Usage of Non-Linear Regression for Modeling the Behavior of Motor Vehicle Crash Fatality (MVF) Rate

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Abstract

Data analysis for vehicular crash counts is essential for transportation and traffic management systems (TTMS) to develop practical and innovative road safety interventions. The crash trend analysis, in particular, is the most popular technique for extracting an underlying trend or pattern of behavior in crash data. The recent years have seen a growing concern in the State of Qatar of the consequences of motor vehicle crashes (MVCs) and their associated fatalities (MVFs) on the economy, society, and the performance of the whole road network. This paper reports on the results of using nonlinear regression for crash trend analysis highlighting the substantial enhancement of road safety level in the State of Qatar during the period between 2003 and 2015. One of the critical findings of the study is the notable decline in the increasing tendency of both the MVF/100,000 population and the MVF/100,000 car over the last thirteen years in the State of Qatar. The matter that makes this finding worthy of comment is that it occurs over the period in which the State of Qatar is witnessing a significant growth in the population density and traffic volume. Several valuable contributions and recommendations were drawn and reported.

Keywords: Road Traffic Crashes; Trend Analysis; Regression Analysis, Road Safety

1. Introduction

Road safety is among the most important problems that modern societies are facing. Analyzing traffic safety performance through understanding the trends of crash fatality rates and influencing factors is a key factor in drawing well-informed policies and in designing effective countermeasures.

Developing sustainable solutions to mitigate road safety problems requires a deep understanding of the performance of road network, crash data characteristics, and influencing factors. The regression and the time series analysis are the most popular techniques applied for analyzing the overtime behavior of road safety measures, for instance, the motor vehicle crashes (MVCs) and fatalities (MVFs). These two approaches, however, have a potential to provide a database framework for addressing road safety problems and contributing to the development of sustainable transportation systems. However, the selection of an appropriate analytic technique depends on data integrity and availability as well. The extent to which the selected modeling approach is suitable depends on upon some important factors such as the validity of statistical assumptions of the corresponding model and the amount of detailed supporting information required as inputs or delivered at the end of the study as outputs. In the following section, we provide a few short excerpts of research works demonstrating the applicability of regression and time series analysis for analyzing dynamic changes in road safety measure and monitoring their abnormal deviations.

Time series methods that combine observations as a response and time as an independent variable have been widely used in many different fields including traffic safety field. Razzaghi *et al.* (2013) extended the application of time series analysis to the road safety field and used data from crashes occurring in Taybad between 2007 and 2011 for investigating the possible patterns of road crashes during the study period. The time series analysis was used to a time lag of one month. Hermans *et al.* (2006) studied the monthly developments in the rate of traffic crashes in Belgium during the period from 1974 to 1999 for the purpose of identifying the trend pattern and investigating the effect of the weather conditions and economy on the road traffic crashes rate. Monfared *et al.* (2013) used Autoregressive Moving Average (ARIMA) models to describe the pattern of fatality rate of road traffic crashes in Iran, 2004-2011. Their analytical studies revealed the power of ARIMA technique in modeling and capturing the variability in a dataset observed at consecutive points of time. Ofori *et al.* (2012) conducted a comparative study between ARIMA and Exponential Smoothing techniques and measured their effectiveness in developing an accurate prediction model for the road crash injuries in Ghana. The study reported the effectiveness of the ARIMA model over its counterpart the Exponential Smoothing models.

The ordinary least squares method (OLS) is widely applied to estimate regression coefficients of prediction models describing the relationship between road traffic crashes and a set of factors describing the underlying transportation system, such as a number of vehicles, speed, traffic volume, road geometry and population size. Emenalo *et al.* (1977) considered the road transportation system in Zambia and conducted analytical studies to identify the trend curves of several of measures such as the frequency of road crashes and the rate of fatalities. Kardara *et al.* (1997) considered the road crashes in Greece over the period 1981 - 1991 and applied the linear regression for extracting useful information describing the abnormal changes in the MVC over the period of study. El-Sadig *et al.* (2002) introduced a research paper using the simple linear model to analyze and investigate the dynamic behavior of road traffic crashes trend in the United Arab Emirates. Quddus (2008) considered the special features of a number of road crashes such as non-negativity, randomness, and integrity and proposed the use of integer-valued autoregressive (INAR) models to study traffic crashes in Great Britain. Tortum *et al.* (2012) applied the linear regression analysis to investigate the effect of road structure failures on the road safety measures. The study revealed the significant effect of factors such as road pits, soft shoulders, and permanent wave on the road traffic crashes rate. Aderamo (2012) used the multiple linear regressions to model the road traffic fatality in Nigeria over the period 1975-2009.

