A CRASH PREDICTION MODEL FOR WEAVING SECTIONS IN THE NETHERLANDS

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ABSTRACT

Weaving is defined as the crossing of two streams travelling in the same direction along a significant section of the road without the assistance of traffic control devices. Merging and diverging vehicles need to make one or more lane-changes in a limited space and time, determined by the weaving section length. This situation creates intensive lane-change maneuvers, combined with heavy traffic volumes and variability in the speeds of the weaving and non-weaving vehicles. This often results in safety and operational problems.

In the literature few studies developed crash prediction models for weaving sections. Therefore, the main objective of this study is to investigate how different geometric and traffic related variables affect the safety performance of motorways' weaving sections, and develop a quantitative model for crash prediction. A sample of 110 weaving sections distributed all over the motorway network in The Netherlands was included. A database composed of the traffic and geometric characteristics of the weaving sections, and of their crash records was prepared. A Negative Binomial regression model was developed and the factors that mostly influence the crash frequency at weaving sections were identified.

The results show that crash frequencies of weaving sections are significantly affected by the length of the weaving section, the average annual daily traffic (AADT), the percentage of weaving cars, the number of lanes on the main motorway and the location of the weaving section relative to the interchange (if inside or outside the interchange).

Keywords: Weaving sections; Crash prediction; Negative Binomial regression; Safety performance; Lane-changing

INTRODUCTION

Traffic safety is undoubtedly a major issue for society and is increasingly attracting a lot of attention *(1)*. Most countries are trying to diminish traffic crashes and especially the resulting number of fatalities *(2)*. Weaving sections on motorways present higher crash probabilities compared to a basic motorway section. More specifically, in the Netherlands, the number of crashes per vehicle kilometer at weaving sections is about twice as high as on the basic motorway road sections *(3)*. Weaving sections on motorways are considered to be the most complex part because of the extensive lane-changing maneuvering creating higher levels of turbulent traffic operations compared to a basic motorway section *(4)*. The frequent lane-changing maneuvers are due to crossing of entering and exiting traffic over a short distance, while traveling in the same direction without the assistance of traffic control devices. This has negative implications on the level of safety and operations of motorways *(5)* and sometimes even have operational impacts that can stretch beyond the localized section *(1, 6, 7)*.

Apart from the length of the weaving segment that constrains the time and space in which drivers must make the required lane-changes, the lack of homogeneity in terms of driving speeds between weaving and non-weaving vehicles are argued to be among the primary causes of crashes on weaving sections *(1)*. Homogeneity of driving speeds is one of the important principles of Sustainable Safety *(8)*. When entering traffic merges with through traffic on the motorway, traffic density increases resulting in higher complexity for the road users. These changes and the increased complexity raises the potential for conflicts and crashes *(9)*. According to Elvik *(10)* the term "complexity" refers to the amount of new information a road user has to process per unit of time. As a result, complexity constitutes a basic risk factor for road crashes and injuries *(10)*.

The horizontal and vertical alignments of the ramps (which are associated with the interchange type) complicate the lane changing maneuvers that are executed by drivers on weaving sections. The road curvature affects vehicles' travel speeds and limits the view of the weaving section ahead. Therefore, drivers do not anticipate approaching traffic from the on-ramps on the right side *(6).*

Although crash prediction models (CPMs) are widely used for assessing the safety of roads, there has been little effort for developing dedicated CPMs for weaving sections *(7).* Relatively few studies have analyzed the relationship between the characteristics of weaving sections and traffic safety *(11)*. The main reason for this is the complexity of collecting traffic and road related data *(7)*. The following paragraphs summarize the state-of-the-art with respect to the safety of weaving sections.

Cirillo *(12)* studied the effects of the length of weaving sections, acceleration lanes and deceleration lanes on crash rate using data collected in 1961. The results showed that longer weaving sections would effectively reduce crash rates if the Average Daily Traffic (ADT) is greater than 10,000 vehicles per day, whereas the increase of the weaving section length of weaving sections with lower traffic volume may not affect crash rates. In case more than 6% of the traffic is merging, the increase of the length of the acceleration lanes can decrease crash rates to a higher extent than the increase of the length of the deceleration lanes.

Glad et al. *(6)* studied collisions' types and severities occurring on weaving sections in Olympia, Washington, using data collected from 1994 to 1996. The results showed that congestion on weaving sections during peak hours could lead to rear-end collisions, while during off peak hours, the increase in speeds of the traffic along weaving sections and ramps increases the sideswipe and rear-end collisions, and leads to more severe collisions. The safety impacts of restricting ramp to ramp traffic movements in the weaving section, adding a lane to existing motorway, providing a collector/distributor lane to remove weaving section, and ramp metering were studied by using traffic simulation models. The authors found that the collector/distributor alternative was the best in improving the operational level of weaving sections.

Golob et al. *(11)* analyzed the safety of 55 weaving sections of various types (A, B, C) in Southern California. The results showed that there was no difference among these three different types in terms of the overall crash rates over one year. However, important differences were found in terms of the types of crashes that occurred, their severity, location, causal factors, and the most probable time period of crash occurrence. It was found that crashes in Type A weaving sections are the least severe among the three types of weaving sections. In Type B on the other hand, because of higher variability of speeds, crash severity is higher compared to Type A or C.

