countermeasures that mitigate injury severity.

Several studies have investigated the various contributors to driver error. Findings indicate that drivers over 60 years of age are more likely to fail to stop or fail to yield the right-of-way at an intersection (*5, 8, 11*). Older drivers also have a higher probability of driving under the influence due to medicine use and disability (*13*). Younger drivers are more likely to violate red signals because of their more aggressive and risky driving behavior (*14–16*). A study conducted by Papaioannou indicated that women are less likely to disregard yellow signals and tend to drive slower than men (*17*). Bonneson et al. suggested that heavy vehicles are more likely to be involved in running a red light (*18*). Devlin et al. discovered the increased probability of failure to notice traffic signs at sign-controlled intersections on vertical and horizontal curves (*3*).

These findings have led to constructive recommendations and the development of specific safety countermeasures that can minimize the probability of driver error (*3, 19–26*). According to NCHRP Report 600 on human factor guidelines, when a road system is properly created, potential errors can be prevented by eliminating (*a*) the unintended use of infrastructure, (*b*) nonuniform and inconsistent traffic control and design applications, (*c*) large speed differentials, and (*d*) uncertain driver behavior (*24*). For example, Wierwille et al. suggested increasing the conspicuity of traffic signs and signals to decrease the probability that traffic rules will be violated (*2*). Devlin et al. recommended offering education and training to teenagers and older drivers to reduce their driving mistakes at intersections (*3*). Tay showed that the enforcement of measures against drinking and driving can help to significantly reduce drinking- and driving-related driver errors in Australia, especially for younger drivers (*23*). From this literature, the study conducted by Devlin et al. (*3*) synthesized previous studies relating to driver error and summarized the most common errors at signal-controlled intersections, sign-controlled intersections, uncontrolled intersections, and roundabouts; analyzed the effects of driver characteristics, environmental factors, roadway and traffic factors, and vehicle type on driver error; and provided specific countermeasures to minimize the probability of driver error at intersections.

Built on previous research, this study is an attempt to reveal the relationship between other observable factors and driver errors made at signalized, sign-controlled, and uncontrolled intersections.

METHODOLOGY

In this section a statistical discrete choice model (ordered-probit model) and an association discovery approach (association rules) are presented. Although the statistical method alone can effectively identify the statistically significant correlation between variables, the association rules may help discover new dependencies between driver errors and other factors. The association rules are based on the relative frequency of sets of items occurring alone and together (*27*).

Ordered-Probit Model

The ordered-probit model is used to account for the ordinal nature of the dependent variables. The structure of an ordered-probit model is derived by defining an unobserved latent variable U, which can be described as a linear function for each observation:

$$U = \boldsymbol{\beta}'\boldsymbol{X} + \varepsilon \tag{1}$$

where $\boldsymbol{X}$ is a vector of independent variables defining the discrete ordering for each observation, $\boldsymbol{\beta}$ is a vector of coefficients needed to estimate, and ε is an error term accounting for the unobservable effects. With regard to this structure, the observed ordinal dependent variable, or the driver error for each observation in this study, is defined as (*28*)

$$\left.\begin{array}{ll} y = 1 & \text{if } U \le \mu_1 \\ y = 2 & \text{if } \mu_1 \le U \le \mu_2 \\ y = 3 & \text{if } \mu_2 \le U \le \mu_3 \\ y = I & \text{if } U \ge \mu_{I-1} \end{array}\right\} \tag{2}$$

where the μ's are estimated thresholds that define y and I is the highest integer level in terms of the dependent variable. If the random error term ε is assumed to follow a standard normal distribution, the model is derived to be an ordered-probit model. The probability of each category can be calculated as follows:

$$\text{prob}(y = i) = \Phi(\mu_i - \boldsymbol{\beta}'\boldsymbol{X}) - \Phi(\mu_{i-1} - \boldsymbol{\beta}'\boldsymbol{X}) \tag{3}$$

where i is the category to be analyzed, and $\Phi(\cdot)$ is the cumulative standard normal distribution.