The generalized linear models (GzLMs) are usually used when the coresponding response variable fails to satisfy the normality assumption. Several authors have given attention to the applications of the GzLM to modeling the behavior of road crash counts, for instance, Sellers & Shmueli (2009) and Zha *et al.* (2015). The Conway-Maxwell-Poisson (COM-Poisson) distribution is a general form of the Poisson distribution. In 1962, Conway and Maxwell proposed the COM-Poisson for queuing systems analysis. The statistical properties of the COM-Poisson distribution were investigated and reported by Shmueli *et al.* (2005). Guikema and Coffelt (2008) proposed a GzLM formulations based on the COM-Poisson distribution and used two different links (dual-link) functions. Lord *et al.* (2008) replaced the second link function in the dual-link model by the estimated value of the variance parameter. Moreover, Sellers and Shmueli, (2010) developed a COM-Poisson GzLM formulation using the log linear form of the Poisson regression by McCullagh and Nelder, (1997). In their work, the authors used a $\eta(E(Y)) = \log(\gamma)$ as a link function. Recently, Sellers and Rim (2016) proposed a zero-inflated COM–Poisson (ZICMP) regression that is capable to model both dispersed data and data with an excess number of zeroes.

This paper is dedicated to promoting the applications of the regression analysis techniques in the context of road safety management and assessment. More specifically, this article uses linear and nonlinear regression and the MK test for analyzing trends in the MVCs and MVFs in the State of Qatar during the period between 2003 and 2015.

The rest of the paper is organized as follows: Section 2 is devoted to illustrate the applications of several of nonlinear regressions techniques for modeling the MVF per 100,000 population and cars as well. In addition, this section describes the procedure followed to identify outliers in the crash dataset. Several valuable conclusions and recommendations were drawn and reported in Section 3.

2. Motor Vehicle Fatality (MVF) Analysis

The State of Qatar has shown considerable concern about the road safety issue in the recent years resulting in substantial enhancement in road crash rate and fatalities. On 13 Jan 2013, the National Road Safety Strategy, NRSS (2013-2022), has been launched as an ambitious step towards safe and efficient transport and traffic networks in the State of Qatar. The NRSS consist of series of road safety action plans to translate the vision and targets of the NTSC into a series of practical initiatives. However, the need for trend analysis has become more imperious since the actual implementation of the NRSS (2013-2022). We dedicated this section for investigating the trends and patterns of the MVFs during the period 2003-2015. The data used in this study is the form of yearly basis. However, knowing the behavior of the MVF is necessary for developing robust contingency plans to reduce the adverse impact of the road crashes on the economic and social aspects. The log-MVF/100,000 population and the log-MVF/100,000 car in the State of Qatar during the period from 2003 to 2015 are graphically shown in Figures 1 and 2, respectively. In the following sections, we will use the log-MVF/P and log-MVF/C to refer to the measures above.