Liu et al. *(13)* investigated the safety impacts of lane arrangements between motorway entrance and exit ramps by selecting 66 motorway weaving segments in the state of Florida. Three different types of weaving sections, Types A, B, and C, were studied to compare their safety performance. Crash prediction models were developed, using Negative Binomial regression, in order to determine the relationship between the number of crashes reported at the selected motorway segments and various explanatory variables. The explanatory variables included the length of the weaving section, the on-ramp ADT, the type of lane arrangement, the main motorway ADT, the number of lanes, and the posted speed limit. It was found that the length of the weaving section, the on-ramp ADT as well as the posted speed limit had negative impact on the safety of weaving sections. On the contrary, Type C presented the lowest average crash frequency.

Pulugurtha and Bhatt *(1)* collected and analyzed crash data, weaving sections' characteristics, and traffic volumes of 25 weaving sections in Las Vegas. Descriptive and statistical analyses were conducted to study the relationships between crashes and the characteristics of the weaving sections (type of configuration, total number of required lane-changes by weaving traffic, length of weaving sections), and traffic variables (entering traffic volume, exiting traffic volume and non-weaving traffic volume). A Poisson distribution was applied and the results showed that the number of crashes tends to decrease with the increase in weaving sections' lengths. In addition, an increase in entering traffic volume increases crashes due to improper lane-changes and run-off-the-roadway crashes, whereas an increase in exiting volume increases rear-end crashes, crashes due to following too closely, and crashes due to inattentive driving.

Park et al. *(14)* conducted a study to investigate the safety effects of important design elements for motorways. Negative binomial regression models were used to estimate the effects of several independent variables on crashes. The final model indicated that crashes on motorway segments were affected by the ADT, on-ramp density, the number of lanes (for urban motorways), and whether the motorway is in an urban or rural area. Off-ramp density was not a statistically significant influencing factor. The effect of on-ramp density on motorway crashes was significant for horizontal curves sections but not for tangent sections, which indicates that motorway designers should avoid designing on-ramps within the horizontal curves. The statistical modelling results were geared into the development of crash modification factors for on-ramp density and horizontal curves. These crash modification factors can be used for safety prediction of motorways.

Le and Porter *(15)* used Negative Binomial regression modelling approach in order to explore the relationship between ramp spacing and safety. Several other traffic and geometric variables were also included to increase the explanatory power of the model. The results of this study indicated that crash frequency increased as ramp spacing decreased, and the safety benefits of having an auxiliary lane decreased as ramp spacing increased.

Recently, Qi et al. *(7)* used a Poisson distribution to develop a crash prediction model based on a data base of 16 weaving sections and crash data over a five years period. Based on the developed model the authors derived crash modification factors. It was found that longer weaving sections had lower crash frequencies per 1000 ft., and that the number of crashes increases as the needed number of lane-changes by diverging traffic increases. Furthermore, while it was found that an increase in the merging traffic volume decreases crash risk, the increase in diverging traffic volume has an opposite effect, i.e. increases crash risk.

The Highway Safety Manual *(16)* presents different crash prediction models and Accident Modification Factors (AMF), however, there is still a lack of an available AMF for the treatment of increasing the length of weaving areas, although the trend regarding the potential change in crashes or user behavior is known. AMFs for other variables related to weaving areas are also not available yet.

As can be seen from the literature review, relatively few studies were conducted which developed CPMs for weaving sections, and some of these previous studies are quite old by now or have limited sample size. Therefore, there is a need to develop newer models and use valid and sufficient sample size for the development of such models.

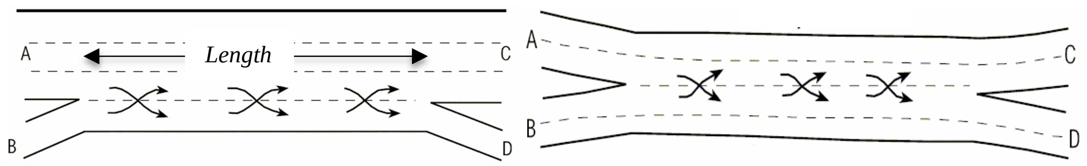
The rest of the paper is organized as follows: the next section presents the research methodology, which includes sites selection, data collection and model formulation. This is followed by the analysis results, and finally, the discussion and conclusions.

RESEARCH METHODOLOGY

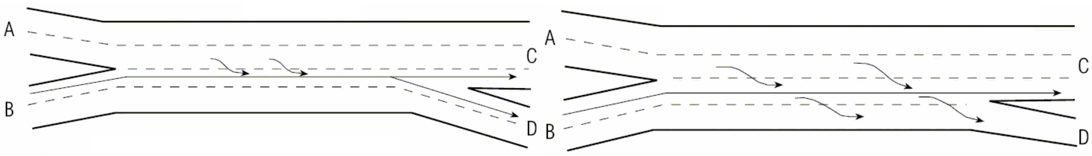
This section summarizes the procedure of the sites selection, data collection, and the crash prediction model formulation.