Association Rules

Association rules are an association discovery approach used to identify the relative frequency of sets of items (i.e., driver error patterns in this study) occurring alone and together in a given event (a crash observation in this study) (*27*). The rules have the form $A \rightarrow B$ in which A is the antecedent and B is the consequent. In association rules, the rules can be expressed by support, confidence, and lift. Support is the percentage of a rule that exists in the whole data set. Confidence is the proportion of consequents among antecedents. Lift is a mathematical measurement to quantify the statistical dependence of a rule. The three indexes can be calculated as follows:

$$\text{support}(A \rightarrow B) = \frac{\#(A \cap B)}{N} \qquad \text{confidence} = \frac{\text{support}(A \rightarrow B)}{\text{support}(A)}$$
$$\text{lift} = \frac{\text{support}(A \rightarrow B)}{\text{support}(A) \times \text{support}(B)} \tag{4}$$

where N is the number of crashes and $\#(A \cap B)$ is the number of crashes in which both Conditions A (antecedent) and B (consequent) are fitted. The lift of the rule indicates the number of co-occurrences of the antecedent and consequent to the expected co-occurrences under the assumption that the antecedent and the consequent are independent. A value smaller than 1 indicates negative dependence between the antecedent and the consequent. A value equal to 1 indicates independence, and a value greater than 1 indicates positive dependence. The higher the lift, the greater the dependence (*27, 29*).

For example, in the rule "reckless driving → alcohol (support = 1%, confidence = 50%, lift = 5)," support indicates that the proportion of observations including both reckless driving errors and alcohol is 1% in the whole data set; confidence indicates that the proportion of observations including both reckless driving errors and alcohol is 50% in the data set including alcohol; and lift indicates that reckless driving errors are positively associated with alcohol.

DATA COLLECTION AND ANALYSIS

Data in this study include 7,203 intersection-related crashes that occurred in Madison, Wisconsin, between 2008 and 2010. Intersection-related crashes accounted for approximately 51% of all crashes in the data set, and 83% of intersection-related crashes were related to driver error. Crashes were further categorized by the intersection's traffic control strategy (uncontrolled, sign-controlled, and signalized) as suggested by Devlin et al. (*3*). Roundabouts were omitted because of their low count and the fact that a very limited number of crashes occurred in roundabouts.

Specific driver errors were extracted from the Wisconsin Motor Vehicle Accident Reporting Form 4000 (MV4000), on which the investigating police officers documented detailed accident information (*30, 31*). It is not unusual for one crash to be associated with multiple violations. If no driver factors (or errors) apply, the "NA" bubble in the traffic accident report was marked (*31*). According to citation documentation for traffic violations in Wisconsin, driver errors are classified as improper, careless, or reckless driving with an increasing ordinal nature to account for the severity of the violation (*32*). For example, improper overtaking, improper turning, or driving too fast for the road conditions are traffic infractions that are punishable by a fine of no more than $500. Careless driving incidents such as following too close, failing to keep the vehicle under control, driving inattentively, driving left of center, or backing in an unsafe manner are often defined as operation of a motor vehicle in an offensive and negligent manner but doing so unintentionally. These offenses are punishable by a fine that is higher than the improper driving fine. Reckless driving is usually defined as a mental state in which the driver intentionally breaks traffic rules. It often causes severe accidents or other damage and is punishable by fines, imprisonment, driver license suspension or revocation, or all three (*14, 15*). Reckless driving violations include a disregard for traffic control, failure to yield, and exceeding the speed limit. The upper part of Table 1 includes all driver errors and describes the distribution of specific driver errors by intersection type. The lower part of Table 1 describes the distribution of specific driver error severities by intersection type; only the most severe driver errors were considered.

