Impact of Variable Speed Limits on Crash Frequency and Crash Rate: Stimulation by Flow Rate and Percentage of Heavy Vehicles

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ABSTRACT

The current transportation system has faces a high number of crashes on road networks, often resulting in damages and human losses. According to WHO, these incidents cost most countries approximately 3% of their GDP. This underscores the need to address the weaknesses in road networks and provide efficient countermeasures to reduce these incidents and consequent losses. This study focuses on Variable Speed Limits (VSL) as a crucial factor that could influence road safety. To model the impact of VSL on the Crash Frequency (CF) and Crash Rate (CR), the researchers also considered other relevant traffic characteristics, such as the Percentage of Heavy Vehicles (PHV) and Average Daily Traffic (ADT). For the purposes of this research, the Mandali-Baqubah highway in Iraq was selected as a case study for the potential implementation of VSL. The statistical regression approach was utilized to model the Safety Performance Functions (SPF) for the road crash count. The findings of the current study revealed that the VSL are positively and significantly associated with CF and CR.

Keywords-road safety; Poisson gamma; R project; safety performance function; traffic volume

I. INTRODUCTION

The rising demand for diverse transportation modes has led to an increase in the number of trips, resulting in a higher frequency of accidents accompanied with significant economic and human losses [1]. According to the WHO, approximately 1.35 million people lose their lives on global roadways each year, and around 50 million individuals suffer severe health consequences from traffic collisions [2, 3]. Furthermore, road crashes substantially aggravate the traffic congestion, making road safety a top priority in transportation [2, 4].

Various transportation and geometric factors may influence road safety, particularly the Operating Speed (Sp), road surface condition, and traffic signs [5-8]. Speed is one of the most critical factors affecting the safety, CF, or CR of these networks [6]. Driver behavior related to speed issues is regulated by posted speed limits, which are typically used as Fixed Speed Limits (FSL) [4, 6, 9-11]. VSL display differing speed limits throughout various periods of the day, depending on the detection of specific traffic or weather conditions using sensors at fixed stations. The displayed speed limit is reduced in 5 to 10 km/h increments when particular thresholds are exceeded. This reduction aims to maintain an uninterrupted traffic flow and address safety concerns [12, 13]. VSL have been found more effective than FSL in mitigating potential traffic collisions [14].

To construct a comprehensive model accounting for the influence of VSL on road safety, other key traffic characteristics, such as the ADT and PHV, should be incorporated. Numerous researchers have examined the impact of traffic volume on road safety, as it represents a typical traffic characteristic affecting the number of crashes in the road

network. The ADT has been employed to represent the traffic volume. Some studies indicate that the ADT is positively correlated with the CF and CR due to increased vehicle conflicts, while others suggest a negative correlation between the ADT and CF [15]. The relationship between the road characteristics, including the average SP, ADT, PHV, and CF has been investigated within 30 km of Tehran's entrance roads in Iran [16]. Poisson and Poisson Gamma (PG) regression models were explored, with the second demonstrating a better fit than the first. The study also revealed that variables related to speeding were more effective in reducing crash incidents. Fixed and random parameter Tobit models were developed to analyze the relationships between the CR and traffic parameters, such as ADT, heavy vehicle effect, and delay time, at selected intersections in Baghdad in Iraq, finding a positive impact of the investigated parameters, particularly delay time [17]. A positive correlation between the variables and CF was reported when examining the effect of the HPV percentage on CF on the old Baghdad—Baqubah rural road using generalized linear regression models [15]. The potential contribution of driver aggressiveness to traffic crashes in Sulaimaniyah City was investigated using questionnaire forms, demonstrating a significant correlation between the speeding and second-order impulsiveness subscales, as well as a stronger correlation between attention and the total score of driving aggressiveness [18]. An analytical framework employing machine learning models to predict the severity of ten-year crash data in the United Kingdom was developed and utilized in identifying vehicle characteristics, maneuvers, road classification, and time of day as the most significant contributing variables [19]. In Marlboro, Maryland Light Detection and Ranging technology (LiDAR) was employed to explore the contribution of vehicle trajectories, including congestion points, traffic volume fluctuations, and speeds, as well as pedestrian and cyclist movement patterns, to the increasing level of traffic safety [20]. The crash-contributing factors along the Duhok-Zakho international road were investigated and can be used to identify high-risk segments based on the CF and CR measures [21]. The findings indicated that speeding is a significant factor, and installing speed cameras is crucial to enforce compliance with the speed limits. In another study, researchers examined the effects of the traffic flow, composition, and service level on the CF at the Girsheen-Suhela Intersections arterial section in Duhok City [22].

