Assessing the Safety Effects of Excessive Speeding Legislation in Canada

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in
Transportation Engineering

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ABSTRACT

Three Canadian provinces, namely, British Columbia (BC), Ontario (ON) and Quebec (QC), introduced legislation to counteract drivers who exceed speed limits by unacceptable margins. The legislation involved the immediate suspension of the driver's licence, vehicle impoundment, hefty fines and demerit points. The legislation has been in effect for a few years now, and the fatality counts seem to have dropped since the inception of the law. However, no statistical evidence has been provided to support such claims. Thus, the primary goal of this thesis is to perform an ARIMA time-series intervention analysis of collision data from the three provinces to help understand the safety benefits of this excessive speed legislation in Canada. Moreover, the thesis provides a framework for statistical assessment of legislative changes in general and develops statistical models, which can be used for accident prediction in the three provinces.

Time series are frequently affected by policy changes, such as the aforementioned legislation; these policy changes are usually referred to as interventions. Interventions can affect the response in several different ways. These effects include changing the level of the series either abruptly or long-term, changing the trend of the series, or having other, more complicated, effects on the series. In this thesis, an intervention analysis of the collision data, at different severity levels, from the three provinces was conducted. The analysis aims to identify any changes in the time series behaviour of the collision data after the implementation of the intervention (legislation). Potential changes were assessed for statistical significance, and the magnitude of the change was quantified in each case. The analysis was also performed on collision data while accounting for exposure, and similar findings were reached. In the process, twelve different models were developed for all provinces, and another set of models was also developed while accounting for exposure effects.

Overall, it was found that a statistically significant drop in fatal collisions occurred in two of the three provinces (BC and ON) after implementing the new policy. In QC, a statistically significant drop was observed in injury, property-damage-only (PDO) and total collision counts; however, these drops could not be fully credited to the new policy alone, as a new distracted driving law was also implemented at the same time. With respect to injury, PDO and total collisions in BC and ON, changes in the series associated with the policy varied and so did their statistical significance.

In general, the findings imply that the excessive speeding legislation was effective in reducing province-wide fatal collisions, indicating a general deterrence effect. The effects of the policy on other types of collisions (injury, PDO and total) are inconclusive. Further analysis, when more post-intervention data is available, could reveal more information regarding the effects of the policy on those types of crashes. Moreover, when combined with other laws and policies, the excessive speeding law could potentially be effective in reducing injury, PDO and total collision counts; this finding, however, would require further testing and investigation.

PREFACE

Work presented in this thesis has been submitted for publication in the Accident Analysis and Prevention journal.

Gargoum and El-Basyouny (2015) "*Assessing the Safety Effects of Excessive Speeding Legislation in Canada*". Accident Analysis and Prevention. Under Review.

Dedicated to my parents

ACKNOWLEDGMENTS

Above all, praise is due to almighty Allah for guiding me and giving me the power and strength to complete this work.

I would like to thank my supervisor Dr. Karim El Basyouny for providing me the opportunity to pursue this degree; his support, belief and confidence in my ability helped me develop in many areas. I am also grateful for the financial support he has provided me throughout my studies.

My sincere thanks are also extended to my defense committee members Dr. Amy Kim (Chair) and Dr. Marwan El-Rich for their advice and assistance.

I am really thankful to my professors at the University of Alberta for the valuable knowledge they provided me through my coursework. I would also like to thank Aalyssa Atley for her editorial support over the past year; her efforts have been an integral part of all my work.

I am extremely grateful to my professors at the UAE University for the knowledge, the help and the advice they have offered me during and after completing my undergraduate degree. Special thanks is due to my former supervisor Dr. Aman Mwafy who has been a remarkable mentor over the years.

I would also like to express my appreciation to my friends and colleagues for their help, encouragement and moral support.

Lastly and most importantly, I would like to extend my deepest gratitude to my parents, my two sisters and my brother for their love, care and unconditional support throughout the years. I will be forever indebted to my mother for her love, continuous encouragement and inspiration; she was the one who taught me to always strive for the best and never be satisfied with anything else. I am also immensely grateful to my father for the endless motivation, sheer guidance and the technical support. I owe it all to my family.

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1. Introduction

1.1 Background

With the improving quality of roads and higher vehicle performance, speeding is an ever-growing problem on roads all around the world. In a review of speed management published in a collaborative effort by the European Transport Research Centre, it was found that, on average, 40% to 50% of drivers drove above the posted speed limit (OECD/ECMT, 2006). The main issue with speeding is that its impacts on safety are lethal, statistics by Transport Canada show that in 2011, 27% of fatalities and 19% of serious injuries on Canadian roads involved speeding (Road Safety Canada Consulting, 2011). Considering the consequences of the problem, serious action is mandatory to improve the situation.

Speeding is known to affect safety in two ways: 1) increases in speed are associated with an increase in the severity of collisions, and 2) increased speed also increases the likelihood of being involved in a collision (Elvik et al., 2004). These effects exist irrespective of whether a driver is exceeding the posted speed limit by low margins, high margins, or even driving at speeds within the posted speed limits but at speeds considered dangerous for existing conditions (e.g. icy roads or foggy conditions). Nevertheless, the margin by which the speed limit is exceeded does impact the consequences of a crash. As evident in the quote below, the relationship between speed and safety is not linear; hence, as speed increases, the likelihood and severity of a collision increase at a higher rate (Aarts and Van Schagen, 2006).

> *"In a 60 km/h speed limit area, the risk of involvement in a casualty crash doubles with each 5 km/h increase in travelling speed above 60 km/h"*(Kloeden et al., 1997).

This information is an indicator that the impacts of excessive speeding on safety are even more serious. Although the safety literature lacks a specific definition of the act, the terms "Excessive Speeding" or "High-Range Speeding" are often used to describe road users exceeding speed limits by extremely high margins, typically more than 40km/h.

Excessive speeding is an issue on roads all across Canada and many countermeasures have been considered in different provinces to overcome this challenge. A common reason for exceeding speed limits by extremely high margins is illegal street racing and stunt driving. However, it is important to point out that street racing is not the only motive for excessive speeding; high tolerance margins and low enforcement activity on some highways could see a high population of drivers exceeding speed limits by margins of over 40 or 50 km/h. The Canadian Traffic Injury Research Foundation reports that "on a four-lane divided highway with a posted speed limit of 100km/h, studies found that 20% of the drivers were travelling in excess of 120km/h" (TIRF, 2003).

Regardless of the motives, excessive speeding puts the offenders at extreme risk, while also affecting the safety of other drivers and road-users. Considering three years of data, (Leal and Watson, 2011) found that drivers who were involved in street racing and stunt driving offences had a history of considerably more traffic infringements and crashes compared to non-offenders. Moreover, it has been shown that monetary fines and demerit points alone do not seem to have enough effect in deterring some speeders (Fleiter *et al.*, 2007, Fleiter *et al.*, 2010). Consequently, more attention has been drawn towards using severe sanctions when dealing with such activities.

Severe sanctions have been used for different reasons over the last two decades, with the sole intention of improving safety. By sending serious warnings to drivers, these sanctions are likely to have a deterrent effect on both the general driving population (general deterrence) and the offenders in particular (specific deterrence). Examples of severe sanctions include licence suspensions and vehicle-related punishment such as vehicle impoundment, vehicle forfeiture or even vehicle-plate impoundment.

The most common vehicle-related sanction implemented in many states and provinces is vehicle impoundment, where the offender's vehicle is confiscated for a temporary period. Vehicle impoundment is adopted as a sanction for different types of violations in traffic safety; however, the literature shows that this policy is often used to supplement licence suspension laws. The main reason is that suspended or unlicensed drivers were found to continue to drive while suspended (DWS) or drive while unlicensed (DWU) (Voas *et al.*, 1997a, Voas and DeYoung, 2002). The reasons for suspension can vary, but one common reason is driving under the influence (DUI) of alcohol. Vehicle-related laws were found to reduce those types of offences and consequently improve safety (Voas and DeYoung, 2002). Accordingly, they have been considered as sanctions for other activities as well.

