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Safety aspects of freeway weaving sections

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Abstract

One source of vehicle conflict is the freeway weaving section, where a merge and diverge in close proximity require vehicles either entering or exiting the freeway to execute one or more lane changes. Using accident data for a portion of Southern California, we examined accidents that occurred on three types of weaving sections defined in traffic engineering: Type A, where every merging or diverging vehicle must execute one lane change, Type B, where either merging or diverging can be done without changing lanes, and Type C, where one maneuver requires at least two lane changes. We found no difference among these three types in terms of overall accident rates for 55 weaving sections over one year (1998). However, there were significant differences in terms of the types of accidents that occur within these types in terms of severity, and location of the primary collision, the factors causing the accident, and the time period in which the accident is most likely to occur. These differences in aspects of safety lead to implications for traffic engineering improvements.

Keywords: Traffic safety; Weaving sections; Freeways; Accident analysis

1. Introduction

In search of safer and more efficient freeway operations, traffic engineers are looking at ways to redesign infrastructure and manage traffic in order to mitigate congestion and reduce vehicle

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conflicts that may have propensity toward incidents resulting in non-recurrent congestion. One source of vehicle conflicts is the freeway weaving section, where a merge and diverge in close proximity require either merging or diverging vehicles to execute one or more lane changes. (A merge and diverge separated by less than 0.4–0.5 miles is typically defined to be within close proximity, depending on the type of weaving section.)

In traffic engineering, three types of weaving sections are traditionally distinguished based on the minimum number of lane changes required for completing the weaving maneuvers (TRB, 1994, 1997, 2000):

Type A weaving sections:	Every weaving vehicle (a vehicle merging or diverging) must execute one lane change. The most common Type A configuration is a pair of on- and off-ramps connected by an auxiliary lane.
Type B weaving sections:	One weaving movement can be made without making any lane change, while the other weaving movement requires at most one lane change. A common Type B configuration has a lane added at an on-ramp; merging traffic does not need to change lanes, but traffic diverging downstream must change onto this added lane to exit at the off-ramp.
Type C weaving sections:	One weaving movement can be made without making any lane change, while the other weaving movement requires at least two lane changes.

It is possible that two of these weaving section types can overlap. In such a situation, encountered on the freeways we studied in Southern California, the resulting compound weaving section will have the joint characteristics of two of the above types.

The latest Highway Capacity Manual (HCM) procedures for weaving sections involve computing the speeds of weaving and non-weaving vehicles, calculating densities, and then performing a table lookup to assign level of service (TRB, 2000). The geometric characteristics required for the analysis of weaving sections are the following: weaving length, configuration (in order to determine which type of weave and which parameter values will be used), and weaving width (represented by the number of lanes in the section). Also, the characteristics of vehicles by type and their distribution over the traffic stream are important issues to be taken into account.

Several methods have been developed to analyze the performance of weaving section designs in terms of average vehicle travel speeds and levels of service. These include: the California method (Moskowitz and Newman, 1963), the 1965 HCM (TRB, 1965), the Leisch method (Leisch, 1983), the PINY procedure (Pignataro et al., 1975), the JHK algorithm (Reilly et al., 1984), HCM (1985) and the Fazio and Rouphail (1986) method. Existing studies involving weaving sections typically have focused on operational and performance characteristics related to traffic flow conditions within the weaving section. For example, Steward et al. (1996), found that the number of lanes was the most critical factor in the determination of the capacity of weaving sections, while Fitzpatrick and Nowlin (1996), using speed as a measure of effectiveness, determined that weaving sections smaller than 656 ft in length will begin to break down at relatively lower traffic volumes compared to weaving sections with lengths at or above 656 feet. Cassidy et al. (1989) compared eight major freeway weaving locations, finding significant discrepancies between predicted and measured average speeds of weaving and non-weaving vehicles. An important result they found was that the speed that resulted was insensitive with respect to changes in geometry and traffic factors over the range of values in the data set. Overall, the research suggests that average travel speed may not be an ideal measure of effectiveness.

Fazio and Rouphail (1986) presented a review of three weaving procedures (Leisch, 1979, 1983; Reilly et al., 1984; HCM, 1985); they concluded that the total number of lane shifts required by drivers in weaving sections affect both weaving and non-weaving speeds, and that the inclusion of lane shift as an independent variable in average weaving and non-weaving speed models enhanced significantly the predictive ability of their models. The researchers recommended that linking such safety characteristics as accident frequencies, type, and location, to design and analysis procedures can result in defining lower bounds on section length and the number of lanes for weaving sections.