Sites Selection

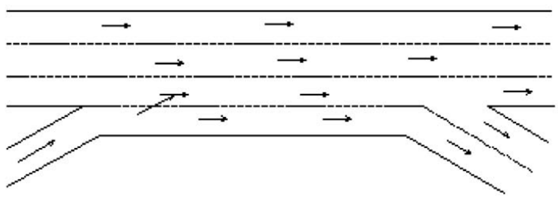
In traffic engineering, three types of weaving sections and their combinations are distinguished based on the minimum number of lane-changes required for completing the weaving manoeuvers *(4)*. Type A requires each and every weaving vehicle to execute at least one lane-change within the weaving area. There are two possible formations of type A weaving sections as shown in Figure 1 (a1) and (a2). In both formations, the lane-changes occur across the dashed line that connects the entrance gore with the exit gore. In type B, one weaving movement can be accomplished without making any lane-change, while the other weaving movement requires, at most, one lane-change (see for example Figure 1b). Finally, in type C one weaving movement is carried out without any lane-change, while the other requires, at least, two lane-changes as shown in the example in Figure 1c *(17)*. It is also possible that two types of weaving configurations can be combined to create one that is a combination of two types of weaving sections (such as Type A-B, presented in Figure 1d).



(a1) Type A weaving section: Ramp weave; (a2) Type A weaving section: Major weave;



(b) Type B (c) Type C



(d) Type AB *(1)*

FIGURE 1 Types of weaving section configurations.

In this case study, using geographical data by Rijkswaterstaat (Dutch Ministry of Infrastructure and the Environment), 121 weaving sections with different geometric configurations, numbers of auxiliary lanes and ramp arrangements, were identified as shown in the motorway network of The Netherlands in Figure 2. The weaving sections were distributed by type as follows: 110 Type A, 4 Type C, and 7 Type AB. This study focuses on type A weaving sections due to the lack of sufficient large samples (>30 observations) for the other types of configurations (types C and AB). The sample size of type A can be explained by the fact that in the Netherlands, this type is the most common.

The weaving section in Figure 1(a1) consists of one lane on-ramp followed by a one lane off-ramp with a continuous auxiliary lane connecting the two ramps. Out of the total 110 type A weaving sections, 94 were of this type, termed ramp-weave. The remaining 16 weaving sections were of the major-weave type (shown in Figure 1(a2)). In a major-weave type, at least three of the entry and exit legs have multiple lanes.

FIGURE 2 Selected weaving sections.

Data Collection

The weaving sections (110 type A) were categorized to two groups based on their proximity to interchanges; either outside interchanges (58 weaving sections) or inside interchanges (52 weaving sections). From the perspective of drivers, these two types are significantly different. Weaving sections that are outside interchanges are part of a through carriageway, while those inside interchanges are preceded by connecting sections of the interchange as illustrated in Figure 3. This categorization is supported by Torbic et al. *(18)* who compared the Safety Performance Functions (SPFs) of both segment types and found that weaving sections "within" interchanges have more crashes than those "outside" interchanges. The authors *(18)* reasoned that this increase is due to the weaving and lane-changing associated with the interchange ramps.

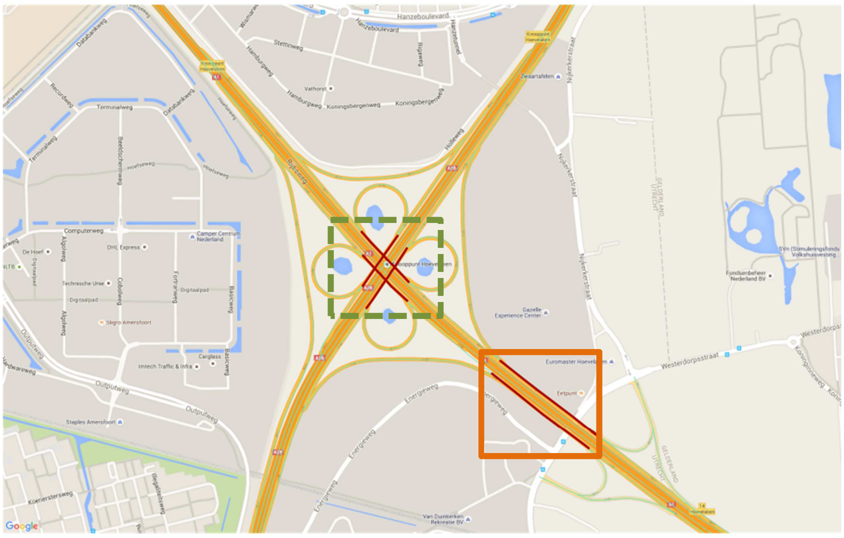


FIGURE 3 Weaving sections located either inside the interchange (red lines inside the dashed green rectangle) or outside the interchange (red lines inside the orange rectangle)

Road design characteristics

Data on the road design characteristics of the selected weaving sections were collected by using Google Earth, Google street view and Geographic Information System (GIS). The resulting database includes: the number of lanes in the main motorway, the number of lanes in the on/off ramps, the total number of lanes in the weaving area, the length of each weaving section and if the weaving section is symmetric or asymmetric. Symmetrical weaving sections need to meet two requirements: (i) the total number of driving lanes of the carriageways to be merged equals the total number of lanes of the carriageways to be split; (ii) the convergence and divergence point are positioned along the same marked line. The weaving section is asymmetrical if the aforementioned requirements are not met *(19)*.

The length of each weaving section was obtained by GIS, i.e. ArcGIS from ESRI *(20)*. The weaving length is measured from the merge gore area to the diverge gore area as shown in Figure 1(a1), following the definition of the length in the HCM 2010 *(4)*.