In recent years, severe sanctions, including administrative licence suspensions and vehicle impoundment, have been adopted to address excessive speeding, street racing and stunt driving activities on roads. Legislative changes introducing those laws were adopted in three Canadian provinces (British Columbia, Ontario and Quebec) to address the issue of excessive speeding. Under the new laws, drivers who violate speed limits by a certain margin, deemed too high, are subject to severe sanctions including immediate licence suspension, hefty fines and vehicle impoundment. In Ontario, the margin at which the fines came into effect was 50km/h over the speed limit; in BC, it was 40km/h; and in Quebec's case, the margin was defined according to the speed limit of the road (40km/h on 60km/h roads, 50km/h on 70-90km/h roads and 60km/h on 100km/h roads).

The sanctions associated with the law in every province vary, but overall, the new laws impose harsh penalties on violators. The legislative changes are believed to have had a positive effect on traffic safety in those three provinces. Fatality statistics show that there was a drop in the number of fatal collisions since the implementation of the new laws. However, unless statistical analysis of the data proves that a) the drop in fatal collisions and/or collisions of other severity levels was statistically significant, and that b) the decrease was statistically associated with the introduction of the new legislation, the observed drop cannot attributed to the new policy.

1.2 Objective and Motivation

Despite the excessive speeding legislation implemented in British Columbia (since 2010), Ontario (since 2007) and Quebec (since 2008) having been in effect for a fairly long time now, apart from a recent paper in Ontario (Meirambayeva et al., 2014a) and another effort in BC (Brubacher et al., 2014), no studies have assessed the impacts of such legislation on safety. Moreover, a review of the literature revealed that even on an international scale, excessive speeding legislation has not received enough attention from researchers, and hence, its effects on safety and collision frequency in particular remain unclear.

From a practical perspective, the lack of a rigorous legislation evaluation has prevented policy-makers in other regions from adopting the law, resulting in a loss of potential road safety benefits. The severity of the sanctions associated with the law also draws controversy among the public, which can be addressed only by providing scientific evidence of the benefits of the legislation.

This thesis aims to address the above-mentioned limitations through assessing the impacts of the excessive speeding legislation, which imposed severe sanctions against drivers, on direct safety indicators. The research is expected to accomplish the following objectives:

1. Perform an evidence-based assessment of excessive speeding legislation in Canada.
2. Determine the effects of the legislation on collisions of all severity levels.
3. Develop time series models that can be used in predicting future collisions in the provinces of interest.
4. Present a comprehensive statistical framework for legislation assessment.

The primary hypothesis in this thesis is that the Excessive Speeding Legislation (ESL) implemented in the three provinces was effective in reducing severe collisions. Moreover, the secondary hypothesis of the analysis is that the legislation was also effective in reducing Property Damage Only (PDO) and total collisions.

1.3 Thesis Structure

The remainder of this thesis is organized as follows:

Chapter 2 provides a thorough literature review of the topics covered in this thesis. The first section introduces the reader to the effect speed has on safety; this is discussed from several different perspectives, including how speed affects the likelihood and severity of collisions. Next is a briefing about different speed management strategies that have been implemented over the years. Section 2.3 provides a review of the main studies that have considered the effects of severe sanctions on safety in general, and against excessive speeders in particular. The section also covers the main issues associated with implementing these sanctions. Finally, section 2.4 includes a brief overview of the main statistical techniques that have been used to assess the effects of legislative changes in traffic safety.

Chapter 3 includes an overview of the legislative changes and states the main hypothesis to be tested in this thesis.

Chapter 4 describes the dataset compiled for use in this study. This includes the details about the outcome variable and the different confounding factors which were accounted for in the models.

Chapter 5 provides a technical discussion of the methodology used in the data analysis.

Chapter 6 presents the framework of the modelling procedure, the outcomes of the preliminary investigation and the main models developed.

Chapter 7 describes the results of the analysis. The main findings of the research and their implications are presented and discussed.

Chapter 8 discusses the main research conclusions with respect to the implementation of the new law, the research contribution from both an academic and practical perspective, the limitations of the analysis and suggestions for future research.

2. Literature Review

2.1 The Effects of Speed on Safety

Whether drivers exceed the speed limit by small or large margins or even drive within the posted speed limit but at speeds inappropriate for the conditions, the effects of speeding are deadly. Speeding is a major contributor to severe collisions all around the world. Recent statistics show that 30% of fatalities on roads in the United States are speed-related (NHTSA, 2012). Furthermore, the statistics show that although the number of fatalities on roads has dropped over the years, the portion attributed to speed-related collisions has not. In Canada, a similar issue is present with 27% of fatalities and 19% of serious injuries involving speeding (Road Safety Canada Consulting, 2011).

What is more devastating with speed-related collisions is the fact that the majority of the victims are people of a young and productive age group. Statistics in Canada show that 40% of drivers involved in fatal crashes belonged to the 16-24 age group (Road Safety Canada Consulting, 2011); similarly, in the US, 37% of both the 15-20 and 21-24 males were involved in fatal crashes because they were speeding (NHTSA, 2012). For females, speeding was the cause of 24% of fatal collisions in the 15-20 and 19% in the 21-24 age groups (NHTSA, 2012).

In a meta-analysis of articles that studied the relationship between speed and collisions, Elvik et al. (2004) reached the following conclusions with respect to the strength and the causality of the relationship:

- The statistical relationship between speed and road safety is very strong; no other risk factor has a greater impact on collisions than speed.
- In the majority of the studies considered in the meta-analysis, speed was positively correlated with collisions. Moreover, speed reduction seems to be the most effective measure to improve road safety.
- The analysis also revealed evidence that the relationship between speed and collisions is causal, since in the majority of the studies considered, most of which were before-after assessments, the cause (changes in speeds) comes before the effect (changes in collisions) in time.

- If potential confounding factors are accounted for, the relationship between speed and collisions is a strong one.
- A clear dose-response relationship exists between changes in speed and changes in road safety (i.e. the higher the speed dose, the higher the impact on safety).
- The relationship between speed and road safety appears to be universal (i.e. the relationship holds regardless of the difference in traffic environment or region).
- Elementary laws of physics show that speed contributes to both the severity and likelihood of collision occurrence.

2.1.1 Speed and Collision Severity

The notion that speed affects safety by increasing the severity of a collisions is well accepted. To anyone with some knowledge of physics, it seems reasonable that as the speed of a vehicle increases, the difficulty to stop it (momentum) increases. This implies that if the vehicle was to collide with another object, the kinetic energy of the vehicle, which also increases with speed (velocity), is transferred into other forms of energy and strong forces that are absorbed by the vehicle and its occupants.

The relationship between speed and collisions at different severity levels has been modelled by several researchers; the most commonly cited work in that context is the paper by Nilsson (1982). Evaluating the effects of the changes in speed limits on accidents in Sweden, the study adopted Newton's relationship between kinetic energy and speed ($1/2mv^2$) to model the relationship between speed and crashes. The author used a mathematical power function to model the effects of a decrease in speed on collisions, and a total of six power models were developed demonstrating the relationship at the different severity levels.

The model seen in the following equation was developed for fatal crashes. The application of the model is fairly straightforward. For instance, a reduction in the speed limit from 100 to 90 km/h is equivalent to a 0.344 (34.4%) reduction in fatal crashes, which is simply the complement of the ratio of speeds raised to the power of four. Based on the modelling results, different powers were assigned to different severity levels.

$$\frac{\text{Fatal Crashes After}}{\text{Fatal Crashes Before}} = \left(\frac{\text{Speed After}}{\text{Speed Before}}\right)^4$$

These powers have received many adjustments, including work by Elvik et al. (2004) in a study where the researchers conducted a meta-analysis to assess the validity of the power model, and more recently by (Elvik, 2009), where separate estimates were made for roads of different class, as seen in Table 1. The table clearly shows that the exponential power of the model increases with the increase in collision severity. Revisiting the example given in the previous paragraph, a change in the speed limit from 100 to 90 km/h on a rural road would reduce property-damage-only (PDO) collisions by 0.146 (14.6%), which is clearly less than the 34.4% reduction in fatal collisions.