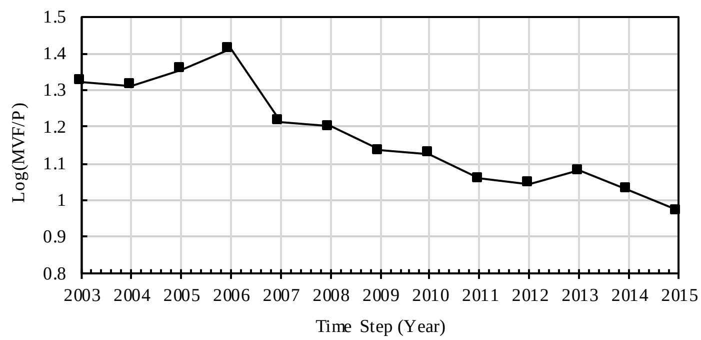

Figure 1. Distribution of the Log of MVF/P in Qatar State during the period (2003-2015)

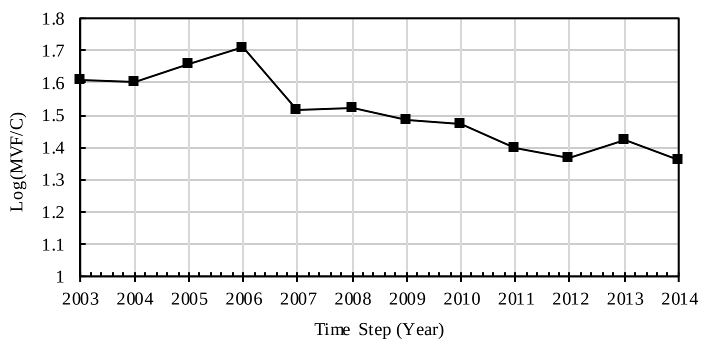

Figure 2. Distribution of the Log of MVF/C in Qatar State during the period (2003-2014)

However, Figure 1 and 2 reveal decreased patterns in both the log-MVF/P and log-MVF/C in the State of Qatar over the study period. One exception here is the increase in the log-MVF/P and log-MVF/C during the year 2006. Our investigation has found that this jump is attributed to the massive traffic congestion and the massive increase in road users due to hosting the Asian Games event in Qatar for the first two weeks of September, which attracted many visitors to the country.

2.1 Outliers Detection

In statistics, outliers are data points that are significantly distant from other observations. Two particular reasons may increase the likelihood of the occurrence of this phenomenon. These are the variability in the measurements and the experimental errors. The outliers can change the statistical properties of the mean distribution. Several detection methods have been made available these days. In this paper, the Grubbs' test – or the maximum normed residual test is applied to detect outliers in both the log-MVF/P and log-MVF/C. This Grubb's test is essentially based on the assumption of the normality. To confirm this assumption, we use the normality test for both of the log-MVF/P and log-MVF/C. Four different normality tests were applied by using the XLSTAT software, and the results were reported in Table 1.

Table 1. Normality test for the log-MVF/P and log-MVF/C car (α=0.05)

Test	Test Statistic		P-Value	
	Log-MVF/P	**Log-MVF/C**	**Log-MVF/P**	**Log-MVF/C**
Shapiro-Wilk test	W=0.943	0.949	0.505	0.632

Anderson-Darling	A^2=0.325	0.236	0.475	0.727
Lilliefors	D= 0.150	0.129	0.578	0.840
Jarque-Bera	JB (Observed)= 0.96 JB (Critical)=5.99	0.75 5.99	0.616	0.686

As all the applied tests resulted p-values that are greater than the significance level α=0.05, the normality assumption is statically confirmed, at least for the observed period. The Grubb's test testing the null hypothesis H_0: there are no outliers in the data set versus H_1: there is at least one outlier. The results of applying the Grubbs' test are reported in Table 2.

Table 2: The results of the Grubb's test for outlier's detection in the log-MVF/P and MVF/C car

Description	Log-MVF/P	Log-MVF/C
G (Observed-value)	1.694	1.739
G (Critical-value)	2.462	2.412
P-value	0.984	0.784
99% Confidence Interval on the P-value	[0.984-0.985]	[0.783-0.785]

As the computed p-values of the log-MVF/P and the log-MVF/C are greater than the significance level α=0.05, one cannot reject the null hypothesis H_0. This indicates that there are no outliers in the observed data set. Accordingly, the year 2006 will not be excluded.

2.2 The Mann-Kendall (MK) Test

This test is one of the popular distribution free tests used for examining the trend in a time series dataset. One advantage of the MK test over the traditional trend analysis techniques is that there are no distributional assumptions required. In this paper, the MK test is used to examine the trend in both the log-MVF/P and log-MVF/C. The MK's test testing the null hypothesis H_0: there is no trend in the data set versus H_1: there is a trend in the data set. The results are reported in Table 3.