Traffic flow data

Beside the road geometric design characteristics, data on traffic flows on the weaving sections is also a significant factor that should be considered in the development of CPMs. The Average Annual Daily Traffic (AADT) was determined from loop detector data. Since there were no empirical data on the share of weaving vehicles, traffic modelling calculations were made by 4Cast company using a strategic traffic model named Nederlands Regionaal Model (NRM 2014) *(21)*. This model is designed to produce regional transport and traffic forecasts and can provide traffic flow data at a link level. The modelling methodology used for this study was based on link analysis. More specifically, for the purpose of this study it was not sufficient only to know how much traffic is assigned to each link, but also from which other links the traffic was coming and towards which links the traffic was travelling. Therefore, selected links were used to acquire this information for the weaving sections. The selection of the relevant links was made by Rijkswaterstaat. The load of a specific weaving movement can then be determined by studying the model output. This is explained in Figure 4. In this example 78 vehicles per hour will weave from the main motorway to the off-ramp during a peak hour. The remaining traffic (312 vehicles per hour) continues to drive on the main motorway. To complete this weaving section an additional selected link analysis was carried out for the on-ramp, which is not shown in Figure 4. For more details on the validation of the NRM model see *(22)*.

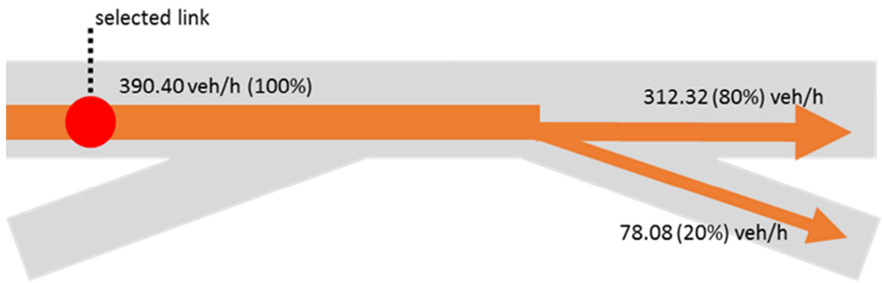


FIGURE 4 Example of a selected link analysis.

In this way, the weaving and non-weaving percentages were determined for each weaving section for both morning and evening peak hours and separately for cars and freight traffic. Figure 5 illustrates an example from one of the included weaving sections in the sample:

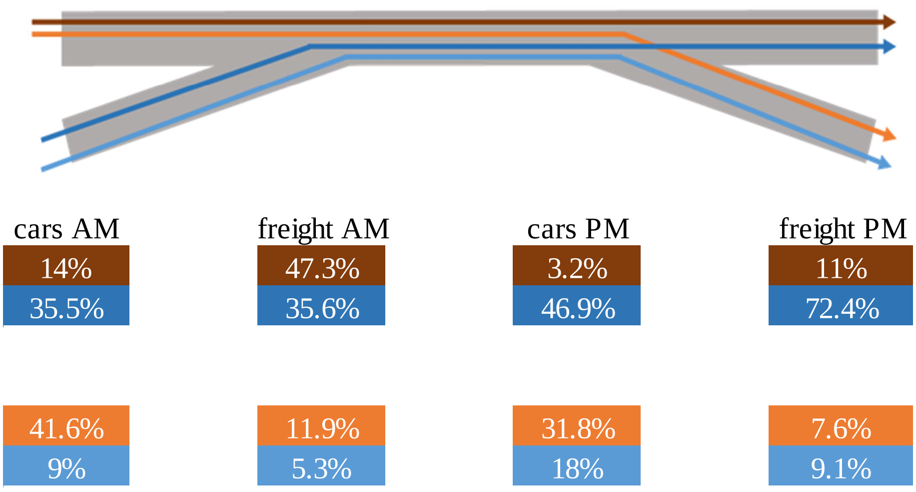


FIGURE 5 Percentage of weaving and non-weaving cars/freight during peak hours in the weaving section Rijnsweerd.

To estimate the AADT on the on-ramps and off-ramps, it was assumed that the calculated percentages of weaving and non-weaving cars and freight during peak hours, presented in Figure 5, remain the same during the day. Thus, by multiplying the average percentages (of AM and PM peak hours) in Figure 5 with the AADT on the weaving section obtained from the loop detectors, the AADT on the on-ramps and off-ramps were estimated. This assumption should be investigated and verified in future studies when empirical data becomes available.

Crash data

A database of police-reported crashes and their level of severity for a 3 year period, (2007-2009), was available from the Dutch national road crash registration (BRON). The crash database contained information on the crash type and on the geographic coordinates of the crash location (longitude and latitude) which enabled a spatial distribution analysis. Based on the crash spatial location information and the crash information in the BRON database, crashes that occurred in weaving sections were identified and selected. Information on the collisions' types and severities were also available. The crash data considered all types of crashes and all levels of severities. Figure 6 shows an example of a map of crashes that were recorded in 2007-2009.

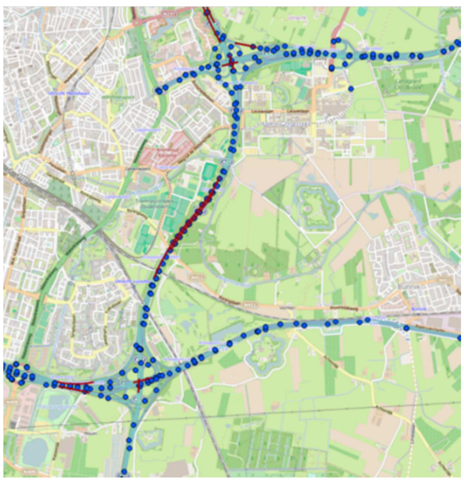


FIGURE 6 Crash map (Red lines: weaving segments, Blue points: number of crashes).