Despite the general acceptance that safety, in addition to capacity, speed, operational flexibility, cost, and level of service, constitute fundamental design criteria, relatively few studies have focussed on analyzing the relationship between the characteristics of weaving sections and traffic safety. Studying accident experiences among weaving sections, from 700 weaving sections in 20 states based on data gathered in the early 1960s, Cirillo (1970) determined that shorter acceleration and deceleration lanes exhibited higher accident rates, for all percentages of merging or diverging traffic. The effect of increasing the length of acceleration lanes appears to be substantial when the percent of merging traffic is greater than 6%, and below the 6% range improvement was speculative and probably not cost beneficial. Similar results for deceleration lanes were reported, but the improvement due to increasing the length of deceleration lanes was not as great as in the acceleration lanes case. Fazio et al. (1993), propose to utilize conflict rates instead of accident rates as an indicator of traffic safety in a freeway facility. They analyzed two types of conflict in weaving sections: rear-end and lane change, and their possible interactions. The INTRAS simulation software was utilized, considering 10 different sites on Interstate 294 in the Chicago Metropolitan Area, generating such types of conflict. The authors concluded that results showed a positive correlation between these two types of conflicts rates and accident rates for weaving sections of moderate length. In addition, accident rates tend to stabilize for weaving sections with lengths greater than 750 ft. They conclude that conflicts do not have to be associated with actual accidents to be a good indicator of safety, arguing that conflict rates have more advantages than accident rates since, for example, not all of the accidents are reported or the exact location and time of occurrence may not be representative.

A recent study sponsored by The Washington State Department of Transportation (Glad, 2001) studied accidents occurring in a particular weaving area by collision type and severity from 1994 to 1996, finding that the predominant accident types during peak hours periods were rear end collisions occurring at lower speeds upstream of the weaving section, while during off-peak hours, the incidence of sideswipe as well as rear end collisions increased considerably. Moreover, the analysis showed that most of the incidents occurred in the right lane of the area with severity depending on the speed. Using HCM (TRB, 1997) and the ITRAF traffic simulation model, four alternatives were simulated in order to estimate the impact of new designs on the safety of this particular weaving section. The study recommended that further research on the safety impacts in weaving sections be conducted.

Our concern in the present research is the safety of various types of weaving sections on urban freeways. Using accident data for Orange County in Southern California, we examine accidents that occurred during 1998 on five major freeways, and develop a series of models that distinguish accident characteristics among the various types of weaving sections. Following a brief description of the data supporting the analysis, we present a comparative analysis of accidents within weaving sections relative both to type of weaving section as well as to the general population of accidents that occurred on mainline sections of the freeways. We next develop and estimate multivariate probit models (MPMs) of accident typology of weaving sections. Based on these results, we draw certain conclusions and directions for future research.

2. Data

2.1. Weaving sections on five Orange County freeways

Weaving sections were identified using as-built diagrams for five Orange County freeways: Interstate Routes 5 and 405 and State Routes 22, 55, and 57. The total directionally-specific length of these routes is 223 miles. They contain 55 weaving sections, covering a total length of 22.9 miles, or an aggregate 10.3% of the routes. The distribution of weaving sections by type is shown in Table 1. Eight of these 55 weaving sections are compound types, as they are composed of two overlapping weaving sections of standard Type A, B, or C; in the analysis that follows, we make no distinction for these compound sections on which type precedes the other. Using standard traffic engineering procedures, each weaving section is defined to cover the section of freeway from the gore of the merge to the gore of the diverge.

2.2. Accident and exposure data

The accident data were taken from the Traffic Accident Surveillance and Analysis System (TASAS) database (Caltrans, 1993). TASAS covers police-reported accidents that occur on the California State Highway System. There were 7400 reported mainline accidents (crashes) in the TASAS database for 1998 on our five freeways. Of these, 829 (11.2%) were within the confines of one of the 55 weaving sections. The percentage of accidents that is within weaving sections is roughly comparable to the percentage of the freeway length that is within weaving sections (10.3%). One of our objectives is to determine how weaving section accidents differ from accidents on mainline freeway sections, and how accident typology is related to weaving section typology.

Table 1
Physical data for 55 weaving sections on five Orange County freeways

Weaving section type	Total number of sections	Mean length in miles	Distribution by freeway route				
			I-5	SR-22	SR-55	SR-57	I-405
A	21	0.36	9	3	2	4	3
B	19	0.37	5	4	4	2	4
C	7	0.41	1	1	2	2	1
AB	1	0.72			1		
AC	3	0.59	2		1		
BC	4	0.74		1	3		
Total	55		17	9	13	8	8

The TASAS database contains information regarding the characteristics of each collision, including: (a) the number of parties (usually vehicles) involved, (b) movements of each vehicle prior to collision, (c) the location of the collision involving each party, (d) the object(s) struck by each vehicle, and (e) the severity, as represented by the numbers of injured and fatally injured parties in each involved vehicle. The database also includes information regarding weather and roadway conditions and ambient lighting. No information was available to us concerning drivers or vehicle makes and models. The database does not cover collisions for which there are no police reports. Most of the collisions included in the TASAS database were investigated in the field, but some were reported after the fact through over-the-counter reports filed with police departments. The TASAS database also contains estimates of annual average daily travel (AADT) on all freeway sections. These AADT estimates for 1998 were used to generate average annual daily vehicle miles of travel (DVMT) for each of our 55 weaving sections.