The number and severity of driver errors vary by intersection type. As shown in Table 1, sign-controlled intersections have the lowest total number of driver errors but the highest percentage of reckless driving violations; this result is almost two times the number of violations occurring at uncontrolled or signalized intersections. More driver errors were recorded at signalized intersections than at uncontrolled and sign-controlled intersections combined, but the severity distributions of signalized intersections and uncontrolled sites are very close. Within each severity type, specific driver errors vary by intersection type as well. For reckless driving, "failure to yield" is fairly prevalent across all intersection types, but it is a dominating violation for sign-controlled intersections. For careless driving, "inattentive driving" is the most frequently made mistake, followed by "following too close," every type of intersection. For improper driving, "improper turning" and "too fast for condition" are most commonly observed at uncontrolled intersections.

Recognizable patterns may exist in other factors than in traffic control. Crashes with driver errors were classified into four categories: driver characteristics, highway and traffic characteristics, environmental factors, and vehicle type. The corresponding distribution is presented in Table 2.

TABLE 1 Distribution of Driver Errors by Intersection Type

	Frequency of All Crashes (%)		
Category	Uncontrolled (1,739)	Sign-Controlled (1,580)	Signal-Controlled (3,884)
All Driver Errors			
No errors	319 (18%)	200 (13%)	682 (18%)
Improper driving			
Improper overtaking	45 (3%)	11 (1%)	27 (1%)
Improper turning	171 (10%)	49 (3%)	235 (6%)
Too fast for condition	151 (9%)	87 (6%)	296 (8%)
Careless driving			
Following too close	232 (13%)	64 (4%)	652 (17%)
Failure to keep vehicle under control	160 (9%)	39 (2%)	182 (5%)
Inattentive driving	329 (19%)	155 (10%)	832 (21%)
Left of center	21 (1%)	6 (0%)	6 (0%)
Unsafe backing	20 (1%)	20 (1%)	26 (1%)
Reckless driving			
Disregarding traffic control	0 (0%)	149 (9%)	588 (15%)
Failure to yield	526 (30%)	937 (59%)	931 (24%)
Exceeding speed limit	65 (4%)	26 (2%)	56 (1%)
Specific Driver Errors			
No errors	319 (18%)	200 (13%)	682 (18%)
Improper driving	247 (14%)	115 (7%)	391 (10%)
Careless driving	598 (34%)	201 (13%)	1,359 (35%)
Reckless driving	575 (34%)	1,064 (67%)	1,452 (37%)

TABLE 2 Selected Independent Variables

Variable	Value	Frequency by Driver Error (%) Uncontrolled (1,420)	Sign-Controlled (1,380)	Signal-Controlled (3,202)
Driver Characteristics				
Gender and age (years)	Male (<25)	274 (19%)	207 (15%)	508 (16%)
	Male (25–55)	384 (27%)	368 (27%)	878 (27%)
	Male (>55)	133 (9%)	140 (10%)	296 (9%)
	Female (<25)	238 (17%)	178 (13%)	505 (16%)
	Female (25–55)	290 (20%)	350 (25%)	754 (24%)
	Female (>55)	101 (8%)	137 (10%)	261 (8%)
DUI	Alcohol or drugs	78 (5%)	35 (3%)	117 (4%)
Highway and Traffic Characteristics				
Curve	Horizontal	158 (11%)	120 (9%)	197 (6%)
	Vertical	219 (15%)	251 (18%)	332 (10%)
Visibility	Obscured	33 (2%)	51 (4%)	19 (1%)
Posted speed limit (mph)	Low (<35)	1,265 (89%)	1,294 (94%)	2,616 (82%)
	Middle (35–55)	123 (9%)	34 (2%)	538 (17%)
	High (>55)	32 (2%)	52 (4%)	48 (1%)
Accident time	Peak morning (7:00–9:59 a.m.)	522 (37%)	546 (40%)	1,315 (41%)
	Day (10:00 a.m.–3:59 p.m.)	194 (14%)	199 (14%)	427 (13%)
	Peak afternoon (4:00–6:59 p.m.)	350 (24%)	395 (29%)	816 (25%)
	Night (7:00 p.m.–6:59 a.m.)	354 (25%)	240 (27%)	644 (21%)
Environmental Factors				
Weather condition	Clear	801 (56%)	764 (55%)	1,808 (56%)
	Cloudy	372 (26%)	396 (29%)	829 (26%)
	Rain	141 (10%)	144 (10%)	357 (11%)
	Snow and hail	106 (9%)	76 (6%)	208 (7%)
Light condition	Day	973 (69%)	1,017 (74%)	2,306 (72%)
	Night without street light	83 (6%)	99 (7%)	142 (4%)
	Night with street light	364 (25%)	264 (19%)	754 (24%)
Road condition	Dry	896 (63%)	896 (65%)	2,142 (67%)
	Wet	253 (18%)	253 (18%)	592 (18%)
	Snow or slush	198 (14%)	156 (11%)	336 (10%)
	Ice	73 (5%)	75 (6%)	132 (5%)
Vehicle Type				
Vehicle	Passenger car	1,221 (86%)	1,203 (87%)	2,735 (85%)
	Light truck	148 (10%)	126 (9%)	354 (11%)
	Heavy truck	51 (4%)	51 (4%)	113 (4%)