Table 3. The MK test results to the log-MVF/P and MVF/C car

Measure	Kendall's τ	S	Var(S)	P-value
log-MVF/P	-0.821	-64.00	0.000	<0.0001
log-MVF/C	-0.758	-50.000	0.000	0.0000

As it can be noted from Table 3, the computed p-values of the log-MVF/P and the log-MVF/C are less than the significance level α=0.05. The S-value is the result of subtracting the number of positive differences from the number of negative differences. The negative sign of the S-value means that the following observation tends to be smaller than previous observation. It is the opposite when S-value reveals a negative sign. According to these results, it can be reported that the State of Qatar has seen decreased trend in both the log-MVF/P and the log-MVF/C over the period (2003-2015).

2.3 Modeling of the MVF/P and MVF/C

The regression analysis is a parametric approach used for analyzing changes in data collected over sequential periods. However, in this section, we apply linear and non-linear regression techniques to identify the pattern of variations in the log-MVF/P and the log-MVF/C. However, when there is a need to match the sizes of two or more tested samples, the gap (missing point) will be occupied by the moving average of the rest of observations. Most of the recent statistical computer packages such as MINITAB, SPSS, and XLSTAT offer several options for an analyzer to choose how the excluded points are to be substituted.

There are many functions, in practice, that can be used for a non-linear regression. The selection of the most appropriate function is not an easy task. However, in this paper, three of non-linear regression models were selected. These are the 2^{nd}-degree polynomial, exponential regression and generalized linear regression with log link.

The mean squared error (MSE) is well known in literature in measuring the accuracy – or quality of the statistical models. The value of the MSE is always positive, and it can be calculated as follow:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2 = \frac{1}{n}\sum_{i=1}^{n}\text{Diff}_i$$

where $\hat{y}_i$ and y_i are the estimated and the actual crash counts values, respectively. In this work, the MSE is used to compare the quality of the proposed regression models in order to specify the most appropriate model describing the MVF/P and the MVF/C in the State of Qatar. The MINITAB software is used to conduct the three aforementioned regression methods and the results are shown in Table 4.

Table 4. Model-fitting results of Log-MVF/P during the period (2003-2015)

Regression Type	Model Coefficients					MSE	Fitted-Model; $\hat{y}_i$
	C_1	C_2	C_3	β_1	β_2		
Simple Linear	1.41	0.033	---	---	---	0.0033	$1.41\text{-}0.033t$
Non-linear							
- 2nd degree Polynomial	1.67	-0.020	-0.001	---	---	0.0034	$1.67\text{-}0.020t - 0.001t^2$
- Exponential	---	---	---	1.702	-0.019	**0.0030**	$1.702e^{(-0.019t)}$
- Generalized Linear	---	---	---	0.354	-0.0285	0.0031	$e^{(0.354\text{-}0.0285t)}$

However, in terms of the MSE, the results in Table 4 show that that non-linear exponential model is the best fit to the Log-MVF/P in the State of Qatar during the period 2003-2015. Note that, the simple linear and the 2nd-degree polynomial models provide a relatively similar MSE values. Figure 3 shows the plotting of the resulted residuals versus the observation order. As it was expected, the maximum residual occurs at the fourth observation (2006). Similar to many other non-linear functions, the choice of the initial values (θ_1, θ_2) are essential for the non-linear exponential and the generalized linear regressions. In this study, the values 0.01 and 0.02 were assigned to these parameters. One should note that, changing these initial values might lead to different regression outcomes. As the MSE of the non-linear exponential model is very close to the zero- value, we believe these values are quite appropriate.