The aforementioned variables were all used in order to build a well-structured database in Geographic Information System (GIS). Table 1 summarizes the geometric and traffic variables that were included in the study.

TABLE 1 Summary of the Considered Explanatory Geometric and Traffic Variables

Explanatory Variables	
Geometric	**Traffic**
Configuration Type of weaving sections (Type A)	AADT[2] on the weaving section
Number of required lane-changes by weaving traffic (merging, diverging)	AADT on the on-ramp
Length of the weaving section (meters)	AADT on the off-ramp
Number of lanes in the main motorway	AADT on the main motorway
Number of lanes in the on/off ramps	Average percentages of weaving cars during peak hours[3]
Total number of lanes in the weaving section	Average percentages of weaving freight during peak hours
Location of a weaving section • Inside the interchange • Outside the interchange	Average percentages of non-weaving cars during peak hours
Interchange type	Average percentages of non-weaving freight during peak hours
Symmetry condition	Percentage of heavy vehicles (freight) during peak hours
Existence of auxiliary lane	Percentage of weaving vehicles (average of AM and PM)

Model Formulation

The fluctuation of the crash counts occurring on a road section during given time intervals can be described by assuming that the crash number is a random variable with the Poisson probability law *(23)*. Therefore, the Poisson regression methodology was initially attempted. However, in this study, the Poisson distribution was rejected because the mean and variance of the dependent variable were different, indicating over dispersion in the data (more variation in the data than predicted). Therefore, a Negative Binomial (NB) model, which accounts for the over-dispersion, was chosen to investigate the impact of different contributing geometric and traffic factors to the safety of motorways' weaving sections. The NB model is widely applied for the development of CPMs *(13, 14, 15, 24).*

NB model allows for the variance of crash counts to be greater than the mean which appears to be the case often when analyzing crash data. The model is derived by introducing

[2] Average Annual Daily Traffic (veh/day)
[3] Average of AM and PM

an additional gamma-distributed error term, $\exp(\varepsilon_i)$, to the mean function of the Poison regression. This error term has a mean equal to 1 and variance α *(25, 26, 27)* as illustrated in *Eq. 1*:

$$\lambda_i = \exp(\beta X_i + \varepsilon_i) \qquad (1)$$

This as a result leads to the following conditional probability function:

$$P(n_i|\varepsilon) = \frac{\exp[-\lambda_i \exp(\varepsilon_i)][\lambda_i \exp(\varepsilon_i)]^{ni}}{n_i!} \qquad (2)$$

Where, λi is the expected mean number of crashes on weaving section i, ni the number of crashes on weaving section i, in this case over a 3-year period, and ε_i is the error term.

The logarithm of the outcome $\ln(\lambda_i)$, and in this case $\ln(crashes)$, is predicted with a linear combination of the predictors (*Eq. 3*).

$$\ln(crashes) = \beta_o + \beta 1X1 + \beta 2X2 + \cdots + \beta iXi \qquad (3)$$

where, $X1, X2..Xi$ are the explanatory variables that affect the number of expected crashes and $\beta 1, \beta 2 \ldots . \beta i$ are the corresponding coefficients. *Eq. 3* is equivalent to:

$$crashes = e^{\beta_o + \sum \beta ixi} = e^{\beta_o} \times e^{\sum \beta ixi} \qquad (4)$$

A backward stepwise elimination procedure was adopted to identify significant variables that contribute to crashes. Following this procedure, all candidate variables are included in the model at the beginning. Then, an iterative testing procedure resumes with deleting variables and testing whether the deletion improves the model. This process is repeated until no further improvement is possible. Thus, different combinations of variables were tested in order to determine the best model.

In order to decide which subset of independent variables should be included in the model, the AIC (Akaike's Information Criterion) was used *(28, 29)*. AIC identifies the best approximating model among a class of competing models with different number of parameters. AIC is defined as follows:

$$AIC = -2 \times ML + 2 \times k \qquad (5)$$

where *ML* is the maximum likelihood and k is the number of variables in the model. AIC can be used to compare the goodness of fit versus the dimensionality or number of free parameters of different models. The model yielding the smallest value of AIC is considered as the best model *(25, 28)*.

The R statistical software, and the 'foreign', 'ggplot2', 'MASS' packages, were used to estimate this model *(30)*.

ANALYSIS RESULTS

Preliminary Analysis Results

Before developing and estimating a CPM, a description of the database and a preliminary descriptive statistics are summarized in Table 2:

TABLE 2 Descriptive Statistics for Initially Considered Independent Variables

Characteristics of the Interchange				
Location	Outside the interchange			58
	Inside the interchange			52
Interchange Type	Cloverleaf			54
	Clover-turbine			26
	Trumpet			13
	other			17
Symmetry	Symmetrical			107
	Asymmetrical			3
Geometric and Traffic Characteristics				
Variables	*Min.*	*Max.*	*Mean/Mode*	*Freq.*
Number of lanes in the main motorway	1	4	2	110
Number of lanes at the on-ramp	1	2	1	110
Number of lanes at the off-ramp	1	2	1	110
Total number of lanes in the weaving section	2	6	3	110
Length of weaving section (meters)	101	1498	417.5	110
Average percentage of weaving cars during peak hours[4], (%)	11%	100%	56%	110
Average percentage of weaving freight during peak hours, (%)	2%	31%	12%	110
Average percentage of weaving vehicles during peak hours, (%)	13%	100%	57%	110
Average percentages of heavy vehicles (freight) during peak hours, (%)	2%	31%	17%	110
AADT[5] on the weaving section (veh/day)	373	100,230	29,916	110
AADT on-the on-ramp, (veh/day)	0	52,335	10,006	110
AADT on-the off-ramp, (veh/day)	91	54,580	10,248	110
AADT on the main motorway, (veh/day)	236	75,455	19,910	110