The distribution by weaving section type and the number of accidents that occurred within each area during 1998 is summarized in Table 2. Mean accident rates per vehicle miles of travel vary across the six types of weaving sections, but these mean differences are not statistically different due to high variances among weaving sections within the same type. Similarly, there is no statistically significant difference in accident rates among the three primary types of weaving sections (Types A, B, and C) as also shown in the test results listed in Table 2.

It is highly possible that accidents that occur within weaving sections are related to the distribution of total traffic in terms of the numbers of vehicles exiting and entering the freeway, versus those that are traveling straight through the weaving section. Unfortunately, due to missing data at one or more critical loop detector station on a ramp or on the freeway mainline, only 13 of the 55 weaving sections, with a total of 77 accidents, had sufficient traffic flow data to calculate weaving totals and ratios of different types of flows. Alvarez (2002) reports on statistical analyses relating breakdown of accident types to various measurements of weaving section movements commonly used in traffic engineering, but these analyses all yielded inconclusive results due to the small sample size. Expansion of the present analyses using detailed data on traffic flow within weaving sections is a subject for future research.

Table 2
Aggregate accident statistics for 55 weaving sections on five Orange County freeways

Weaving section type	Number of weaving sections	Number of accidents during 1998	Mean accidents per 10^6 daily vehicle miles	Std. deviation of accidents per 10^6 daily vehicle miles	Test of equality of all six mean accident rates	Test of equality of first three mean accident rates
A	21	265	154.5	131.3	$F_{5,49} = 0.707$,	$F_{2,44} = 1.252$,
B	19	224	165.7	94.9	$p = 0.621$	$p = 0.296$
C	7	145	233.6	119.3		
AB	1	37	211.4	–		
AC	3	40	114.5	58.0		
BC	4	118	199.6	152.0		
Total	55	829	170.6	115.2		

3. Traffic safety profiles of weaving sections versus elsewhere

3.1. Collision type and related characteristics

We begin by comparing the characteristics of the mainline accidents that occurred within the 55 weaving sections, versus the mainline accidents that occurred elsewhere on the five freeways. One way of characterizing accidents is by typing the primary collision of the accident. The three major types of primary collisions for mainline freeway accidents are: rear end, sideswipe and hit object. Types of collisions that are relatively rare on freeways, such as head-on and broadside accidents were combined into an "other" category. A cross tabulation of these four types of collisions by spatial location (weaving section versus elsewhere) revealed that, as expected, weaving section accidents are more likely to be sideswipes. While the spatial difference in the distributions is statistically significant ($\chi^2 = 11.97$ with three degrees of freedom; $p = 0.007$), the difference in the percentage of sideswipes is not a dramatic one: 23.9% versus 19.8%. The traffic safety characteristics that distinguish weaving sections are too subtle to be captured solely by collision type.

The higher likelihood of a sideswipe is also reflected in a statistically significant difference in terms of the movements performed by vehicles prior to collision. Weaving section accidents are more likely to involve vehicles changing lanes, because the requirement for either merging or diverging vehicles, or both, to execute a lane change is a defining feature of weaving sections. Also, accidents within weaving sections are more likely to involve citations other than speeding, because sideswipes are more likely to be attributed to violations such as failure to yield or other dangerous driving.

3.2. Collision location

The locations of the primary collisions for accidents is significantly different for weaving section versus non-weaving section accidents ($p < 0.0005$). As shown in Fig. 1, the location of the primary collision for 36.8% of weaving section accidents is the interior lane (or lanes) of the freeway. Relatively fewer weaving section collisions are located in the left or right lanes of the freeway. However, further analyses are called for, because this difference could be due in part to differences in the number of freeway lanes in weaving sections versus other locations.

3.3. Other accident characteristics

There are no statistically significant differences between accidents located within weaving sections and those located elsewhere on the same freeways on any of the following characteristics: severity (measured in terms of injuries versus property damage only), number of vehicles involved, whether or not a truck was involved in the accident, weather conditions, and the temporal distributions of accidents by time of day, day of the week, and daytime versus nighttime. In the remainder of this paper we explore differences in accidents among types of weaving sections.