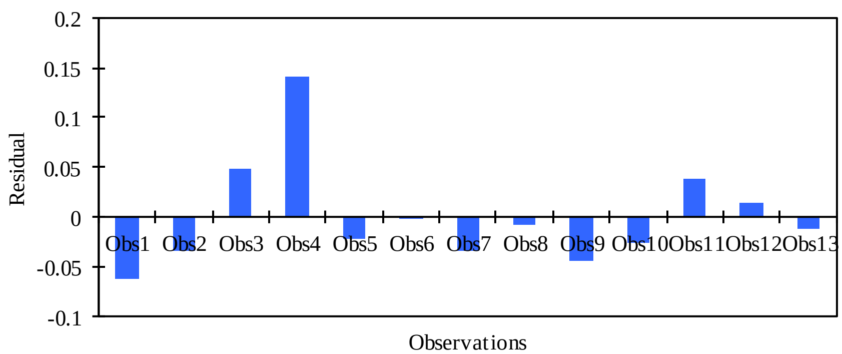

Figure 3. Plotting the residuals versus the observation using non-linear exponential model to Log-MVF/P

The same above regression models are used to fit the MVF/C in the State of Qatar for the same period of study. The results are reported in Table 5.

Table 5. Model fitting results of Log-MVF/C during the period (2003-2015)

Regression Type	Model Coefficients					MSE	Fitted-Model; $\hat{y}_i$
	C_1	C_2	C_3	β_1	β_2		
Simple Linear	1.69	-0.028	---	---	---	0.0031	$1.69\text{-}0.028t$
Non-linear							
- 2nd degree Polynomial	1.67	-0.020	-0.001	---	---	0.0031	$1.67\text{-}0.020t - 0.001t^2$
- Exponential	---	---	---	1.70	-0.019	0.0030	$1.70e^{(-0.019t)}$
- Generalized Linear	---	---	---	0.53	-0.018	0.0031	$e^{(0.53\text{-}0.0186t)}$

Table 5 shows that the non-linear exponential model is the best fit to the MVF/C. However, the very low values of the MSE of the developed models reported in Tables 4 and 5 confirm the appropriateness of the non-linear exponential model for describing the dynamic changes in both the MVF/P and the MVF/C.

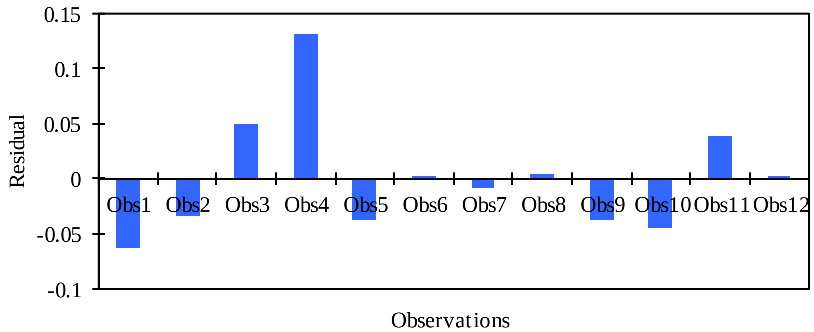

Figure 4. Plotting the residuals versus the observation using non-linear exponential Model to Log-MVF/C

2.4 Predicting the MVF/P and MVF/C in Qatar State

The statistical crash models are often used for predicting the future of road safety measures. In this paper, the developed models are applied to provide a clear insight about the MVF/P and MVF/C in the State of Qatar for the year 2016. To expand the range of our analysis, two more time series techniques, namely the exponential smoothing and the Holt-Winters, are applied as well. The following two Tables (6 and 7) illustrate the prediction and residuals for the period from 2003 until 2016.

The results in Table 6 and Table 7 reveal a significant enhancement in the MVF/P and MVF/C in the State of Qatar in the year 2016.