As can be seen from Table 2 almost half of the weaving sections were located outside the interchange while the rest were located inside the interchange. Almost half of the interchanges were of the Cloverleaf type (49%), some of the clover-turbine type (24%), few of the Trumpet type (12%), and the rest (25%) of other mixed complex types of interchanges. Almost all of the weaving sections were symmetrical. Other details on the geometrical and traffic related variables of the selected weaving sections are described in Table 2.

[4] Average of AM and PM
[5] AADT – Average Annual Daily Traffic (veh/day)

Estimation Results

The best estimated three crash prediction models are presented in Table 3. The results show that all the remaining variables in the models are of plausible sign (with a positive sign for an increase in the crash frequency and negative sign for a decrease). These variables are significant at the 95% confidence level (p-value≤0.05), except for the location variable which is significant at the 90% confidence level (p-value≤0.1).

According to the results in Table 3, the model with the smallest AIC is Model C. However, for Model C, the values of the AADT on the ramps were not measured from loop detectors but they were derived by the NRM (Nederlands Regionaal Model) model mentioned earlier. These modelled values create uncertainty since they depend on the accuracy of the models and the assumptions made regarding the share of weaving and non-weaving cars and freight, and therefore, may abstain from reality. From a theoretical perspective, Model B seems more suitable as the variables are derived by using the least modelled values, i.e., AADT is measured by loop detectors and only the share of weaving cars during rush hours was estimated using NRM.

Model B has 5 independent variables plus a constant term (intercept). The independent variables include the AADT of the weaving section, the length which equals the distance between the entrance gore and exit gore, the percentage of cars that are weaving, the number of lanes on the main (through) motorway, and the location of the weaving section related to the interchange (inside or outside). The equation for the crash prediction model, based on *Eq.3,* is given as following:

$$\ln(crashes) = -10.02 + 0.46 \times \ln(Length) + 0.88 \times \ln(AADT\ of\ weaving\ section) + 0.35 \times (\text{No. of lanes on the main motorway}) + 1.05 \times (\text{Percentage of weaving cars}) - 1.67 \times (Location\ related\ to\ the\ interchange) \quad (6)$$

It can be seen from Table 3 that the dispersion parameter value is over 1 confirming the existence of over-dispersion, and the necessity to use the NB model. To measure the overall goodness of fit statistics, the deviance value $2(LL(\beta) - LL(0))$ which follows a chi-square (χ^2) distribution was used to test the overall goodness of fit *(25)*. The χ^2 test of the deviance value (145.4 with 5 degrees of freedom) supports the rejection of the null hypothesis that the obtained model has explanatory power equal to that of the model with the constant term only. Therefore, the model shows an overall good statistical fit.

According to Model B, the coefficients for the natural logarithm of the exposure variables (the sections' length and AADT) were found to be significant and positive. This indicates that the number of crashes tends to be higher on longer weaving sections and with higher traffic flows. Both coefficients are lower than 1 (0.46 and 0.88) meaning that the number of crashes increases less than proportional with the traffic flow and length. However, if the crash frequency is transformed to crashes per unit length *(31)*, the exponent of the length variable becomes 0.46 - 1= -0.54, implying that the number of crashes per unit length is decreasing as the length of the weaving section increases. This is reasonable since on longer sections, weaving vehicles have more space and time to complete the necessary lane-changes.

TABLE 3 Results of Crash Prediction Models' Estimation

	Model A		Model B (selected)		Model C	
	β	**P-value**	**β**	**P-value**	**β**	**P-value**
Intercept	-9.55	<0.0001	-10.02	<0.0001	-8.75	<0.0001
Length of weaving section (m.)	0.48	0.036	0.46	0.043	0.53	0.018
Location (Outside=1; Inside=0)	-1.75	0.0918	-1.67	0.106	-2.35	0.018
No. of lanes on the main motorway	0.36	0.0294	0.35	0.033	0.38	0.016
Average (of AM and PM peak hours) number of cars on the weaving section (cars/h)	0.84	<0.0001	-	-	-	-
Average (of AM and PM peak hours) percentage of weaving cars (%)	1.05	0.026	1.05	0.025	-	-
AADT on the weaving section (veh/day)	-	-	0.88	<0.0001	-	-
ln(AADT on the on-ramp, veh/day)	-	-	-	-	0.52	<0.0001
ln(AADT on the off-ramp, veh/day)	-	-	-	-	0.38	0.017
Std. Error	0.476		0.484		0.51	
AIC	516.4		515.62		504.89	
2 x log likelihood	-502.39		-501.62		-490.89	
α (dispersion parameter)	1.966		1.993		2.083	

Both the percentage of weaving cars during rush hours as well as the number of lanes in the main motorway are significant and positive, i.e. have negative impact on the safety of weaving sections. During the weaving movements the traffic flow becomes more turbulent thus drivers are required to change speeds more frequently leading to increased crash risk *(32)*. Similarly, the increase of the number of lanes on the main motorway suggests more lane-changes for vehicles directing to the off-ramp which can lead to increased turbulence and crash risk *(7)*. Therefore, reducing the number of lane-changes required to exit the motorway will decrease the crash probability on the motorway weaving sections.