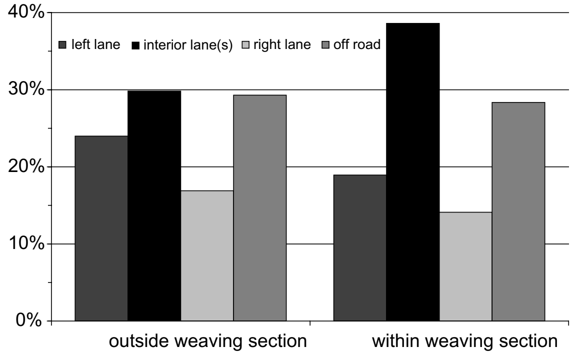

Fig. 1. Breakdown of collision location for accidents in weaving sections versus accidents elsewhere on the five freeways.

4. Traffic safety profiles among different types of weaving sections

4.1. Accident type

In order to better understand accident typology, we created a composite accident type variable with three categories based on the movements of the involved vehicles prior to collision as well as the type of collision. (1) Rear end accidents are defined to be those in which all the primary vehicles were traveling in the same lanes. (2) Weaving accidents were defined to be either sideswipe or rear end collisions in which at least one of the primary vehicles was executing a lane change. (3) Hit object accidents were defined to be all other types of collisions, the vast majority of which involved the primary vehicle hitting a fixed object, usually off road. A few accidents defined as "hit object" involved vehicle rollovers, head-on, or other types of collisions.

There is a statistically significant difference between accident type and type of weaving section ($p < 0.0005$). While, overall, rear end accidents have the highest likelihood of occurrence, weaving accidents are high among the three compound types of weaving sections, particularly Type AB (Fig. 2). (It is noted that conclusions drawn here and elsewhere regarding such compound weaving

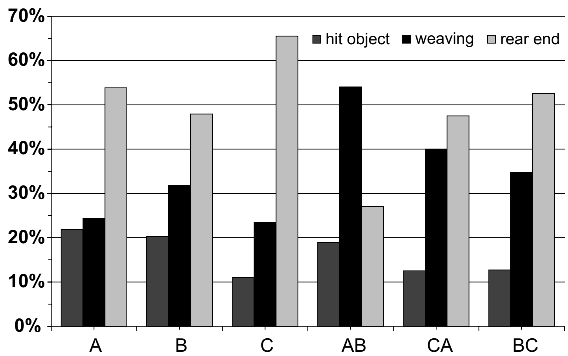

Fig. 2. Breakdown of accident type for six types of weaving sections.

sections should be viewed with caution, owing to the relatively small number of these sections in our data set; the results for these sections may be influenced by localized situational aspects, rather than of the inherent characteristics of the defined type.) In contrast, Type C weaving sections most resemble non-weaving sections in terms of a preponderance of rear end accidents and a relatively low number of hit object accidents. Of the three simple types of weaving sections, Type B has the highest proportion of weaving accidents.

Similar differences in accident type are reflected in the relationship between weaving section type and movement of the vehicles prior to collision. Compound weaving sections Type AB accidents are more likely to involve the first vehicle changing lanes (18.2% versus no higher than 10.3% for the other section Types). In contrast, Type C weaving section accidents are more likely to involve a vehicle slowing or stopping (53.4% versus an overall average of 44.1% for all weaving section accidents). Accidents within the boundaries of Type C weaving sections appear to be more congestion related.

4.2. Timing of accident

The association of congestion with Type C accidents is reinforced by the strong relationship between section Type and whether or not accidents occur during weekday peak rush hours (defined to be 6:00 through 9:00 in the morning and 3:30 through 6:30 in the afternoon-evening, Monday through Friday). Fig. 3 shows that Type C accidents, and also Type CA and BC accidents, are more likely to occur during rush hours ($p = 0.023$). Types A and B have a almost identical rate of approximately 32% rush-hour accidents, while nearly half of Type C accidents occur during rush hours. This result is intuitive, because Type C weaving sections are distinguished by having either a diverging or merging maneuver that requires two or more lane changes. That appears to have negative safety consequences during periods of heavier flows.

4.3. Road conditions at time of accident

There are also differences among weaving section types in terms of the breakdown of their accidents by weather conditions ($p = 0.002$). Wet-road accidents are more prevalent on Type CA

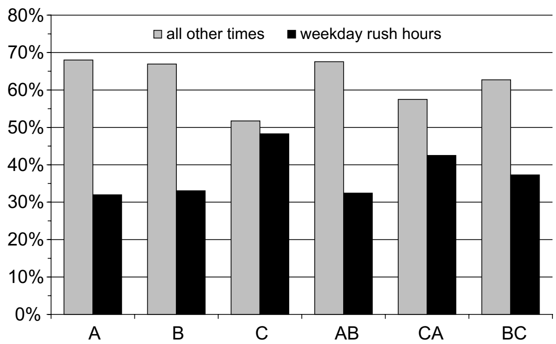

Fig. 3. Breakdown of accident timing for six types of weaving sections.