NOTE: DUI = driving under the influence.

First, the distribution of drivers by age and by gender is consistent irrespective of traffic controls. Next, a very high percentage of driver errors took place at intersections with a low speed limit (<35 mph). The posted speed limit is the speed limit of the street on which the crash occur. Next, when all intersection types are considered, the percentage of driver mistakes made in the morning peak hours is considerably higher than during other time periods. When nighttime errors for all intersection types are observed, a higher percentage of errors occur when streetlights are present as opposed to when they are not present. Last, the percentage of driver errors involving only passenger cars is markedly higher than that of trucks.

ORDERED-PROBIT REGRESSION RESULTS

The ordered-probit model results for driver error severities are shown in Table 3, where a positive coefficient means a possible increase in driver error severity and a negative value means a possible decrease in driver error severity.

Driver characteristics and behavior appear to have a great influence on the error severity outcome. Male drivers younger than 25 have a significantly higher probability of making severe mistakes when compared with other age groups except women older than 55. This finding is consistent with a previous study in which reckless driving was most prevalent among male drivers younger than the age of 25 (*15*). Female drivers older than 55 are prone to committing more severe violations at uncontrolled and sign-controlled intersections. Male drivers older than 55 are more prone to errors at sign-controlled intersections. Traffic signs can be a challenge for older drivers because of deteriorating vision, slower recovery from glare, and misjudgment of gap or speed of other vehicles. These challenges may contribute to an increased likelihood of making more severe mistakes at sign-controlled intersections (*33*). From a behavior perspective, the probability of making severe mistakes while under the influence of alcohol drastically increases at intersections with all kinds of traffic control.

In terms of highway design factors, the coefficient of the horizontal curve seems to suggest that driver error severity decreases

TABLE 3 Coefficient Estimates of Ordered-Probit Model for Driver Errors

		Coefficient Estimates by Intersection Type		
Variable	Value	Uncontrolled	Sign Controlled	Signal Controlled
Driver Characteristics				
Gender and age (years)	Male (<25)	Base level	Base level	Base level
	Male (25–55)	−0.327 (*.002*)	−.127 (*.048*)	−0.180 (*.003*)
	Male (>55)	−0.083 (*.003*)	.080 (*.059*)	−0.138 (*.095*)
	Female (<25)	—	−.003 (*.021*)	—
	Female (25–55)	—	−.206 (*.074*)	−0.154 (*.014*)
	Female (>55)	0.332 (*.025*)	.020 (*.085*)	—
DUI	Alcohol or drugs	0.224 (*.005*)	0.591 (*.001*)	.266 (*.004*)
Highway and Traffic Characteristics				
Curve	Horizontal	—	−0.323 (*.004*)	−0.234 (*.002*)
	Vertical	−0.184 (*.026*)	—	−0.193 (*.001*)
Visibility	Obscured	0.718 (*.001*)	0.271 (*.071*)	0.798 (*.007*)
Posted speed limit (mph)	Low (<35)	Base level	Base level	Base level
	Middle (35–55)	−0.159 (*.089*)	−0.573 (*.001*)	−0.189 (*.001*)
	High (>55)	0.324 (*.049*)	0.594 (*.016*)	—
Environmental Factors				
Weather conditions	Clear	Base level	Base level	Base level
	Snow	−0.333 (*.014*)	−0.399 (*.015*)	−0.196 (*.048*)
Light conditions	Day			
	Night without street light	—	—	0.275 (*.011*)
	Night with street light	—	—	0.189 (*.002*)
Road conditions	Dry	Base level	Base level	Base level
	Snow	—	−0.304 (*.022*)	−0.202 (*.012*)
	Ice	−0.795 (*.001*)	−0.867 (*.001*)	−0.908 (*.001*)
Vehicle Type				
Vehicle type	Passenger car	Base level	Base level	Base level
	Light truck	−0.136 (*.093*)	−0.183 (*.038*)	—
	Heavy truck	−0.483 (*.002*)	−1.008 (*.000*)	−0.552 (*.001*)
Thresholds				
µ1	na	−1.257	−1.678	−1.271
µ2	na	−0.668	−1.310	−0.889
µ3	na	0.322	−0.847	0.109