Table 1: Power Estimates by Road Type and Collision Severity (Elvik, 2009)

	Rural roads/freeways		**Urban/residential roads**		**All roads**	
Accident or injury severity	**Estimate**	**95% CI***	**Estimate**	**95% CI**	**Estimate**	**95% CI**
Fatal accidents	4.1	(2.9, 5.3)	2.6	(0.3, 4.9)	3.5	(2.4, 4.6)
Fatalities	4.6	(4.0, 5.2)	3	(-0.5, 6.5)	4.3	(3.7, 4.9)
Serious injury accidents	2.6	(-2.7, 7.9)	1.5	(0.9, 2.1)	2	(1.4, 2.6)
Seriously injured road users	3.5	(0.5, 5.5)	2	(0.8, 3.2)	3	(2.0, 4.0)
Slight injury accidents	1.1	(0.0, 2.2)	1	(0.6, 1.4)	1	(0.7, 1.3)
Slightly injured road users	1.4	(0.5, 2.3)	1.1	(0.9, 1.3)	1.3	(1.1, 1.5)
Injury accidents-all	1.6	(0.9, 2.3)	1.2	(0.7, 1.7)	1.5	(1.2, 1.8)
Injured road users-all	2.2	(1.8, 2.6)	1.4	(0.4, 2.4) #	2	(1.6, 2.4)
PDO accidents	1.5	(0.1, 2.9)	0.8	(0.1, 1.5)	1	(0.5, 1.5)

* CI: Confidence Interval

2.1.2 Speed and Collision Occurrence

When studying the relationship between speed and safety, modelling the effects speed has on collision occurrence is more complex than modelling the effects of speed on collision severity. Common sense implies that, the higher the speed, the less time (lower perception reaction time) the driver has to react to an issue that may suddenly arise on the road and, thus, the higher the risk of not taking appropriate action. However, modelling the relationship has been challenging (Shinar, 1998, Elvik *et al.*, 2004, Hauer, 2009, Wang *et al.*, 2013). The complexity is often attributed to different masking factors that confound the relationship.

Many researchers have attempted to address this topic (Nilsson, 1982, Finch *et al.*, 1994, Baruya, 1998, Taylor *et al.*, 2000, Taylor *et al.*, 2002, Kockelman and Ma, 2010, Quddus, 2013, Tian, 2013). Each study used different experimental setups; for instance, some studies used before-and-after assessment criteria, where collision statistics were compared (over time) before and after speed limit changes. In contrast, in other studies, a cross-sectional design where speed and collision observations from multiple sites were used to identify the relationships between speed and collision occurrence. Different statistical modelling techniques were also considered in previous studies (e.g. linear regression, multiplicative Poisson models); likewise, different measures of speed (e.g. average speed, speed variance, proportion of speed limit violators or individual vehicle speeds) were also considered when analyzing the relationship. In the next few paragraphs, a summary of a selection of those studies is provided.

Some of the most commonly cited works, which evaluated the effects of individual vehicle speed on the risk of crash involvement, include studies by (Kloeden *et al.*, 1997, Maycock *et al.*, 1998, Quimby *et al.*, 1999)). The latter two were self-reported studies where drivers themselves report their crash involvement over a given period of time; this information is then linked to their driving speed, which is measured before they report their crash history. Both Maycock et al. (1998) and Quimby et al. (1999) found similar relationships and defined rules of thumb, stating that a 1% increase in free-flow speed is associated with 13.1% and 7.8% increases in crashes, according to each study respectively.

In a project assessing the impacts of speed limit changes on average speed and crash rates on road segments, Finch et al. (1994) performed a meta-analysis on data from Finland, Switzerland, the U.S. and Denmark to develop three different models. The first model was based on a simple linear relationship between average speeds and changes in accidents; the second model used a power function inspired by Nilsson's function, discussed earlier in this thesis; and the third model was an asymptotic function, which was developed to account for other factors, besides speed, that have effects on accidents. The linear and asymptotic trends are displayed in Figure 1. Finch et al. 1994 found that average speeds were positively correlated with crash rates, stating that, typically, a speed reduction of one mile per hour corresponds to a 5% decrease in crash rates.

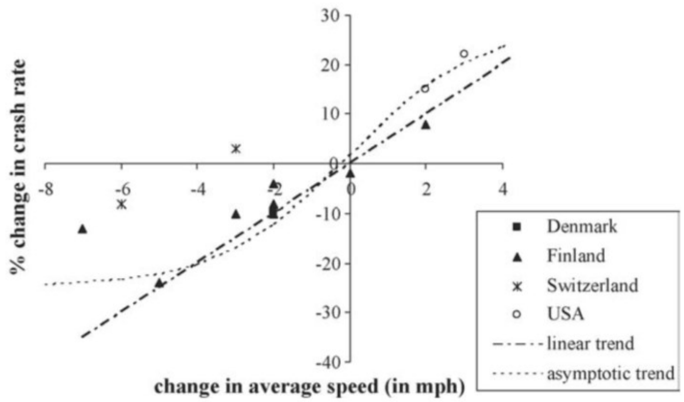

Figure 1: Linear and Asymptotic Trends for Speed and Safety (Finch et al., 1994)

As part of a research program by TRL (Transportation Research Laboratory) in the U.K., Taylor et al. (2002), attempted to assess the effects of several variables, including speed, on injury crashes observed at rural single carriage roads across the country. Data used in the study included traffic flows, geometric attributes and other road features. The data were collected from 174 different road sections where the speed limits were all 60mph.

A preliminary analysis of the data revealed that for the compiled dataset, the average speed was negatively related to accident frequency. The authors attributed this finding to the difference in road quality at the road segments sampled; therefore, the authors created homogenous groups, through which the effects of road quality on the relationship between collisions and speed could be unmasked. Indeed, further analysis of the data, while including a group variable, revealed average speed was positively correlated with collisions.

The reasoning behind such a phenomenon, as expressed by (Elvik *et al.*, 2004) is that the "best roads tend to have the highest speed limits;" in this case, a better road refers to a road with higher quality attributes. In fact, even in the study by (Taylor *et al.*, 2002), the variables on which the grouping was based were all attributes of road quality.

Of the other factors considered by (Taylor *et al.*, 2002), only the flow, the length, the density of sharp curves and the density of minor crossroad junctions had significant effects on collisions. Moreover, another important finding of the work was that, compared to other measures of speed (e.g., speed variance), average speed was the best predictor of collisions.

In an earlier study, Taylor et al. (2000) assessed the effects of speed on urban classified roads; data were collected from 300 different road sections and linked with 1590 injury crashes. In this case, a statistical cluster analysis was used to classify the sites into homogenous groups based on their speed characteristics. The speed attributes used in the classification included average speed, variability in speeds and the proportion of slow vehicles. This classification yielded the following four groups:

1. Highly congested roads in towns.
2. Typical inner city link roads.
3. Suburban roads.
4. Outer suburban fast roads.

The findings of this study revealed that, among other variables, average speeds were strongly related to accident frequencies. As evident in Figure 2, the relationships between average speeds and frequency were positive in all four groups, wherein, as expected, higher average speed was associated with more accidents. The analysis also expanded on the rule of thumb defined in the study by (Finch *et al.*, 1994), stating that the accident reduction per 1mph on speed depends on the road type. The reductions were defined as 6% for urban roads with low average speeds, 4% for medium speed urban roads and lower speed rural main roads and 3% for the higher speed urban roads and rural main roads.