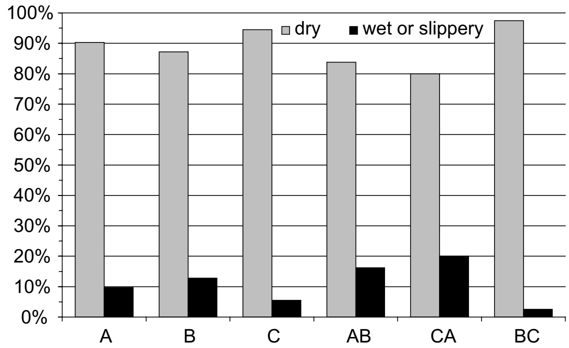

Fig. 4. Breakdown of road conditions at time of accident for six types of weaving sections.

and AB weaving sections, while dry-road accidents are more prevalent on Type BC and C sections (Fig. 4). We speculate that types AB and CA exhibit the compounding of effects evidenced in their component section types. These compound sections require multiple weaves by two streams of traffic (merging and diverging), producing a higher propensity toward accidents in wet conditions, while compound Type BC typically requires a multiple weave by only one of the traffic streams.

4.4. Other accident characteristics

Taxonomic dimensions that were statistically unrelated to weaving section type included: accident location ($p = 0.115$), severity ($p = 0.313$), number of involved vehicles ($p = 0.607$ for an F-test of equality of means), truck involvement ($p = 0.610$). There was a marginally significant relationship between the ambient lighting conditions at the time of the accident, in terms of daylight versus darkness ($p = 0.043$), with the one outstanding feature that Section AB accidents are more likely to occur at night (45.9% in darkness, versus an overall average of 23.9% nighttime for all weaving section accidents). These negative results from the bivariate tests notwithstanding, we show below that some of these accident characteristics are different across types of weaving sections, when considered in combination.

5. A multivariate probit model of accident typology

The above bivariate analyses of accident characteristics can fail to identify important combinations of accident characteristics, because many individual accident characteristics are correlated. To better understand the accident typology of weaving sections we employed a MPM to uncover such conditional relationships and to determine which characteristics were most important in explaining the typology. An MPM has multiple discrete dependent variables and a common set of independent variables. Here, there are $T = 3$ endogenous variables, representing weaving section Types A, B, and C. The MPM model handles the compound weaving section Types AC, BC and AC elegantly, because these are simply composed of combinations of the three discrete variables representing weaving section. There are $N = 829$ observations, being the accidents that occurred on all types of weaving sections, including the compound types. For observations (accidents) that occur on any of the compound Types AB, CA, or BC, two (rather than one) dependent discrete variables are triggered. For each accident we have $K = 12$ exogenous variables. Eleven of the independent variables represent categories of accident characteristics found to be important in the univariate analyses. The 12th independent variable, DVMT, controls for vehicle exposure at each weaving section. These variables are listed in Table 3. The methodology underlying our application of MPM is described in the Appendix A.

The model goodness-of-fit chi-square value was 21.51 with 16 degrees of freedom, corresponding to $p = 0.160$. This chi-square measures the difference between the observed variance–covariance matrix and the one reproduced by the model. The level of statistical significance indicates the probability that the differences between the two matrices are due to sampling variation. Thus, the objective is to attain a chi-square value with $p > 0.05$ (95% confidence level). Our model cannot be rejected as an accurate representation of the relationship between weaving section type and accident characteristics. Our model also scores well on all chi-square based goodness-of-fit indices that differ in terms of the normalization used to account for the effects of sample size and model parsimony on goodness-of-fit statistics (Golob, 2003).

The root mean square error of approximation (RMSEA) measures the model discrepancy per degree of freedom. A rule-of-thumb for a good model is that the upper bound of the 90% confidence interval of the RMSEA be less than 0.05 (MacCallum et al., 1996). The value of the upper bound for our model is 0.0408, less than this critical value.

The Akaike Bayesian information criterion (AIC; Akaike, 1974) or the consistent Akaike information criterion (CAIC; Bozdogan, 1987) can be used to compare the goodness-of-fit versus the dimensionality or number of free parameters (parsimony) of different models. The model that yields the smallest value of on each of these Bayesian criteria is considered best. The AIC and CAIC for our model are 229.51 and 824.42, respectively. The AIC and CAIC for a MPM with only three independent variables—exposure (DVMT) for each type—are 404.66 and 902.32. The AIC and CAIC for a saturated model in which every regression effect is present, even those with

Table 3
Multivariate probit model coefficient estimates (z-statistics in parenthesis)