NOTE: — = coefficient is not statistically significant with a 10% level of significance. Italic values in parentheses are *p*-values. na = not applicable.

at horizontal curves at sign-controlled and signal-controlled intersections. The vertical curve seems to decrease error severity at uncontrolled and signal-controlled intersections. When the driver's vision is obstructed, the chance of committing more severe mistakes is higher. The likelihood of committing more serious mistakes escalates from the intermediate posted speed limit (35 to 55 mph) to the low speed limit (<35 mph) and the high speed limit (55 mph). The conditions are worst at high-speed, sign-controlled intersections.

With regard to environmental factors, all inclement weather conditions and adverse roadway surface conditions seem to be associated with a lower severity of driver errors, which is possibly due to the fact that most drivers reduce speed while driving under these conditions (*34*). Nighttime driving seems to be associated with higher driver error severity at signal-controlled intersections; this finding is likely due to the driver's poor night vision. Compared with passenger car drivers, truck drivers are more likely to avoid severe mistakes, maybe because truck operators have more driving experience in general.

The thresholds of the ordered-probit model can offer a clear hierarchy for the driver errors distributed among the three types of intersections. It is obvious that the distributions of driver errors vary among the types of intersection. The probability of making mistakes at sign-controlled intersections ($p > -1.678$) is the highest; signal-controlled intersections are the next highest ($p > -1.271$), and uncontrolled intersections ($p > -1.257$) are lowest. The probability of making reckless driving errors at sign-controlled intersections ($p > -.847$) is apparently highest, followed by signal-controlled intersections ($p > .109$) and then uncontrolled intersections ($p > .322$). These findings concur with the data in Table 1.

Although the probit model establishes the quantitative relationship between contributing factors and driver errors, a small number of independent variables were statistically significant even at the 10% level of significance. This finding may be due to the fact that some variables influence driver errors in an indirect fashion (*35*). To address this issue, the association rules were implemented because they are based on the relative frequency of sets of items that occur alone and together. In addition, the rules are not necessarily treated as a direct causation but as the associations between sets of items (*27*).

ASSOCIATION RULE RESULTS

Creating critical association rules for each type of intersection includes four steps: (*a*) generate all two-item rules, (*b*) determine threshold values, (*c*) eliminate the rules with lift values outside of the thresholds, and (*d*) eliminate the remaining rules that have both support and confidence values lower than the thresholds. The threshold value for support is set at 1%. For confidence, there are three thresholds: one is set at 30% for both careless driving and reckless driving at uncontrolled and signal-controlled intersections; the second is 10% for careless driving; and the third is 50% for reckless driving. Both the second and third thresholds are for sign-controlled intersections. For lift, the threshold value is set to be greater than or equal to 1.1 (positive correlation) or smaller than or equal to 0.9 (negative correlation). The purpose of choosing different confidence values is to accommodate the different distributions of careless driving and reckless driving among three types of intersections. For brevity, only the rules involving more severe mistakes (i.e., careless and reckless driving) at uncontrolled, sign-controlled, and signal-controlled intersections are shown in Tables 4, 5, and 6, respectively.