The reviewed studies have shown a positive correlation between the increase in CF and the rise in the PHV. However, this relationship may be influenced by the type of road under consideration. For instance, two-lane highways exhibit a greater increase in the CF and CR compared to other road types, due to the rise in the PHV. Furthermore, determining the optimal speed limit is crucial to enhance safety. The impact of speed values on crash likelihood cannot be ascertained without accounting for the influence of other factors, such as the ADT and PHV. Consequently, it is imperative to investigate the range of speed limit values that maintain the highest level of safety based on the prevailing traffic conditions. CF is the simplest and most widely used metric, while CR is also employed to reflect the influence of exposures, such as ADT, on CF. CR serves as an effective safety measure to assess the performance of a particular intersection or segment relative to the average roadway within the network [23, 24].

Modeling factors such that describe the relationship between the CF and CR, which is a crucial step in understanding the relationship between these factors and the safety performance levels on road networks. Verifying and validating the models can provide accurate future estimates, which could aid in developing more precise investment plans and enhancing road safety. These models include regression models, such as Generalized Linear Models, Log-Linear Models, Poisson, Poisson-Gamma, and Random Parameter Models. Poisson regression models are one of the most widely employed regression models to represent the effect of traffic and geometric characteristics on CF. However, the overdispersion in this method led researchers to consider an alternative regression analysis method. Consequently, Poisson-Gamma regression models have been utilized as an alternative to Poisson regression to develop CF models [25-30].

The literature review revealed the potential of VSL to mitigate crash risk by focusing on multilane highways [31-33]. This research aims to examine the influence of VSL on the CF and CR by modeling the relationship between the analyzed traffic features and the response variables along the Mandali–Baqubah corridor. The novelty of the current research lies in considering VSL in the modeling of CF and CR on two-lane highways. The outcome of this research can be used to identify the safe range of the VSL based on the traffic conditions of the case study in terms of ADT and PHV.

II. METHODOLOGY

A case study approach was employed to gather the necessary data. The SPF will be modeled by incorporating traffic characteristics as the independent variables, while the ADT and PHV, along with the CF and CR, will be investigated as the dependent variables. The VSL displayed for drivers are utilized as the SP in the developed models in order to reflect the impact of the speed variability on the CF and CR for specific ADT and PHV.

A. Case Study Selection

The selected case study for this investigation is the Mandali–Baqubah highway, which spans a length of 84 km and is considered one of the most vital routes in Iraq due to its strategic location near the Iranian border. This has contributed to an increase in the heavy truck traffic and a corresponding rise in traffic collisions. According to the Traffic Directorate in Diyala province, between 2010 and 2019, there were 772 reported fatal and injury-involved crashes on the Mandali–Baqubah Road. The majority of these incidents were attributed to excessive speeding and high traffic volumes [34].

B. Data Collection

The research required the collection of both independent and dependent variables for the developed model. The dependent variables consisted of crash data, while the independent variables included observed speed, ADT, and PHV. Crash data were gathered from various sources, such as the traffic authorities in Baqubah governorate, local police stations, and the Diyala Traffic Directorate. Data quality

techniques were employed to test the crash data for potential entry errors. Additionally, due to the random nature of crash events, the PG method was utilized to minimize the weight of the true outliers providing the best estimate considering all crash data [35].