Independent variable	Dependent variable		
	Type A	Type B	Type C
Accident location: left lane			0.046 (2.85)
Accident location: interior lane(s)	0.084 (3.36)	−0.117 (−4.73)	
Accident location: right lane			
Accident type: weaving (lane change maneuver)		0.032 (1.82)	−0.100 (−5.13)
Accident type: 2-vehicle rear end		−0.047 (−2.33)	
Accident type: 3-or-more-vehicle rear end		−0.039 (−2.10)	
Speeding cited as primary factor		−0.068 (−3.35)	
Accident occurs during weekday rush hours	−0.057 (−2.19)	−0.040 (−1.65)	0.101 (3.84)
Accident is injury or fatality	−0.057 (−2.41)	0.075 (3.05)	
Accident occurs on wet road surface	0.059 (2.43)	0.047 (1.77)	−0.049 (−2.58)
Accident occurs during darkness	0.044 (3.23)		
Daily average vehicle miles of travel $\times 10^6$	−0.033 (−1.38)	0.389 (14.40)	0.442 (15.47)

coefficients not significant at the $p = 0.05$ level, are 240.00 and 926.43. Based on these criteria, our model outperforms both the more parsimonious model with no accident types effects and the saturated model.

The estimated regression coefficients are listed in Table 3. These coefficient values can be directly compared because they are standardized, as the estimation being performed uses a correlation matrix. We interpret these results, which control for vehicle exposure, as follows.

5.1. Type A weaving section accidents

A Type A weaving section accident is more likely to be located in an interior lane. The accident is likely to be less severe than a accident within the other two types of weaving sections. The accident is more likely to occur off-peak, especially after dark. It is also more likely to occur on wet road surfaces. Accidents on Type A weaving sections are not strongly related to vehicle miles of travel. Based on these results, potential treatments to enhance the safety of Type A weaving sections are discussed in Section 6.

5.2. Type B weaving section accidents

Alternatively, a Type B weaving section accident is less likely to be located in an interior lanes, and more likely to result in injuries. The accident is more likely to be involve a vehicle executing a lane-change maneuver, and less likely to be a rear end accident with vehicles proceeding straight ahead. The accident is more likely to be caused by factors other than speeding. Accidents on Type B weaving sections are strongly related to vehicle miles of travel, a simple measure of exposure. This indicates that speed disparity might be a causal factor in accidents that occur within Type B weaving sections, as discussed below.

5.3. Type C weaving section accidents

Finally, a Type C weaving section accident is more likely to occur during weekday peak periods and more likely to be located in the left lane. The accident is less likely to involve a lane changing maneuver and are less likely to occur on wet road surfaces. As with Type B, accidents on Type C weaving sections are very strongly related to vehicle miles of travel.

6. Summary and conclusions

The statistical comparison between accidents occurring in weaving sections versus those on the freeway mainline highlights the factors that differentiate the prevailing accident conditions for these two situations. The most significant influences were found to be related to the type of movement performed by the vehicles involved in the accident, and to the exact location where the incident takes place. As expected, sideswipe collisions have the highest likelihood of occurrence in weaving sections, with most occurring in an interior lane, which is also the location for which accidents of any type have the highest chance of occurrence in weaving areas.

The most revealing assessment of the distinguishing characteristics of weaving section accidents was accomplished using a multivariate model of accident typology across weaving section types A, B, C, and their combinations. Using 11 independent variables representing categories of accident characteristics found to be important in the bivariate analyses, the multivariate model revealed distinct patterns of accident characteristics. A twelfth independent variable is used to control for differences in vehicle exposure among the weaving sections. Because this modeling approach explicitly treats the compound weaving section Types AC, BC and AC as combinations of the three discrete variables representing weaving section Types A, B, and C, the multivariate model minimizes problems associated with the relatively small number of compound sections.

Results indicate that the safety of Type A weaving sections, where every merging or diverging vehicle must execute one lane change, is compromised by vehicle conflicts within the interior lanes. These conflicts are more prevalent at off-peak periods, especially at night, and on wet roads. While no specific type of collision is predominant, Type A section accidents are the least severe among the three types of weaving sections. Based on these results, traffic engineering improvements for Type A weaving sections might include improved signage, improved lighting, and/or pavement resurfacing in the form of scoring or with wet-friction materials. It is recommended that signage in advance of all Type A weaving sections be reviewed in order to determine if drivers are being given sufficient warning of the need to change lanes in order to exit or enter the freeway, especially at night and during inclement weather, and when traveling at posted speeds under free-flow conditions.

Safety of Type B weaving sections, where one of the merging or diverging movements can be done without changing lanes, while one lane change is required for the opposite movement, is compromised by conflicts involving vehicle lane changing, predominantly in either the right or left lanes. These accidents are likely to be the more severe than accidents in either Type A or Type C weaving sections. Ostensibly, the results indicate that the root cause of these accidents may stem from the disparity between the speed of the movement requiring the lane change and that of the through and non-lane-change merge. In such cases, special speed restrictions may be warranted, or more effective enforcement of posted speeds. Signage and driver education should also be reviewed as means of alerting drivers to potential problems in negotiating Type B weaving sections.