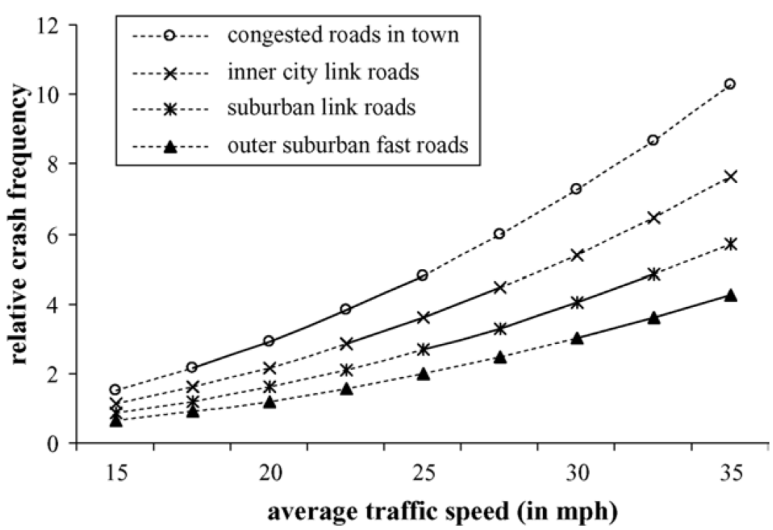

Figure 2: Speed and Safety by Class (Taylor et al., 2000)

In a study covering roadway segments in Austria, Knoflacher H. et al. (1994) used a variation of the mean speed from the posted speed limits as a measure of speed when modelling collisions. The relationship found in this study was a positive and significant relationship, in which accident density increased exponentially with an increase in the variation of the mean speed from the speed limit, as seen in Figure 3.

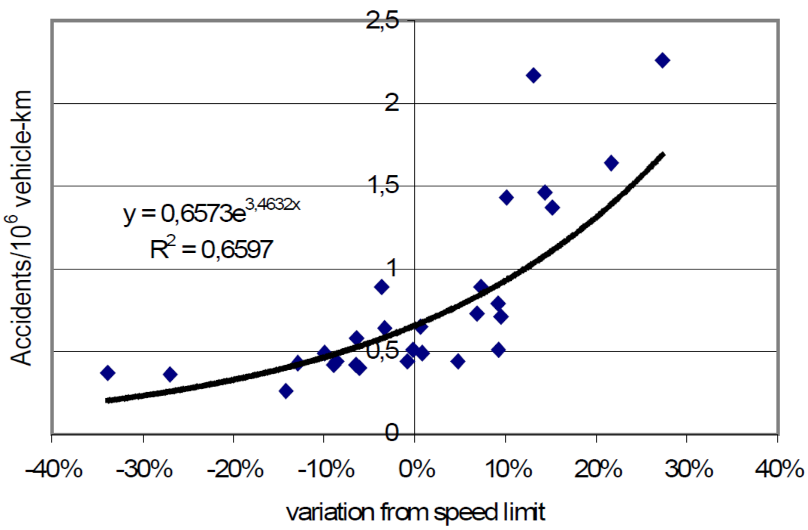

Figure 3: Variation from Mean Speed and Accident Frequency (Knoflacher et al., 1994)

Baruya (1998) analyzed the relationship between speed and safety as part of the MASTER (MAnaging Speeds of Traffic on European Roads) project, which, according to the authors, commenced with the primary objective of providing "information for decision making concerning speed management on both community and national levels." In the project, researchers studied the effects of several variables, including average speed, speed variation and the proportion of speeders on crashes.

A multiplicative Poisson model was developed using data from three different European countries. The findings revealed that traffic flow was the primary predictor of collisions and that locations with higher posted speed limits are associated with higher crash frequency. Furthermore, the study also reached the conclusion that, the higher the proportion of speed limit violators, the higher the crash frequency, indicating that speed limit violation is a serious matter. Contrary to expectation, higher average speed was found to be associated with a lower number of collisions.

Aarts and Van Schagen (2006) attributed the findings regarding average speed to three reasons, (1) the interactions between the variables considered in Baruya's model, (2) the fact that the data used were collected from different countries without accounting for national differences, and (3) the time frame for flow data (24-hour observations) and speed data (off-peak periods) not matching.

Using two years of data from six different types of high-speed roads in the U.S., Lave (1985) fitted 12 different regression models to understand the effects of speed measures on fatality rates. The research showed that average speed had negative but insignificant effects on fatalities in 10 of the 12 models. Nevertheless, speed variance was found to have positive and statistically significant effects on fatality rate, compelling the author to conclude that speed variance kills.

It is worth mentioning here that Solomon (1964) in an earlier paper also reached the conclusion that speed variance was an issue. According to the study, vehicles travelling significantly higher or lower (+/- 30mph) than the modus speed on a road had higher crash rates than vehicles travelling within a 6mph margin. This conclusion was illustrated with the renowned U-curve presented in Figure 4. Almost six years later, there was an attempt to replicate Solomon's work by the (Research Triangle Institute, 1970); however, the RTI found that the U-curve was actually due to the inclusion of maneuver crashes, which are not typically considered as speed-related crashes, in the analysis. The study determined that variance was only associated with an increase in collisions when vehicles were travelling significantly higher than the modus speed.

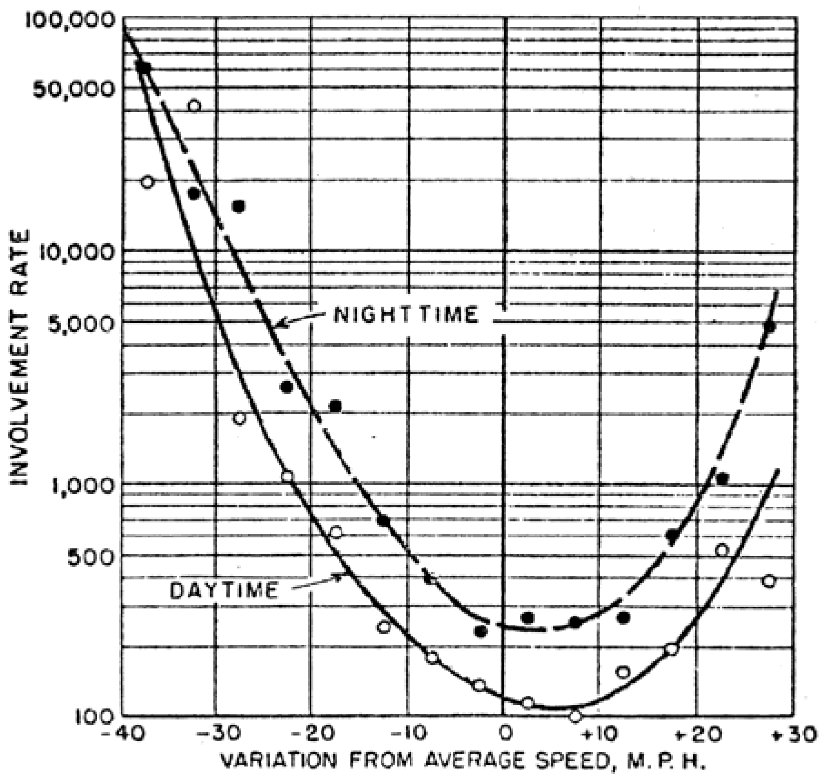

Figure 4: Solomon's U-Curve for Speed Variation (Solomon, 1964)

The issue of speed variance was also raised in (Garber and Gadirau, 1988) . In their analysis, the authors used data from three types of roads (interstate, arterials and collectors) in Virginia. In addition to the negative relationship between mean speed and crash rates, the results also revealed that locations with higher speed variance had higher crash rates. In an attempt to explain their findings, the authors argued that the negative relationship found between mean speed and collisions was actually due to the effects of geometric road characteristics masking the actual effects of mean speed. Evidence of such a masking effect was found in other studies such as (Baruya and Finch, 1994). Nonetheless, Quddus (2013) stated that the unexpected outcomes, with respect to mean speed, in both the studies by (Garber and Gadirau, 1988) and (Lave, 1985) could also be due to model specification bias, since both studies used linear regression models.

In his paper, Quddus (2013) attempted to address the deficiencies in previous work analyzing the speed-safety relationship by using spatial analysis. The paper argued that improper statistical model specification and omitted variable bias were clear limitations in previous studies. Using data from the Greater London region in the U.K., the author developed both a random effects negative binomial and a mixed effects spatial model to understand the effects of average speed, speed variance and other variables on slight injury and Killed Seriously Injured (KSI) collisions. In the later model, the aim was to account for potential spatial correlation between neighbouring segments. In terms of the results, both models indicated an insignificant relationship between average speed and collisions. Speed variation, however, was found to have a positive and significant association with crashes.