The highway of interest was segmented into 84 fixed 1 km sections for the purpose of traffic data collection. The traffic datasets encompassed traffic characteristics, such as SP, ADT, and PHV, which were gathered for each weekday section using video recording methods with the observation hours being from 7:00 to 15:00. Specifically, the data comprised the counts of passenger cars and heavy vehicles, which were then analyzed to determine the ADT. Furthermore, the datasets included the average SP, calculated through video-based techniques that accounted for the distance traveled and time required between distinct fixed landmarks, such as utility poles or road markings.

C. Modeling of Safety Performance Functions

SPF are equations used to predict the expected number of accidents that occur annually at a specific location. These predictions are based on exposure data and, in some cases, the characteristics of the roadway or intersection. The significance of developing SPF models lies in their ability to capture the influence of geometric and traffic factors as independent variables on CR as the dependent variable [23].

This study employed regression analysis, specifically the PG technique, to model the traffic characteristics of the Mandali–Baqubah highway. The crash and traffic datasets for this highway were utilized as input data to develop the SPF model. To ensure the model's reliability, the standard error values for the crash and traffic datasets were examined to mitigate potential collinearity issues. The Variance Inflation Factor (VIF) technique was employed to assess collinearity, and a maximum acceptable VIF value of 5 was considered [36]. The descriptive statistics for the crash and traffic datasets are presented in Table I.

TABLE I. DESCRIPTIVE STATISTICS FOR THE CRASH AND TRAFFIC DATASETS.

Parameter	Min	Max	Mean	S.D.
CF	0	10.2	1.29	1.11
CR	0	11.5	1.83	1.36
SP	44	132	71.49	14.73
Ln(ADT)	4.61	9.92	8.14	0.47
PHV	5	17	6.13	2.97

The recorded SP on the Mandali – Baqubah highway exhibited significant variability, with a minimum of 44 kph, a mean of 71.39 kph, and a maximum of 132 kph. This substantial disparity between the minimum, maximum, and average speed values suggests unstable traffic flow characteristics in the area. This inconsistency may stem from a considerable difference between the design speed and the posted speed limit. Furthermore, under certain conditions, such as low traffic volume, drivers tend to exceed the legal speed limit, which could potentially lead to increased accident rates. In these cases, implementing VSL systems may be the preferred approach.

D. Implementing VSL

The proposed VSL strategy in this research relies on thresholds for the ADT and PHV. The sensors require these thresholds to trigger the implementation of VSL in any highway segment when the specific thresholds are attained.

The PHV was calculated as a proportion of the total traffic volume observed at each sensor station. As heavy vehicles occupy greater road space compared to passenger cars and maintain longer gaps with the preceding vehicles, slow-moving commercial vehicles can substantially impact traffic efficiency and safety, potentially contributing to bottlenecks on two-lane roadways [37]. Consequently, it is necessary to define a threshold for the PHV. For the purposes of this study, the threshold was set at 11%.

The ADT is another factor that could impact VSL. This factor was evaluated based on the traffic flow, which serves as a suitable indicator to reflect the congestion levels on road networks. A threshold of 1490 vehicles per hour was set as the traffic volume at which a bottleneck may start forming, leading to congested conditions [38, 39]. The traffic flow data would be collected at 5-minute intervals by sensors located along the highway, typically dual loop detectors spaced approximately 1 km apart.

III. RESULTS AND DISCUSSION

The impact of the VSL on the CF and CR models for the Mandali - Baqubah highway was investigated deploying the PG statistical method. VSL was incorporated as the SP parameter in these models to capture the effect of speed reduction on the CF and CR. The collinearity among the independent variables was assessed and found to be acceptable. The statistical parameters for the CF and CR models, derived from the R Project software, are displayed in Tables II and III, respectively.