Table 4 gives 17 association rules for uncontrolled intersections. According to support, the frequent antecedents leading to careless driving are younger male drivers, younger female drivers, and cloudy weather. The most frequent antecedent leading to reckless driving is younger male drivers. With regard to confidence, when the posted speed limit is between 35 mph and 55 mph, the percentage of careless driving increases to 51%. The possibility of committing a reckless driving error is higher than 50% if a driver is an older woman, the driver is under the influence of drugs or alcohol, or the driver's visibility is obstructed. Lift describes the association between an antecedent and a consequent. Not bounded to any statistical assumptions, association rules can reveal new relationships between variables that are not statistically significant in a statistical model. Two variables—posted speed limit (35 mph to 55 mph) (Rule 8) and light truck drivers (Rule 13)—are found to be highly associated with careless driving. These variables were not identified in the previous ordered-probit model.

Table 5 shows 25 rules for sign-controlled intersections. The highest support value for rules leading to careless driving is nighttime (5%), and the highest support value for rules leading to reckless driving is passenger car drivers (76%). With respect to confidence, the highest value for rules leading to careless driving is 34%, which is the intermediate posted speed limit (35 mph to 55 mph). However, the values for rules leading to reckless driving are all higher than 50% except for snowy weather and icy roads. This finding is caused by the high proportion of reckless driving (67%) committed at sign-controlled intersections. New findings that are highly associated with careless driving other than those found in the ordered-probit model are posted speed limit (35 to 55 mph) (Rule 9), nighttime (Rules 12 and 14), and truck drivers (Rules 19 and 20).

Table 6 contains 20 association rules for signal-controlled intersections. The posted speed limit (35 to 55 mph) and nighttime with streetlights have higher support values leading to careless driving. A driver's age and gender have the highest support value for rules leading to reckless driving. High confidence values for rules leading to careless driving can be found for the following circumstances: driving under the influence of alcohol or drugs, higher posted speed limits, and light-truck drivers. Visibility obstruction has the highest confidence value for rules leading to reckless driving (70%). According to the lift value, the posted speed limit (35 to 55 mph) (Rule 8) and light-truck drivers (Rule 14) are highly associated with careless driving. These are the relationships that cannot be identified by the ordered-probit model, only by the association rules.

Clearly, the rules vary among intersection types. In general, sign-controlled intersections generate the highest number of rules, followed by signal-controlled and then sign-controlled intersections.

TABLE 4 Association Rules for Driver Errors at Uncontrolled Intersections

		Careless Driving			Reckless Driving		
Rule ID	Antecedent	Support	Confidence	Lift	Support	Confidence	Lift
Driver Characteristics							
1	Age = young; gender = male	8%	41%	1.2	8%	41%	1.2
2	Age = young; gender = female	7%	41%	1.2	na	na	na
3	Age = old; gender = female	2%	27%	0.8	4%	51%	1.5
4	DUI = alcohol or drugs	na	na	na	3%	51%	1.5
Highway and Traffic Characteristics							
5	Curve = horizontal	na	na	na	2%	20%	0.6
6	Curve = vertical	na	na	na	4%	27%	0.8
7	Visibility = obstruction	na	na	na	1%	68%	2.0
8	Posted speed = middle (35–55 mph)	5%	51%	1.5	2%	20%	0.6
9	Time = day time (10:00 a.m.–3:59 p.m.)	4%	27%	0.8	na	na	na
Environmental Factors							
10	Weather = cloudy	7%	27%	0.8	na	na	na
11	Weather = snow	2%	27%	0.8	na	na	na
12	Road = snow	3%	24%	0.7	na	na	na
Vehicle Type							
13	Vehicle = light truck	4%	41%	1.2	3%	27%	0.8