In a recent paper, which developed collision prediction models based using speeds on urban roads in China, it was found that both the mean speed and the standard deviation in speed were positively correlated with crash frequency (Tian, 2013). In other recent work, Islam and El-Basyouny (2015) used a full Bayesian before-after comparison to assess the effects of reducing the speed limits in urban areas on safety. The authors found that reduced speeds were associated with a reduction in crashes of all severity levels.

As evident from the review, modelling the relationship between speed and safety and accounting for all the confounding factors is a quite challenging task. Nevertheless, whether it is speed variance, average speed or individual speeds, it is clear from the review that an increase in speed results in a decrease in safety. In a thorough review of the most significant empirical studies that addressed the relationship between speed and safety, Aarts and Van Schagen (2006) concluded the following:

- Studies that looked at absolute speeds (i.e. not speed dispersion) at the individual vehicle level found that the relationship between speed and crash rates followed an exponential behaviour.
- Studies considering absolute speeds at the road section level also found that crash rates increase with increases in speed; however, in this case, the relationships were best represented using the power model.
- Increases in speed were associated with a higher crash rate on minor roads when compared to major roads.
- The most common factors that influenced the relationship between speed and crash rates were traffic flow, lane width and junction density.
- Higher speed variance was associated with higher crash rates, particularly for vehicles moving faster than the vehicle platoon.

2.2 Speed Management Strategies

Given the size of the problem and the deadly consequences of speeding, many attempts and several different techniques have been considered for managing speed on roads. These techniques generally fall into three categories (engineering, enforcement and education); however, it is usually a combination of measures from these three categories that yields the best results. Research has shown that initiatives falling into those three categories are the only reasons why some drivers would consider reducing their speeds (Fuller et al., 2009).

The next few paragraphs define the three different categories while giving examples on strategies implemented within each category and providing information about the effectiveness of these techniques.

- Enforcement:

The basic idea of enforcement is to patrol roads with the goal of detecting offenders (speeders) and sanctioning them. A range of sanctions has been considered for dealing with speeders, the most common of which are monetary traffic fines. However, due to the controversy among the public surrounding monetary fines and the low deterrence effects of those measures particularly when dealing with aggressive drivers, traffic departments have considered other sanctions, such as demerit (black) points, licence suspensions or even vehicle confiscations. Sanctioning often depends on the severity of the offence committed. In terms of detection strategies, speed enforcement programs use a variety of resources; the enforcement could be mobile or fixed, using speed cameras or speed guns. With the aim of achieving higher compliance rates (general deterrence), road users are often warned about the existence of enforcement activity; however, in some cases, the enforcement activity is covert.

Recent studies have shown that enforcement initiatives are highly effective in increasing compliance to speed limits and improving safety (Tay, 2010, Carnis and Blais, 2013). In a review of studies that evaluated fixed speed enforcement programs, Thomas et al. (2008) found that injury crash reduction that could be attributed to the programs ranged from 20% to 25%.

Studying the effects of enforcement on 80km/h rural roads in the Netherlands, Goldenbeld and van Schagen (2005) compared the mean speed of enforced and non-enforced roads, and found a significant drop in mean speed and violation rates over time, as seen in Figures 5 and 6 respectively.

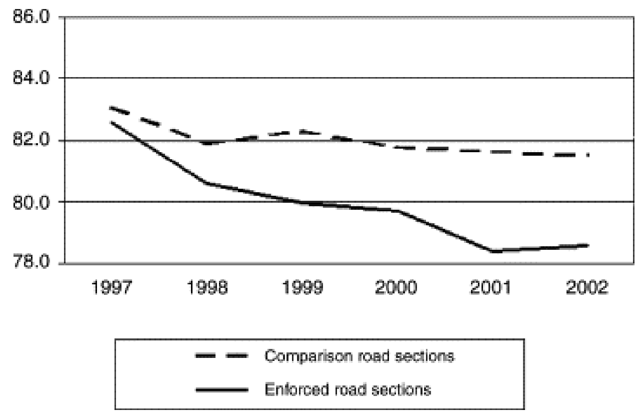

Figure 5: Effects of Enforcement on a Segment with Mean Speed of 80km/h (Goldenbeld & van Schagen, 2005)

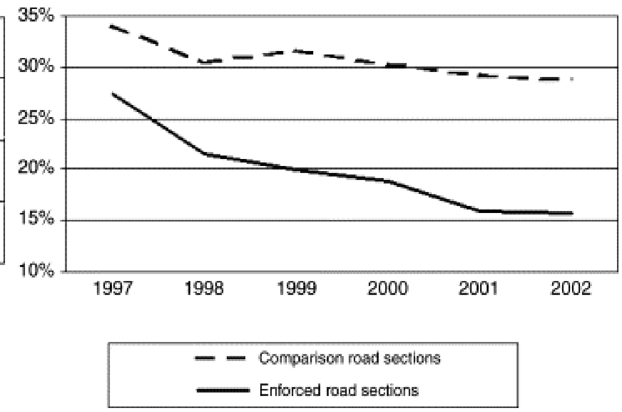

Figure 6: Effects of Enforcement on Percentage of Offenders (Goldenbeld & van Schagen, 2005)

As part of the effort to manage driving speeds, the *Arrive Alive* program was launched in Victoria, Australia. The program included intensifying enforcement, making it unpredictable and targeting low-level speeding (reducing tolerance). Assessment of the program revealed that in the first four years of implementation, fatalities dropped by 16%; in addition, the average speed in 60, 70 and 80km/h zones in Melbourne dropped below the speed limits (Auditor General Victoria, 2006).

In addition to safety improvements, (Shin *et al.*, 2011) showed how the reduced number of collisions due to the use of safety enforcement cameras can also decrease delays and, thus, produce more travel time savings, challenging the perception that lower speeds tend to increase travel times and increase economic losses.

- Engineering:

Engineering initiatives to manage speed include making changes to the road's geometric characteristics, the road's surface or the vehicle design characteristics to promote safer driving. Examples of these are traffic calming techniques (such as installing road humps or narrowing road width), installation of roundabouts, transition zones between low speed and high speed locations or even installing horizontal curves at certain locations. Previous studies have found these techniques to be effective in improving safety and reducing speeds (Cambridge Community Development, 1999, Bahar, 2007, Parkhill *et al.*, 2007) Moreover, engineering countermeasures include adjustments to the roadside environment and road surface (e.g. road marking, rumble strips); these measures, although low cost, have also been effective in reducing speed in some circumstances (Islam and El-Basyouny, 2013). Overall, road-related engineering initiatives seem to be effective in increasing driver compliance to speed limits and reducing the frequency and severity of collisions (Elvik, 2001, Dumbaugh, 2006).

A different type of engineering countermeasures includes devices that are added to vehicles to control their speeds; a review of those measures and effects can be found in the study by (Várhelyi, 2002). One example is speed limiters, which have been in effect in Europe since 1992 and have recently been added to all trucks in Ontario and Quebec, limiting their speeds to 105km/h (Gillam, 2006). The motive for introducing these measures in Europe was to improve safety and reduce environmental effects (European Commision, 2001). Moreover, these devices have also been found to improve car-following behaviour and the approach speeds at intersections (Várhelyi and Mäkinen, 2001). Active accelerator pedals were also found to improve compliance to speed limits and reduce average speeds, indicating the effectiveness of such measures (Várhelyi et al., 2004).

- Education:

Educational initiatives target road user behaviour through knowledge, rather than influencing behaviour through other measures such as roadway design or threat of punishment. Tactics can be in the form of long-term campaigns, where they are integrated into driving knowledge tests or school educational programs, or in the form of short-term educational initiatives such as flyers or specific messages targeting a certain community where speeding is an issue.

Isolating the effect of educational techniques on speed reduction and safety is somewhat challenging; however, the combined effect when used with engineering or enforcement initiatives is believed to result in further speed reduction (Blume et al., 2000). Furthermore, in a meta-analysis of studies that attempted to understand the effects of road safety campaigns on collisions, Phillips et al. (2011) found that these campaigns were positively correlated with accident reduction.