The coefficient for the location of weaving sections is negative. This means that weaving sections located outside the interchanges have a lower crash likelihood compared to those located inside the interchange. However, this variable, as indicated earlier, is significant at the 90% confidence level.

DISCUSSION & CONCLUSIONS

In this study the safety performance of freeway weaving sections was investigated and a quantitative model for predicting the safety impacts of different geometric and traffic related factors was developed and estimated. NB regression was applied for the model development.

The estimation analysis results show that crash frequency of weaving sections is significantly affected by the length of the weaving section. Weaving sections with longer lengths will have a lower crash frequency per unit of length. This result is in accordance with the findings by Qi, et al. *(7)*, Cirillo *(12)*, and Pulugurtha and Bhatt *(1)*. Furthermore, it was found that the number of crashes tends to increase with the increase in traffic volume in the weaving section. Increase in the traffic volume means higher exposure and thus higher crash likelihood *(1, 33)*.

Higher percentage of weaving cars, corresponds to higher crash risk. During the weaving movements the traffic flow becomes more turbulent thus drivers are required to change speeds more frequently leading to increased crash risk *(8, 32)*. Higher number of lanes on the through/main motorway also increases the crash risk on weaving sections. More lanes on the main motorway imply more lane changes required to exit the motorway, which lead to increasing the crash probability. Similar results were found by Qi et al. *(7)*. Finally, weaving sections that are located inside interchanges present higher risk compared to those located outside interchanges. Torbic et al. *(18)* reached in their study similar results. A possible reason for this finding could be that speed differences between weaving streams are higher at weaving sections inside interchanges because a tight curve is frequent at one of the on-ramps preceding such weaving sections. Another reason could be that the length of weaving sections located inside the interchange are shorter than those located outside the interchange, and thus have higher levels of turbulence due to the limited space for weaving movements.

In model C, it was found that an increase in the entering and exiting traffic to the motorway increases the number of crashes on the weaving section. In the study by Qi et al. *(7)* only the diverging traffic volume was found to increase the crash risk, whereas the increase in the merging traffic volume decreases the crash risk. These differences in the results require further investigation.

In light of these results, this paper contributed to better understanding of the factors that affect the safety performance of weaving sections. The developed models can be used for quantitative assessment of the safety of different weaving sections, with different geometric and traffic characteristics. This can assist practitioners in comparing different design alternatives in terms of predicted numbers of crashes.

However, this study has a number of limitations that require further research. The first limitation is that only Type A weaving sections were included in the study. Future studies should investigate other types of weaving sections (such as types B, C). The second limitation is the fact that the percentage of weaving and non-weaving vehicles were derived from NRM (Nederlands Regionaal Model) and not from empirical data. This data seems to have a sufficient quality, as most of the traffic parameters derived from NRM were statistically significant (which would hardly be possible with a ‘random’ variable). Still, the accuracy of the results is dependent on the goodness of the NRM model. Hence, data collected by means of video cameras, field observations or measurements from loop detectors can provide even more certainty on the validity of the data. A third limitation is the lack of speed data of the weaving and non-weaving vehicles, as well as, the horizontal and vertical curvature elements, which are important factors in crash occurrence.

Future studies should attempt to consider those limitations in the development of crash prediction models. Furthermore, a number of variables (share of freight, weaving freight, interchange types, symmetry) that were assumed to have an impact on the safety of weaving sections were examined during the procedure of the formulation of the model but were not found to have a significant impact on crashes. Future research is needed to further investigate the impact of those factors on crashes. Other directions for model improvement could be the development of crash prediction models that account for the type and severity of the crash, and locations of crashes (i.e. left or right lane), and the types of vehicles involved. Another important direction for the improvement of those models is the consideration of the human behavior and drivers' characteristics as influencing factors on the safety of weaving sections. The use of advanced driving simulators to test the effect of the human behavior can be useful in this regard *(7)*. A multi-disciplinary approach combining insights across disciplines in the field of both road and human behavior should be adopted *(22)*.

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REFERENCES

1. Pulugurtha, S. S., and J. Bhatt. Evaluating the role of weaving section characteristics and traffic on crashes in weaving areas. In *Traffic injury prevention*, Vol. 11, No. 2, 2010, pp. 104-113.
2. OECD. *Road Safety Annual Report 2014.* International Transport Forum
3. Vos, E., N*ormstelling natte stroefheid van rijkswegen (Wet skidding resistance standards at state roads).* Published by Rijkswaterstaat, Delft, 2008.
4. Highway Capacity Manual (HCM) 2010. TRB, National Research Council, Washington, D.C., 2010.
5. Kusuma, A., R. Liu, C. Choudhury, and F. Montgomery.Lane-Changing Characteristics at Weaving Section. Presented at Transportation Research Board 94th Annual Meeting of the Transportation Research Board, Washington, D.C., 2015.
6. Glad, R., W. Milton, C. John, and D.K. Oslon. Weave Analysis and Performance: The Washington State Case Study. Report No. WA-RD 515.1, Washington State Department of Transportation, 2001
7. Qi, Y., X. Chen, and J. Liu. Safety Performance of Freeway Weaving Sections. Presented at 94th Annual Meeting of the Transportation Research Board, Washington, D.C., 2015.
8. Wegman, F., and L. Aarts. *Advancing Sustainable Safety: National Road Safety Outlook for 2005-2020*, SWOV Institute for Road Safety Research, Leidschendam , 2006.
9. Garber, N. J., M.A. Chowdhury, and R. Kalaputapu. *Accident characteristics of large trucks on highway ramps*. AAA Foundation for Traffic Safety, Washington, D.C., 1992.
10. Elvik, R. To what extent can theory account for the findings of road safety evaluation studies?In *Accident Analysis and Prevention*, Vol. 36, No. 5, 2004, pp. 841-849.
11. Golob, T. F., W. W., Recker, and V.M. Alvarez. Safety aspects of freeway weaving sections. In *Transportation Research Part A: Policy and Practice*, Vol. 38, No. 1, 2003, pp. 35-51.
12. Cirillo, J. A. The relationship of accidents to length of speed-change lanes and weaving areas on Interstate highways. Presented at the 49th Annual Meeting of the Transportation Research Board,Washington, D.C.,1970.