TABLE II. STATISTICAL PARAMETERS FOR THE CF MODEL FOR THE MANDALI – BAQUBAH HIGHWAY

Variable	Coefficients	S.E.	z	Probability
Intercept	-0.48	1.93e-02	17.25	<2e-16
SP	0.008	4.92e-01	22.71	0.000552
Ln(ADT)	0.061	5.59e-01	31.77	<2e-11
PHV	0.009	2.90e-01	14.35	0.000249

TABLE III. STATISTICAL PARAMETERS FOR THE CR MODEL FOR THE MANDALA – BAQUBAH HIGHWAY

Variable	Coefficients	S.E.	z	Probability
Intercept	-0.51	3.4399	17.25	8.19e-07
SP	0.009	0.0352	22.71	3.27e-05
Ln(ADT)	0.072	0.4315	31.77	6.09e-11
PHV	0.011	0.9227	14.35	3.78e-08

The findings suggest that the ADT is a significant factor in modeling the CF counts. Furthermore, the results indicate a positive correlation between the CF, as well as CR, and the ADT. Additionally, the study revealed that the peak hourly volume significantly impacts both the CF and CR. The statistical analysis showed a positive correlation between the PHV and the dependent variables at a 95% confidence level. This positive relationship could be attributed to the high

number of overtaking maneuvers performed on the Mandali-Baqubah highway to pass slow-moving heavy vehicles, leading to a greater frequency of crashes, particularly head-on collisions. The VIF technique was utilized to assess multicollinearity among the independent variables. Linear regression analyses were employed/performed and the results demonstrated that the VIF values were within the acceptable limits, as portrayed in Table IV.

TABLE IV. VIF FOR THE INDEPENDENT VARIABLES

Variable	SP	LnADT	PHV
VIF	1.532	1.783	1.849

To evaluate the accuracy of the developed model, two datasets were analyzed and visualized. The first dataset comprised the Q-Q normal plot. As illustrated in Figures 1 and 2, the data points are distributed along a curved line, suggesting that the data follow the assumed PG distribution [27].

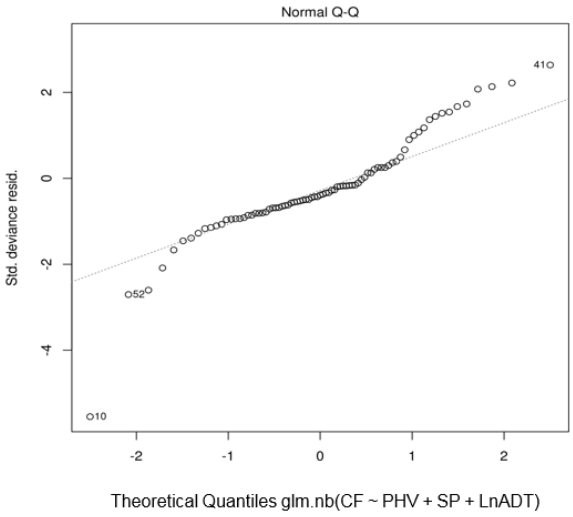

Fig. 1. Q-Q normal plot of the PG regression for the CF model.

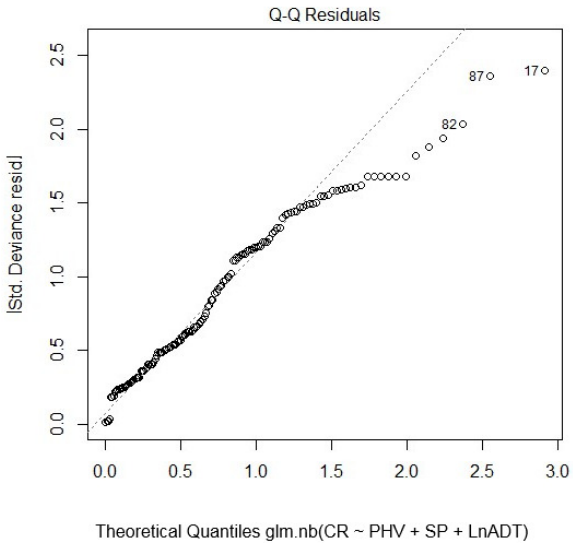

Fig. 2. Q-Q normal plot of the PG regression for the CR model.