Overall, all three types of initiatives (enforcement, engineering and education) seem to have positive effects on safety. The following list is composed of strategies considered the most effective in speed management and speed control on an international scale by the World Health Organization (Peden, 2004).

- Posting speed limits and continuously enforcing them.
- Variable speed limits.
- Photo-radar enforcement.
- Traffic calming measures.
- Road design features.
- Vehicle design features.

Despite the variety of these strategies, they all fall into the three categories defined above.

2.3 The Effects of Severe Sanctions on Safety

As means of improving enforcement-related speed management strategies, legislators have considered increasing the severity of sanctions against some violators. One reason for this consideration is that current sanctions do not seem to deter violators, particularly those with an aggressive nature. As an outcome of discussions with offenders who were used to form focus groups to study the factors influencing driver speed, Fleiter et al. (2010) revealed that apart from financial stress, monetary fines did not seem to have any deterrence effects on some speeders. Moreover, Fleiter et al. (2007) found that even demerit points were not effective in deterring those drivers.

Excessive speeders are often aggressive drivers by nature and, hence, threats of severe sanctions seem to be the only means of discouraging those drivers from violating the law. A recent study considering the characteristics of high-range (excessive) speeders in Queensland, Australia, found that these offenders tend to be young males who have a history of traffic offences and are more likely to have been involved in a multi-vehicle crash, compared to low-range speeders and other offenders (Watson et al., 2015).

Based on the deterrence theory, the fear of being caught is widely accepted as the reason for compliance to laws and legislation. This fear is known to deter (discourage) drivers from violating the law and is a function of three factors: (1) the apparent *severity* of the law, (2) the *certainty and the speed* with which an offender is sentenced, and (3) the *administrative penalties* associated with the law (Watson, 2004, Davey and Freeman, 2011). Deterrence theory also advises that a law be properly publicized and enforced to be effective in deterring potential violators (Tay, 2005a). In addition to educating drivers about the risks, publicity and enforcement promote the certainty of being caught to the driving public. This should not be confused with the *certainty* mentioned in factor (2), as that was in reference to the certainty of being punished after being caught.

Deterrence can be observed in two different forms, general deterrence and specific deterrence. General deterrence is the most commonly used type of deterrence by policy makers; the risk of being sanctioned or witnessing sanctions being issued to others discourages the general population from committing a certain offence. In contrast, specific deterrence is the impact of a law in discouraging offenders who have already violated the law from repeating their offence (Piquero and Paternoster, 1998, Tay, 2005b).

Common severe sanctions in road safety include licence suspensions, vehicle impoundment, vehicle-plate impoundment and even, in some cases, vehicle forfeiture. As evident from the definitions in the two preceding paragraphs, these penalties seem to fit most categories of a policy for which high deterrence is anticipated. There is no doubt that these sanctions are harsh, and, in most cases, convictions are rapid. Moreover, vehicle impoundment and licence suspension often take place on the roadside (i.e. they are immediate). Finally, these laws are also usually combined with financial sanctions, and as already noted, most penalties are administrative.

2.3.1 Previous Use of Severe Sanctions

Over the past few decades, licence suspension has been a common policy used to deter drivers who violate traffic laws (Ross, 1973, Vingilis et al., 1988). At the time of its introduction, licence suspension was launched with the hope of reducing impaired driving related to alcohol (Wagenaar and Maldonado-Molina, 2007). Although licence suspension in the post-conviction stage was found to have encouraging specific deterrence effects (Homel, 1989, Mann *et al.*, 1991), not many studies were able to find general deterrence effects for the policy (Asbridge et al., 2009). As a result, legislators started considering administrative licence suspensions, where licence suspension occurs before conviction.

In a study evaluating the effects of alcohol-related licence suspension laws in 46 American states, Wagenaar and Maldonado-Molina (2007) found that administrative licence suspension (ALS) had a statistically significant effect on reducing alcohol-related fatal crashes. On the contrary, and in line with other research, the study found that licence suspension after conviction had no apparent general deterrence effects. From a Canadian perspective, the assessment of Ontario's ALS law against driving with a Blood Alcohol Concentration (BAC) over the legal limit of 80 mg% revealed similar findings (Asbridge et al., 2009). The research, which analyzed the effects of the law on monthly driver fatalities from January 1988 to December 1998, found a statistically significant drop (i.e. general deterrence effect).

In recent years, ALS has been combined with vehicle-related sanctions to increase the severity of the punishment and to ensure that suspended drivers comply with the law. The literature shows that the main reason vehicle-related sanctions have been implemented is that suspended or unlicensed drivers continue to drive while suspended (DWS) or drive while unlicensed (DWU) (Voas and DeYoung, 2002). In fact, it is estimated that as many as 75% of suspended drivers continue to drive after suspension (Peck and Voas, 2002). As a result, police and traffic safety departments found that the most appropriate penalties against such offenders was the impoundment of their vehicles (vehicle plates in some cases) for a certain period of time, which would ensure they do not drive again within the suspension period and that they would think twice before repeating the offence.

Vehicle impoundment can be defined as the confiscation of an offender's vehicle for a temporary period; this is slightly different from vehicle forfeiture, where the vehicle is taken away permanently. Vehicle impoundment of suspended drivers has been implemented in a few parts of North America, including Manitoba in Canada and both California and Ohio in the United States. The studies that have assessed the effectiveness of such a policy in those cities and their conclusions can be found in Table 2; moreover, the work by (Voas and DeYoung, 2002) provides a summary of all the studies that have dealt with evaluating vehicle sanction, impoundment and forfeiture policies prior to that date.

Most studies that have evaluated the legislation conclude that vehicle impoundment does have an effect on specific deterrence (i.e. drivers who were sanctioned under the law did stop DWS), and hence, an alleged improvement in the safety for other road users see, for example, (DeYoung, 1999) and (Voas *et al.*, 1997b). The studies considered the records of violators after their violations in both the pre- and post-law periods, and found that rearrests decreased after the law was enforced. A specific deterrence effect was also found for the administrative vehicle-plate impoundment program introduced in Minnesota in 1991. Studies evaluating the effects of this law found that future DWI and DWS violations for those penalized under the law dropped significantly in the post-sanction period (Rodgers, 1994, Leaf and Preusser, 2011).

DeYoung (2000), who evaluated the effects of vehicle impoundment on general deterrence in California, found no statistical evidence to support the existence of such an effect (i.e. simply threatening to impound the vehicles of those DWS did not influence the crash rates). Furthermore, a focus group discussion that reviewed the effects of the vehicle impoundment against the honing activities (eg: speeding, burnouts,, or screeching tires) in Queensland, Australia, also revealed that the policy had no general deterrence (Leal et al., 2009). Even though participants admitted the sanctions were harsh, they were still adamant to violate the law.

In contrast, a study by Beirness et al. (Beirness *et al.*, 1997) that evaluated the effects of a vehicle impoundment program in Manitoba did find a general deterrence effect. However, this effect could not be fully attributed to the vehicle impoundment legislation, since, unlike other states where vehicle impoundment was added to licence suspension at a later date, the administrative licence suspension (ALS) impaired driving law and the vehicle impoundment law in Manitoba were both introduced at the same time.

2.3.2 Severe Sanctions Against Excessive Speeders

One common reason for excessive speeding is street racing. Along with other unacceptable driving habits, such as stunt driving and honing activities, street racing has been associated with an increase in motor vehicle crashes. Accordingly, it has been highlighted in previous studies as an important safety problem (Knight *et al.*, 2004, Vingilis and Smart, 2009, Smart *et al.*, 2012), and consequently, severe sanctions have been considered when dealing with drivers who adopt those habits.

Although severe sanctions against excessive speeders have been implemented in a few provinces and states, to the extent of the author's knowledge, only a few previous studies have considered evaluating the effectiveness of such legislation on collision statistics and fatalities. In fact, most of the studies that did address the legislation were mostly focus group discussions and survey-based analysis, which did not consider the effects of the law on direct safety measures such as collisions; see, for example, (Vingilis *et al.*, 2013).