13. Liu, P., H. Chen, H., J. J. Lu, and B. Cao. How Lane Arrangements on Freeway Mainlines and Ramps Affect Safety of Freeways with Closely Spaced Entrance and Exit Ramps. *Journal of Transportation Engineering*, Vol. 136, No. 7, 2010, pp. 614-622.

14. Park, B. J., K. Fitzpatrick, and D. Lord. Evaluating the Effects of Freeway Design Elements on Safety. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2195*, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 58-69.

15. Le, T. Q., and R. J. Porter. Safety Evaluation of Geometric Design Criteria for Spacing of Entrance-Exit Ramp Sequence and Use of Auxiliary Lanes. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2309*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 12-20.

16. Highway Safety Manual. American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2010

17. Roess, R. P., E. S. Prassas, and W. R. McShane. *Traffic Engineering*, Third Edition, Prentice Hall. Upper Saddle River, New Jersey, 2004.

18. Torbic, D., Harwood, D., Gilmore, D., Richard, K. and Bared, J. Safety analysis of interchanges. In *Transportation Research Record: Journal of the Transportation Research Board No. 2092*, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 39-47

19. Rijkswaterstaat, Nieuwe Ontwerprichtlijn Autosnelwegen (NOA).Rijkswaterstaat Department of Traffic & Transport, 2007. Available at: http://www.rijkswaterstaat.nl/images/Nieuwe%20Ontwerprichtlijn%20Autosnelwegen%20(NOA)_tcm174-325052.pdf, retrieved on 20/12/2014.

20. Johnston, K., J. M. Ver Hoef, J. M.,K. Krivoruchko, and N. Lucas. *Using ArcGIS geostatistical analyst*, Esri, Redlands, 2001.

21. Rijkswaterstaat Ministerie van Infrastructuur en Milieu. http://www.rijkswaterstaat.nl/zakelijk/slimmer_werken/NRMLMS/. Accessed 1 February, 2015.

22. Tavasszy, L., Snelder, M., Duijnisveld, M., Haaijer, R., Meurs, H., van Nes, R., Verroen, E., van Schie, C., Bates, J., Jansen, B., TNO-060-DTM-2012-01993A, Audit LMS en NRM Syntheserapport, 2012, TNO.

23. Caliendo, C., M. Guida, and A. Parisi. A crash-prediction model for multilane roads. In Accident Analysis & Prevention, Vol 39, No4, 2007, pp. 657-670.

24. Chengye, P., and P. Ranjitkar. Modelling Motorway Accidents using Negative Binomial Regression. *Journal of the Eastern Asia Society for Transportation*, Vol. 10, No 0, 2013, pp. 1946-1963.

25. Abdel-Aty, M. A., and A. E. Radwan. Modeling traffic accident occurrence and involvement. In *Accident Analysis & Prevention*, Vol. 32, No 5, 2000, pp. 633-642.

26. Lord, D., and F.Mannering, F. The statistical analysis of crash-frequency data: a review and assessment of methodological alternatives. In *Transportation Research Part A: Policy and Practice*, Vol. 44, Issue 5, 2010, pp. 291-305.

27. Sawalha, Z., and T.Sayed. Traffic accident modeling: some statistical issues. *Canadian Journal of Civil Engineering*, Vol. 33, Issue 9, 2006, pp. 1115-1124.

28. Dissanayake, S., and J. Lu. Factors influential in making an injury severity difference to older drivers involved in fixed object–passenger car crashes. In *Accident Analysis & Prevention*, Vol. 34, Issue 5, 2002, pp. 609-618.

29. Miaou, S. P. *Measuring the good ness-of-fit of accident prediction models*. Publication FHWA-RD-01-113. FHWA, U.S. Department of Transportation, 1996.

30. R Core Team. R: A language and environment for statistical., R Foundation for Statistical Computing, Vienna, 2012. Available at: http://www.R-project.org/.

31. Brüde, U., and J. Larsson. Models for predicting accidents at junctions where pedestrians and cyclists are involved. How well do they fit? In *Accident Analysis & Prevention*, Vol. 25, No 5, 1993, pp. 499-509.

32. Lee, C., B. Hellinga, and F. Saccomanno. Evaluation of variable speed limits to improve traffic safety. In *Transportation research part C: emerging technologies*, Vol. 14, No 3, 2006, pp. 213-228.

33. Bared, J., G. L. Giering, and D. L.Warren. Safety evaluation of acceleration and deceleration lane lengths. *ITE Journal*, Vol. 69, 1999, pp. 50-54.