The second dataset is the residuals-fitted values plot, which provides another means to assess the relationship between the dependent variables, CF and CR, and the independent variables, namely SP, ADT, and PHV. As demonstrated in Figures 3 and 4, the regression line, which depicts the relationship between the variables, aligns with the PG distribution [35].

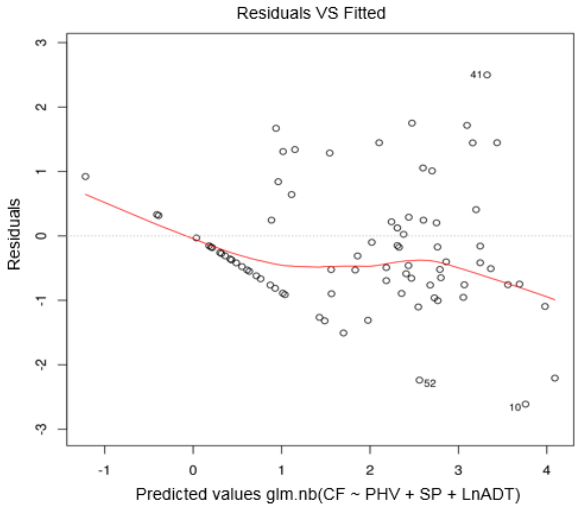

Fig. 3. Residuals against fitted values of the PG regression for the CF model.

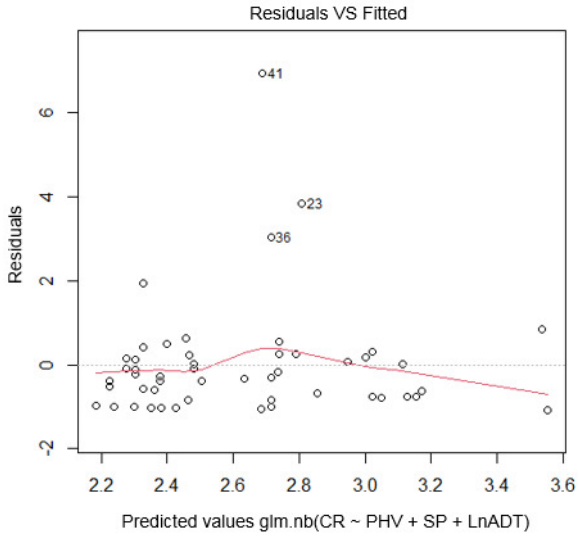

Fig. 4. Residuals against fitted values of the PG regression for the CR model.

It is observed that the VSL could improve the traffic performance and safety. Gradually reducing speed limits in successive road sections upstream of a potential bottleneck could reduce rear-end crashes and overtaking maneuvers, which would cause a decline in head-on crashes.

The VSL system was implemented across various sections of the Mandali-Baqubah highway. A PG model was developed to simulate the changes in the CF and CR by considering the

VSL as the SP. Ten sections with the highest traffic volume were evaluated to assess the changes in the CF and CR after the implementation of VSL. The findings indicated that when the average 5-minute traffic flow reached a certain threshold, the estimated average CF for different peak hour volumes was reduced by up to 31% and the average CR by up to 28%, as shown in Figures 5 and 6. Additionally, ten sections with the highest PHV were examined to study the impact of the VSL activated by a high PHV. The results demonstrated that a gradual reduction in posted speed limits led to a decline in the average CF of up to 28% and an average CR of up to 27%. Furthermore, the impact of the changes in PHV on the system was observed to be lower with the utilization of VSL, as illustrated in Figures 5 and 6.