Meirambayeva et al. (2014b) studied the effects of the excessive speeding legislation in Ontario on the violation rates (i.e. the number of drivers caught driving at excessive speeds). The violations before and after the introduction of the law were compared, and it was found that in the male drivers' group, the rates dropped (general deterrent effect); whereas, for females the rates remained almost constant.

Leal (2010), who also assessed the effects of anti-street racing/stunt driving laws in Queensland, Australia, on violations, found that the vehicle impoundment policy did result in the reduction of street racing/stunt driving infringements in the offender sample (specific deterrence).

In one of the few papers that studied the road safety impacts of excessive speeding legislation, Meirambayeva et al. (2014a), found that the policy was effective in reducing speed-related casualties among males aged 16-25 years; a drop of 58 casualties per month was observed, which was found to be statistically significant. The paper argues that since excessive speeding offences and stunt driving activities are highest in the young male age group the finding seem reasonable.

The paper also analyzed the effects of the legislation on speed-related casualties for mature males (26-65 years) and found that the effects of the legislation on this group were insignificant. In order to account for temporal trends, the paper used female casualties from similar age groups as comparison groups. Moreover, non-speed-related casualties were used as a comparison group to control for general casualty trends.

Figure 7 shows the time series of the casualty data, which was analyzed for each of the four age groups. The figure also shows the time series of the combined non-speed-related casualties. The authors concluded that the legislation had a general deterrence effect.

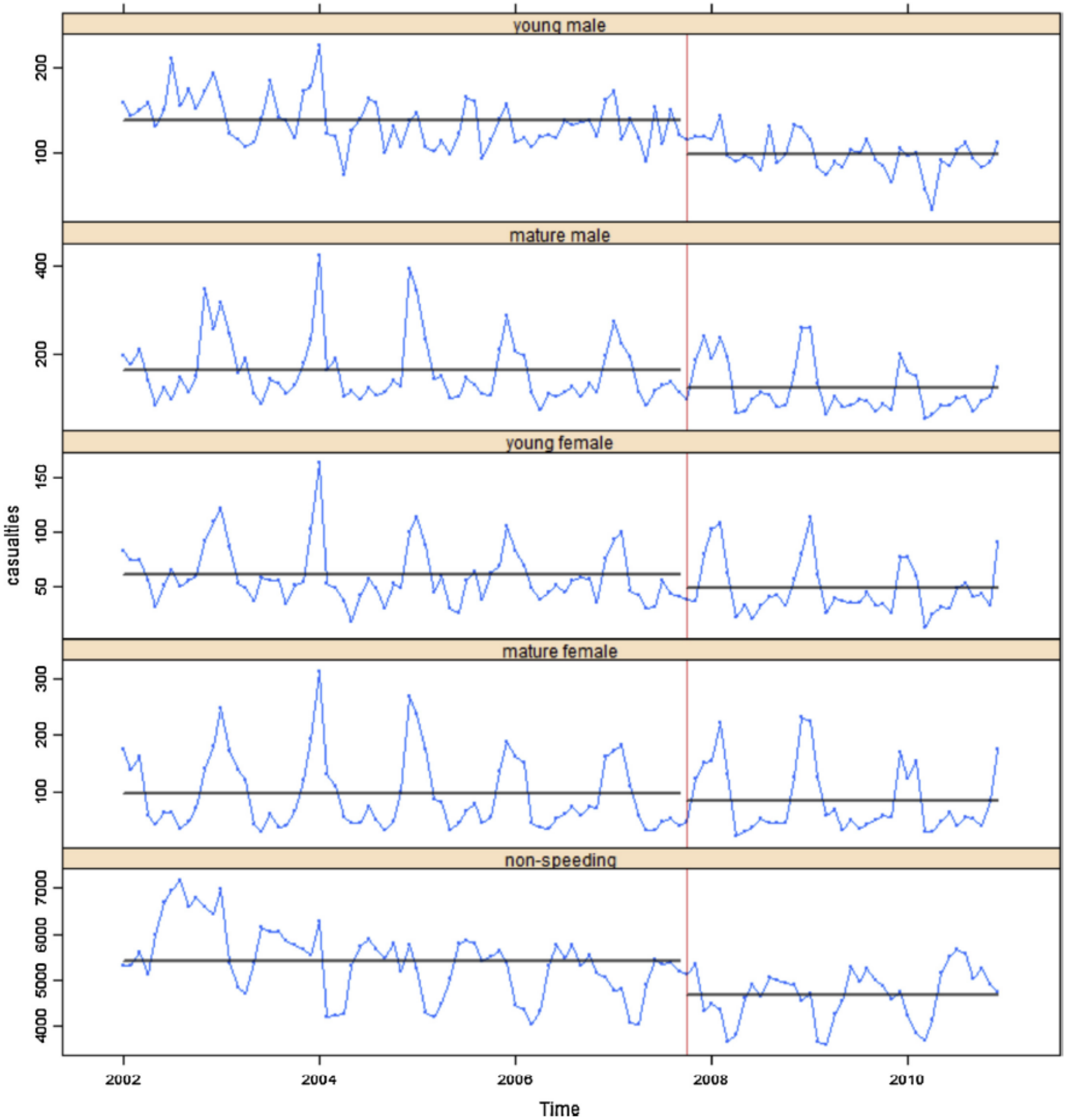

Figure 7: Time Plots Showing Intervention Effects (Meirambayeva et al., 2014)

The potential effects of excessive speed legislation on safety were also analyzed in part of the work by Brubacher et al. (2014). In this paper, the effects of the legislation in BC on three different outcome variables were examined. These variables were fatal collisions, ambulance calls for traffic/transportation incidences, and road-related hospital admissions. With respect to traffic collisions, the researchers found that the post-intervention period was associated with a significant drop in fatal collisions where both speed and alcohol were causal factors. An analysis of all fatal collisions (irrespective of their causal factor) also indicated that the policy was associated with a statistically significant drop in collisions.

When evaluating the effects of the policy on collisions where speed was the only causal factor (i.e. excluding collisions that were caused by both alcohol and speeding as well as collisions that were caused by other factors), the analysis revealed a drop in fatal collisions, but this finding was statistically insignificant. The study concluded that imposing severe and roadside sanctions against aggressive drivers has a significant effect in reducing road trauma. It is worth noting here that in this study, only two years' worth of data was used for the post-intervention period; whereas, for the pre-intervention period, the authors considered more than twice the amount—five years of data.

Despite vehicle forfeiture not being part of the sanctions analyzed in this thesis, it is important to point out that this law was also found to have a significant effect on reducing illegal street-racing fatalities in San Diego (Worrall and Tibbetts, 2006). Moreover, in an assessment of the policy in California, vehicle forfeiture was found to have the greatest effects when used against repeat offenders (Peck and Voas, 2002).

In general, as pointed out in Table 2, previous studies have shown that there is some sort of compliance associated with severe sanctions, including vehicle impoundment policies and licence suspensions. However, not much work has been done to understand the effects on traffic collisions and fatalities, particularly in the case of excessive speeding. As a result, this thesis conducts an analysis to help understand the value of these laws in improving traffic safety, using direct safety indicators as dependent variables.