TABLE 5 Association Rules for Driver Errors at Sign-Controlled Intersections

		Careless Driving			Reckless Driving		
Rule ID	Antecedent	Support	Confidence	Lift	Support	Confidence	Lift
Driver Characteristics							
1	Age = old; gender = male	na	na	na	9%	87%	1.3
2	Age = young; gender = female	na	na	na	11%	87%	1.3
3	Age = middle; gender = female	3%	11%	0.8	na	na	na
4	Age = old; gender = female	na	na	na	8%	87%	1.3
5	DUI = alcohol or drugs	na	na	na	2%	80%	1.2
Highway and Traffic Characteristics							
6	Curve = horizontal	na	na	na	5%	54%	0.8
7	Curve = vertical	2%	9%	0.7	10%	54%	0.8
8	Visibility = obstruction	na	na	na	3%	78%	1.2
9	Posted speed = middle (35–55 mph)	1%	34%	2.6	na	na	na
10	Posted speed = high (>55 mph)	1%	11%	0.8	3%	80%	1.2
11	Time = afternoon peak (4:00–6:59 p.m.)	3%	10%	0.8	na	na	na
12	Time = night time (7:00 p.m.–6:59 a.m.)	5%	20%	1.5	na	na	na
Environmental Factors							
13	Weather = snow	na	na	na	2%	40%	0.6
14	Light = without street light	1%	20%	1.5	na	na	na
15	Road = wet	2%	10%	0.8	13%	74%	1.1
16	Road = snow	1%	10%	0.8	6%	54%	0.8
17	Road = ice	na	na	na	2%	27%	0.4
Vehicle Type							
18	Vehicle = passenger car	na	na	na	76%	87%	1.3
19	Vehicle = light truck	2%	22%	1.7	5%	54%	0.8
20	Vehicle = heavier truck	1%	18%	1.4	na	na	na

TABLE 6 Association Rules for Driver Errors at Signal-Controlled Intersections

		Careless Driving			Reckless Driving		
Rule ID	Antecedent	Support	Confidence	Lift	Support	Confidence	Lift
Driver Characteristics							
1	Age = young; gender = male	na	na	na	8%	48%	1.3
2	Age = middle; gender = male	na	na	na	8%	30%	0.8
3	Age = young; gender = female	na	na	na	7%	44%	1.2
4	Age = old; gender = female	2%	25%	0.7	4%	52%	1.4
5	DUI = alcohol or drugs	2%	46%	1.3	2%	48%	1.3
Highway and Traffic Characteristics							
6	Curve = vertical	na	na	na	3%	26%	0.7
7	Visibility = obstruction	na	na	na	1%	70%	1.9
8	Posted speed = middle (35–55 mph)	8%	49%	1.4	5%	30%	0.8
9	Posted speed = high (>55 mph)	1%	42%	1.2	1%	30%	0.8
10	Time = night time (7:00 p.m.–6:59 a.m.)	6%	28%	0.8	na	na	na
Environmental Factors							
11	Weather = snow	na	na	na	2%	30%	0.8
12	Light = with street light	7%	28%	0.8	na	na	na
13	Road = snow	3%	25%	0.7	3%	26%	0.7
Vehicle Type							
14	Vehicle = light truck	5%	46%	1.3	3%	30%	0.8

Sign-controlled intersections have the highest number of driver errors, especially due to reckless driving, which is likely why these intersections lead the group. This example shows how association rules can reveal new findings and add to the knowledge gained from probit models.

SUMMARY AND RECOMMENDATIONS

Overall, the findings from the ordered-probit model and association rules are consistent, and association rules effectively capture the associations between the variables that were not available in the ordered-probit models. The results of both methods unambiguously state that human factors strongly influence the number and type of driving errors.

Younger drivers are more likely to be reckless on the road when compared with other drivers. Older drivers, especially women, have a high probability of making severe mistakes at all three types of intersections. Accordingly, driver education and training about proper vehicle control and crash risk are recommended for teenagers and older drivers (*3*). For older drivers, this study recommends increasing the conspicuity of traffic signs and signals by increasing the signs' size and installing additional warning signs at the approach to the intersection (*3, 19, 24*). Alcohol and drug use dramatically increase the probability of severe driver errors; hence, measures such as random breath tests and public campaigns against drugs and alcohol are recommended (*3, 23*).