The results of this study showed that the VSL systems could improve safety levels on two lane highways. This came in line with other studies that revealed the contribution of VSL to a reduced crash potential on multilane highways [36-38].

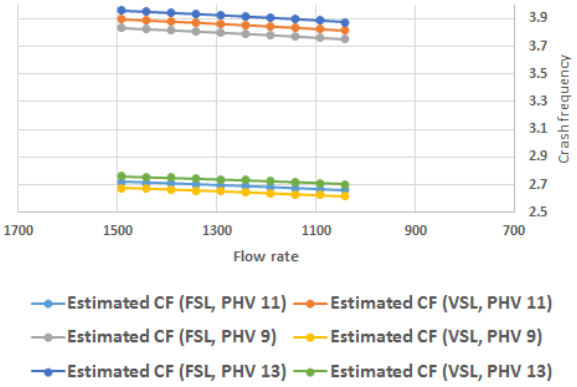

Fig. 5. Reduction in estimated CF when VSL was activated for various PHV and flow rates.

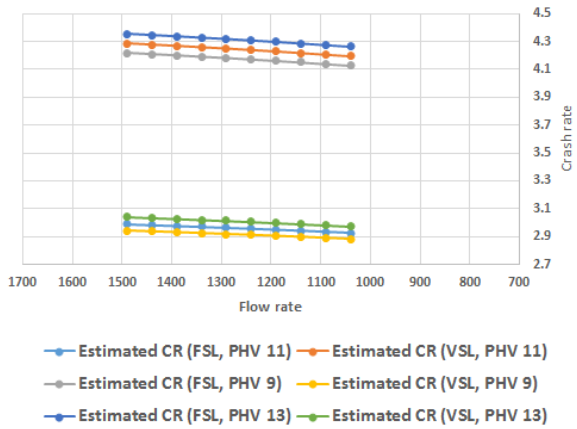

Fig. 6. Reduction in estimated CR when VSL was activated for various PHV and flow rates.

IV. CONCLUSIONS AND RECOMMENDATIONS

The road network in Iraq encompasses numerous two-lane highways that experience a high incidence of crashes, particularly head-on collisions. Consequently, it is imperative to examine the road safety parameters contributing to this issue. For this study, the Mandali – Baqubah highway was selected as a case study to explore the potential implementation of Variable Speed Limits (VSL) in Iraq. Relevant road safety parameters pertaining to traffic conditions, including Operating Speed (SP), Average Daily Traffic (ADT), and Percentage of Heavy Vehicles (PHV), were considered to develop models capable of estimating the impact of VSL on road safety. The PG regression technique, a widely accepted statistical regression method for modeling crash data, was utilized to overcome the challenge of overdispersion. This regression technique was employed to generate two Safety Performance Functions (SPF) for the Mandali - Baqubah highway. Additionally, a collinearity check was conducted utilizing the Variance Inflation Factor (VIF) technique on the independent variables, revealing acceptable levels of collinearity. The crash and traffic datasets were then incorporated as input data into the R Project software. The results of the developed models demonstrated a positive and significant correlation between the analyzed variables.

The study findings, based on the developed models, demonstrate that implementing VSL at ten sections yielded a reduction of up to 31% in the estimated average Crash Frequency (CF) and up to 28% in the average Crash Rate (CR) when the traffic flow reached the threshold of 1490 vehicles per hour in a 5-minute average volume. Similarly, implementing VSL at the other ten sections resulted in a reduction of up to 28% in the estimated average CF and up to 27% in the average CR when the PHV reached the threshold of 11% in a 5-minute average volume. The study was conducted on a highway in level terrain, and it is recommended that the impact of VSL on other terrain types be investigated. Additionally, the effect of VSL on the crash potential is influenced by the driver behavior and compliance with VSL, suggesting the need to further investigate this impact and evaluate the potential requirement for speed enforcement countermeasures. The feasibility of implementing VSL systems should be assessed through cost-effective research, as the cost of implementation was not considered in this study.

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