Finally, safety of Type C weaving sections, where one weaving movement can be made without making any lane change, while the other weaving movement requires at least two lane changes, is compromised by vehicle conflicts that tend to occur in the left lane during weekday rush hours. There may be no simple safety mediation for these accidents involving complex successive lane changing other than restriction of the merge during periods of peak traffic, which may not be practical. However, changeable message signs warning of potential hazards at Type C weaving section locations might be effective in alerting drivers to potential hazards during periods of heavy traffic flow.

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Appendix A

In a multinomial probit model (MPM) with T discrete dichotomous variables, it is assumed that there is a set of T corresponding continuous underlying latent variables defined by the regression relationship

$$y_{it}^* = \beta_t' x_{it} + \varepsilon_{it} \tag{1}$$

where the k-dimensional vector x_{it} represents $i = 1, \ldots, N$ observations on K exogenous variables for each of the $t = 1, \ldots, T$ endogenous variables, β_t is matrix of regression coefficients for the T endogenous variables on the K exogenous variables, and ε_{it} are the disturbances (unexplained portions) of the endogenous variables. These latent variables are unobservable, but are related to observed discrete variables according to

$$\begin{aligned} y_{it} &= 1 \quad \text{if } y_{it}^* > 0 \\ y_{it} &= 0 \quad \text{otherwise} \end{aligned} \tag{2}$$

The ε_{it} disturbance terms are T-variate normally distributed with a (T by T) positive definite covariance matrix Ψ. The parameters to be estimated are the elements of β_t and Ψ.

The MPM can be traced to Ashford and Sowden (1970), in which an exact maximum likelihood (ML) solution was developed for the bivariate case of two dependent variables. However, until relatively recently, joint estimation of three or more equations with dichotomous dependent variables was computationally infeasible. In the last 20 years, and especially in the last decade, several methods for estimating multivariate models have been developed in three different fields: (1) econometrics and marketing science, (2) biometrics and biostatistics, and (3) other social sciences and education particularly psychometrics and sociometrics. We use a structural equations model (SEM) approach (Golob, 2003; Golob and Regan, 2002) to MPM, which was pioneered in part by Muthén (1979, 1983) and Amemiya (1978). Multinomial logit models (MLM) have also been advanced (e.g., Glonek and McCullagh, 1995), but these efforts require substantial approximations due to the lack of a multivariate logistic distribution.

All structural equation models are estimated using a covariance analysis method (method of moments), and our SEM approach to MPM employs the generalized least squares covariance analysis method first implemented by Muthén (1984). The method proceeds by defining the sample variance–covariance matrix of the combined set of endogenous and exogenous variables, partitioned with the endogenous variables first:

$$S = \begin{bmatrix} S_{yy} & S_{yx} \\ S_{yx}' & \Phi \end{bmatrix} \tag{3}$$

where S_{yy} denotes the variance–covariance matrix of the latent endogenous variables defined in (1) and (2), S_{yx} denotes the covariance matrix between the latent endogenous and exogenous variables, and Φ denotes the variance–covariance matrix of the exogenous variables (which, by definition, is taken as given). In our model, there are three endogenous variables and twelve exogenous variables, so S is a (15 by 15) symmetric matrix.

In the first step of the estimation, estimates of the correlations between each pair of latent endogenous variables are obtained using a maximum likelihood solution. Each correlation between the two latent endogenous variables is the unobserved correlation of their bivariate normal distribution that would generate the cross-tabulations as a most likely outcome. They are known as tetrachoric correlation coefficients, and solution to the problem is described in Olsson (1979). Similarly, the unobserved correlations between each endogenous variable and each continuous observed exogenous variable, known as polyserial correlation coefficients, are estimated also using a standard maximum likelihood technique (Olsson et al., 1982).

The second stage of the estimation involves finding parameters such that the model-replicated variance–covariance matrix is as close as possible to the sample covariance matrix (3), according to some objective function. It can be easily shown using matrix algebra that the corresponding variance–covariance matrix replicated by an identified model system (1) with a given vector of parameters, θ, is

$$\Sigma(\theta) = \left[\begin{array}{c:c} (\beta\Phi\beta' + \Psi) & [\beta\Phi'] \\ \hdashline \Phi\beta' & \Phi \end{array}\right] \tag{4}$$

where Φ is taken as given. An optimal vector of parameters, which are here the regression coefficients (elements of β) and error-term covariances (elements of Ψ), is determined by finding vector for $\hat{\theta}$ which the model-implied covariance matrix (4) is as close as possible to the matrix of tetrachoric and polyserial correlations. For continuous variables with observed product–moment correlations, it is appropriate to use normal-theory maximum likelihood (ML) estimation to define an objective function. However, ML assumptions do not hold for discrete observed endogenous variables, and ML parameter estimates, while consistent, will have incorrect standard errors, and the method will yield incorrect goodness-of-fit (chi-square) statistics.