Table 6. Model fitting results of Log-MVF/P during the period (2003-2016)

Method		**Estimated Log-MVF/P**													
		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Exponential Smoothing	Estimation	---	1.32	1.32	1.33	1.34	1.32	1.29	1.26	1.24	1.20	1.17	1.15	1.13	**1.10**
	Residual	---	-0.01	0.04	0.09	-0.13	-0.12	-0.16	-0.14	-0.18	-0.15	-0.09	-0.12	-0.15	---
Holt-Winters	Estimation	---	1.32	1.32	1.33	1.35	1.32	1.29	1.25	1.21	1.15	1.11	1.07	1.03	**0.99**
	Residual	---	-0.01	0.04	0.08	-0.14	-0.12	-0.16	-0.12	-0.15	-0.11	-0.03	-0.04	-0.06	---
Exponential Regression	Estimation	1.32	1.31	1.36	1.41	1.21	1.20	1.13	1.13	1.06	1.05	1.08	1.03	0.97	---
	Residual	1.39	1.35	1.31	1.27	1.24	1.20	1.17	1.13	1.10	1.07	1.04	1.01	0.98	**0.96**

Table 7. Model fitting results of Log-MVF/C during the period (2003-2016)

Method		**Estimated Log-MVF/C**													
		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	**2016**
Exponential Smoothing	Estimation	---	1.61	1.61	1.62	1.64	1.61	1.59	1.57	1.55	1.52	1.49	1.48	**1.45**	**1.61**
	Residual	---	0.00	0.05	0.09	-0.12	-0.09	-0.11	-0.10	-0.15	-0.15	-0.07	-0.12	---	---
Holt-Winters	Estimation	---	1.61	1.61	1.62	1.64	1.62	1.60	1.57	1.54	1.49	1.44	1.42	**1.38**	**1.61**
	Residual	---	0.00	0.05	0.09	-0.13	-0.09	-0.11	-0.09	-0.13	-0.12	-0.02	-0.06	---	---
Exponential Regression	Estimation	1.67	1.64	1.61	1.58	1.55	1.52	1.49	1.47	1.44	1.41	1.39	1.36	**1.34**	**1.31**
	Residual	-0.06	-0.03	0.05	0.13	-0.04	0.00	-0.01	0.00	-0.04	-0.04	0.04	0.00		

3. Conclusions and Recommendations

This paper mainly concentrates on the applications of linear and non-linear regressions techniques in modeling and analyzing the trend in MVF/P and the MVF/C in Qatar State during the period (2003-2015). This study is important for developing functional and innovative road safety plans and interventions. The analysis showed significant decrease in the MVF/P and MVF/C in the State of Qatar during the period between 2003 and 2015. In addition, the study has shown that there is a high likelihood for further enhancement in the road safety in the State of Qatar for the years to come. Furthermore, this study also introduced several statistical models for predicting the MVF/P and MVF/C in the State of Qatar. Exploring the contributory factors effecting the MVF/P and MVF/C in the State of Qatar are potential area for future work. Moreover analyzing the spatial and temporal distributions of fatal and severe injury crashes considering population density, land use, and road infrastructure is of prime importance to draw proper countermeasures that consider local conditions.

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Biography

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Dr. Hamouda is currently the Associate Dean for Research and Graduate Studies, Qatar University. He is an active member of a number of International Scientific Committees, professional societies, and Standards Boards. Dr. Hamouda is a member of the American Society of Mechanical Engineering (ASME). He is also a senior member of Institute of Industrial Engineering (IIE), USA, and Member of the Institute of Highway Transportation, UK. Member of American Society for Engineering Education, ASEE, USA. Dr. Hamouda has published over 400 papers of which about 200 Journal Publications. He has several patents and he has edited several conference proceedings. He is currently managing research fund worth over US$ 4,000,000. He set in the editorial board of a number of international journals. He and his co-workers have received a number of prestigious awards; Gold Medal at the British Invention Show Alexandra Palace, UK, in 2004 and 2006. Silver Medal and Bronze at the 32nd International Exhibitions on Inventions, New Techniques and Products, Geneva, Switzerland, and another Silver Medal at the 63rd IENA, Nuremberg, Germany. In 2006, Dr. Hamouda was selected by the Organization of Islamic Countries (OIC) as one of the 200 Top scientists within the OIC. In 2010, he was honored with the Takreem Scientific and Technological Achievement Award, one of the highest awards in the Arab world. Also, he won Qatar University Merit Award for the years 2010 and 2014. Very recently, he won Qatar University Research Excellence Award 2016.