Uncontrolled intersections have a very high percentage of both careless driving and reckless driving errors. Relevant countermeasures such as installing "Intersection Ahead" warning signs can help raise drivers' awareness (*25*). In addition, setting appropriate speed limits to improve drivers' gap selection, especially for truck drivers, is also recommended (*24*). In particular, visibility obstruction is found to significantly increase the driver error severity at uncontrolled intersections. One recommendation is to eliminate objects that obstruct the driver's vision and therefore help to maintain visibility from all directions (*3*).

Sign-controlled intersections have the highest percentage of driver errors and the highest percentage of reckless driving errors. Increasing the visibility and conspicuity of stop signs by installing them on both the left- and right-hand sides of the road may help lower this percentage (*3*). Also, installing rumble strips across the lane may prompt drivers to slow down when approaching intersections (*21*). Nighttime is strongly associated with careless driver errors, which are probably caused by driver fatigue. Drivers should take turns driving and use rest areas to prevent driver fatigue (*22*). FHWA recommends raising pavement markers and installing reflective strips on traffic signs to improve nighttime driving safety at unlighted or dark sign-controlled intersections (*24*). FHWA also recommends setting a lower speed limit to improve traffic safety at sign-controlled intersections, especially for trucks, which have much longer stopping distances (*24*).

At signalized intersections, the probability of severe driver error increases with visibility obstruction and high posted speed limit. Devlin et al. suggested increasing the visibility of traffic lights by removing objects that obstruct the driver's vision (*3*). FHWA recommends setting appropriate speed limits to account for roadway design, traffic, and environmental conditions (*24*). Increasing the length of the yellow interval (not to exceed 5.5 s) or installing "No Turn On Red" signage has also been proved to efficiently prevent red-light-running crashes (*3, 24*).

CONCLUSIONS

In recent decades, studies of driver error have increased in an effort to reduce the number of crashes, especially severe crashes at intersections. Driver error can be categorized as improper driving, careless driving, or reckless driving based on citation information from traffic violations. The reasons behind errors can be complicated and can include driver characteristics, highway and traffic characteristics, environmental factors, and vehicle type.

This study attempted to establish a strong association between facts and driver error by using both statistical models and data-mining techniques. An ordered-probit model was developed to identify the effects of selected variables on driver error severities. Association rules were used to discover new dependencies between driver errors and other factors. It is found that the results of the ordered-probit model are consistent with those from association rules. Furthermore, association rules can capture the relationships between the variables that were not statistically significant in the ordered-probit model, since the rules are based on the relative frequency of sets of items that occur alone and together. In addition, the rules are not necessarily treated as a direct causation, as is assumed in the ordered-probit model, but as the associations between sets of items.

The study shows that sign-controlled intersections have the highest percentage of driver errors, followed by signal-controlled and then uncontrolled intersections. Furthermore, sign-controlled intersections have the highest percentage of reckless driving occurrences, followed by signalized and then uncontrolled intersections. One of the most important findings of this study is that younger drivers are more likely to be reckless drivers, and older drivers, especially women, tend to make severe mistakes at all three types of intersections. This finding may raise the attention of driver education and training about proper vehicle control and crash risk for teenagers and older drivers to improve intersection safety. Driving under the influence of alcohol or drugs apparently increases the severity of driver errors. Visibility obstruction significantly increases driver error severity at intersections with all types of traffic control. Recognizing traffic signs at sign-controlled intersections is increasingly challenging at night. High-speed intersections are significantly associated with severe driver errors, especially for sign-controlled intersections. Passenger car drivers have higher driver error severities at all types of intersections.

From the findings, specific countermeasures were recommended for the issues related to these causal factors to improve intersection safety. It is expected that this study can shed light on the possible causes of driver error and can offer additional insight about intersection design to improve intersection safety.

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