The method used to estimate parameters when a SEM has discrete or otherwise censored observed endogenous variables is asymptotically distribution-free weighted least squares (ADF-WLS). The fitting function for ADF-WLS is

$$F_{\mathrm{WLS}} = [s - \sigma(\theta)]' W^{-1} [s - \sigma(\theta)] \tag{5}$$

where s is a vector of tetrachoric and polyserial correlation coefficients for all pairs of latent endogenous and observed exogenous variables, $\sigma(\theta)$ is a vector of model-implicated correlations for the same variable pairs, determined according to (4), and W is a positive-definite weight matrix, given by asymptotic estimates of the covariances of the covariances (fourth-order moments). Minimizing F_{WLS} implies that the parameter estimates are those that minimize the weighted sum of squared deviations of s from $\sigma(\theta)$. This is analogous to weighted least squares regression, but here the observed and predicted values are variances and covariances rather than raw observations. Browne (1982, 1984) has demonstrated that the ADF-WLS estimation based on objective function (5) will yield unbiased parameters estimates with asymptotically correct goodness-of-fit statistics.

This method is known as ADF-WLS (asymptotically distribution free, weighted least squares) and it is described in detail in Golob and Hensher (1998) and van Wissen and Golob (1990). The method has been shown to yield consistent estimates which are asymptotically efficient with asymptotically correct covariances, and the chi-square statistic computed from the fitting function will produce an asymptotically correct test of overall model fit, provided that the sample size is large enough compared to the scope of the problem. Biometricians and statisticians have also developed several variance analysis methods for MPM that have many properties in common with the ADF-WLS method, and these are reviewed in Golob and Regan (2002).

MPM can also be estimated using simulation methods, which avoid evaluation of multiple integrals in maximum likelihood estimation (McFadden and Ruud, 1994). When comparing our structural MPM estimated using ADF-WLS to maximum likelihood (simulation) methods, there are advantages and disadvantages to each (Golob and Regan, 2002). One advantage to our structural MPM, is that it uses a well-established estimation method that has been widely applied in the behavioral, social, biological, and educational sciences to model relationships involving multiple dichotomous and ordinal endogenous variables. Thus, there is extensive documented knowledge about data requirements, assessing goodness-of-fit, and robustness of the estimates under violations of assumptions. The solution algorithm is well behaved and its performance under a variety of model specifications has been extensively studied. In contrast, MPM simulation estimation methods, at their current state of development, are subject to numerous computational difficulties in finding an optimal solution for all but the simplest models. The performance of these algorithms will undoubtedly improve with experience and with attention from a growing body of developers and users.

The limited empirical studies that have compared simulated maximum likelihood and generalized least squares methods (like that used here) have shown that the two methods yield similar estimates. Bock and Gibbons (1996, p. 1187) compared MPM maximum likelihood estimates to those of a structural MPM and concluded that "all results agreed to second and third decimal places except for a few of the correlations and their standard errors." They observed that the correlation estimates should be more accurate in the simulated maximum likelihood solution, but the same may not be true of the standard errors of the correlations, which are approximations in many full-information methods. They concluded that the generalized least squares procedure is quite satisfactory in many applications.

All MPM require a fairly large sample size. Both structural MPM and simulated maximum likelihood methods rely on asymptotic theory, and it is not well known how either set of asymptotic assumptions holds up with realistic sample sizes. Sample size problems are likely to be manifested in biased inference due to poor estimates of parameter variance–covariances. One rule of thumb is that the number of observations should be greater than $1.5k(k+1)$, where k is the total number of variables (Jöreskog and Sörbom, 1993). Our case of 829 observations and thirteen variables (3 dependent plus 10 independent) satisfies this criterion. We do fall somewhat short of the recommended minimum sample sizes of 1000 for ADF-WLS estimation (Hoogland and Boomsma, 1998), but our final model, which contains 20 free parameters, meets the criterion that sample size for structural equation modeling with non-normal data should be at least ten times the number of free parameters (Boomsma and Hoogland, 2001).

Collinearity, which manifests itself in non-positive definite moment matrices and is difficult to foresee, is another limitation of the structural MPM that plagues all simultaneous equations systems with a relatively large number of variables, particularly systems comprised mostly of dichotomous variables. In addition to being constrained by sample size to no more that

20 exogenous variables, we were constrained to finding exogenous variables that did not lead to singularity when combined together with the endogenous variables. In the present application, this limits the number of accident characteristics that can be included in the MPM.

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