Table 2: Previous Studies

Author(s)	Location	Focus	Findings
DeYoung (2000)	California	General deterrent effect of vehicle impoundment of drivers DWS on crash rates.	No significant evidence was found to support the hypothesis that threatening to impound vehicles of suspended drivers affected overall nighttime crash rates.
DeYoung (1999)	California	Specific deterrent effects of vehicle impoundment by comparing the records of offenders who were sanctioned and those who were not.	Findings provide strong support for impounding vehicles of those DWS. The policy resulted in fewer violations and better crash records for those who were sanctioned.
Vaos et al. (1997)	Ohio	Evaluating the effects of vehicle immobilization on moving violations and repeat DWI. The study compares the records of offenders who were sanctioned and offenders who were not during and after the sanction period.	The study found a specific deterrent effect of vehicle impoundment (i.e. offenders who were sanctioned had improved records), which lasted even after the vehicle was returned.
Beirness et al. (1997)	Manitoba	Effects of vehicle impoundment and (ALS) on nighttime crash rates.	The study found a general deterrent effect, but it could not be determined whether it was due to the vehicle impoundment or the ALS law, since they were implemented at the same time.
		The specific deterrent effect of the two laws was measured by comparing the number of repeat violators before and after the law took effect.	A specific deterrent effect was found; however, the analysis was statistically weak.
Brubacher et al. 2014	British Columbia	The effects of severe sanctions in BC, including excessive speeding legislation, on fatalities.	The legislation was found to have significant effects in reducing fatal collisions, indicating a general deterrence effect.
Meirambayeva et al. (2014b)	Ontario	General deterrent effect of excessive speeding legislation on violation rates, considering the violation rates before and after the introduction of the law.	The study found that, in the male drivers' group, the rates dropped; whereas, for females, the rates were almost constant.
Meirambayeva et al. (2014a)	Ontario	Safety impacts of excessive speeding legislation on speed-related collision casualties among different age groups	The study concluded that the law was effective in reducing spee- related casualties for males aged 16-25 years, indicating a general deterrence effect

*NOTE: DWI: Driving While Influenced, DWS: Driving While Suspended, ALS: Administrative Licence Suspension

2.3.3 Issues Associated with Vehicle-Related Sanctions

Although significant evidence exists to prove that vehicle-related sanctions are effective in reducing crashes and violations (Voas and DeYoung, 2002, Brubacher *et al.*, 2014, Meirambayeva *et al.*, 2014a), these sanctions are also associated with many issues and disputes, which has led legislators to refrain from adopting these policies. The next few paragraphs provide an overview of those challenges and discuss how they have been dealt with in different circumstances.

One important aim of any legislation is sanctioning the offender in order to ensure that the offence is not repeated (specific deterrence). With vehicle sanctions, however, this is not always the case, the reason being that the offender might not commit the offence using his/her own vehicle, and hence, might escape punishment. In fact, previous studies have revealed that more than half the offenders caught under vehicle sanctioning programs are either not the owner or only partially own the vehicle (Voas and DeYoung, 2002). This matter results in several different issues.

Voas et al. (2000) shows how courts often back the impoundment/forfeiture decision if evidence exists that the non-offending owner knew or should have been aware of the offence. However, in the court hearing, owners are sometimes given the opportunity to provide evidence that he/she was unaware that the driver was committing an offence using his/her vehicle. If the evidence is accepted, the owner signs an agreement indicating that, if he/she surrenders the vehicle to the offender while unlicensed again, the vehicle is forfeited.

While providing evidence of innocence might be possible in cases when the legislation targets drivers who were driving while suspended (DWS), in offences involving driving under the influence (DUI) or excessive speeding, the issue is more complicated. It is worth noting here that, in cases where the offender is not the only owner of the vehicle, officials are sometimes required to consider early release for other reasons. These include companionate cases where a family owns only one vehicle with multiple licensed divers who need the vehicle for work or school and have no other mode of transport available, or cases of economic hardship, where the business owner demonstrates that impounding the vehicle will be an economic burden (BC MOJ, 2014). Whatever the reason, early release of the vehicle means the offender escapes full punishment.

Another important issue related to non-offending-owners is the towing and storage costs. In order to recover the confiscated vehicle, vehicle impoundment programs often charge a service fee that must be paid before return of the vehicle. While this is an effective way to fund an impoundment program (Peck and Voas, 2002), the issue of who pays the fee when the owner is a non-offender is another liability issue, which is often resolved by charging the owner who then attempts recovering the payments from the offender (Voas et al., 2000).

Storage (during the court hearing) and towing fees pose a greater burden in forfeiture programs. In these programs, the vehicle is not returned to the owner and instead sold in auctions, and hence, an offender cannot be charged a service fee. In cases where the vehicle has a market value, this is not an issue; however, when the vehicle is a "junker" with no value, the storage costs might outweigh the sale value. As a result, Voas and DeYoung (2002) recommend that, in these cases, the hearing process be expedited in order to avoid costs falling on the community.

An alternative way to sanction offenders without having to deal with all the associated costs is through vehicle-plate impoundment. This law has been in effect in Minnesota since 1991 and has been effective in reducing DUI recidivism.

Changing the vehicle registration while the court trial takes place is also a common issue in impoundment programs when the vehicle is not confiscated immediately. This problem was addressed in Ohio by passing a law that prevents offenders from changing their vehicle registration during the trial period(Voas *et al.*, 2000, Peck and Voas, 2002). Even though this is an effective measure, it is often recommended that, for this reason and for an impoundment program to achieve higher deterrence rates, vehicles must be seized at the time of arrest and not post-conviction (Voas and DeYoung, 2002).

2.4 Statistical Techniques Used to Assess Legislative Changes

Whether they be seat belt laws, speed limit enforcement cameras, or excessive speeding legislation, several different statistical tools have been used to assess policy changes. This section provides a brief review of previous studies that have assessed the impacts of legislative changes, with a focus on the different statistical techniques used in each study.

One of the most commonly assessed legislative changes in the traffic safety literature was the introduction of seat belt laws. Wagenaar et al. (1988) examined the effects of compulsory seat belt use on the number of occupants fatally injured in traffic crashes. Their methodology was based on the ARIMA (Auto-Regressive Integrated Moving Average) time-series intervention analysis, which was run for eight states. Their results revealed a statistically significant decline in the rate of fatalities in some U.S. states.

Assessing the impacts of mandatory seat belt laws, along with other legislative changes in 50 states, Houston et al. (1995) used a pooled time series analysis with fatalities per Vehicle Miles Travelled (VMT) as a dependent variable. The study found that legislative changes implemented to improve safety were effective.

In their highly referenced paper, Harvey and Durbin (1986) analyzed the effects of seat belt legislation on British road casualties through a case study in structural time series modelling. Although still a form of intervention analysis, a substantial difference in some aspects exists between structural time series analysis and the custom ARIMA interventional analysis. In this paper, structural modelling intervention techniques were implemented to predict the changes in casualty rates, post-intervention, for various categories of road users.

In another study evaluating the impacts of mandatory seat belt laws on traffic fatalities in the U.S., Cohen and Einav (2003) used a panel data ordinary least squares (OLS) regression to model the relationship among fatalities, the law and several independent variables.

Voas et al. (2003) assessed the effectiveness of raising the minimum legal drinking age (MLDA) in decreasing alcohol-related highway deaths. A regression model was proposed in this study, relating the dependent variable (the odds that a driver in a fatal crash will have been drinking) to the independent variables/covariates (laws of primary interest).

In (Hingson *et al.*, 1994), a simple before-and-after comparison was used to measure the impacts of the lower legal blood alcohol limits implemented in 12 states targeting drivers younger than age 21. The outcome variable used in the assessment was single-vehicle night crashes involving the age group targeted by the law. In order to account for confounding factors, the study used 12 comparison states where the law was not implemented.

In another paper evaluating the impacts of several drinking-driving laws on fatal crashes, Structural Equation Modelling (SEM) was used (Fell et al., 2009). SEM is a statistical method where a series of regression models is often used to analyze conceptual relationships between several variables.

Assessing the effects of raising speed limits on Illinois rural highways, Rock (1995) used an ARIMA time series analysis; however, the author stated that other techniques were also applicable, according to the author "a variety of statistical methods could be applied to this problem. They range from simple (before-after comparisons) to more sophisticated (multiple regression) to complex (ARIMA models)." ARIMA intervention analysis was also used to assess the impacts of London's congestion toll on traffic casualties among motorists, cyclists and total casualties in the study by (Noland *et al.*, 2008).

Hess and Polak (2003) analyzed the effects of Speed Limit Enforcement Cameras (SLEC) on accident rates in Cambridgeshire, U.K. They used ARIMA /SARIMA (Seasonal Auto-Regressive Integrated Moving Average) in modelling the accident data. Since the study was a disaggregate analysis of data from specific locations, the authors had to account for confounding factors, such as regression to the mean, by considering a time series over a longer period of time. Their research showed that, after removing the effects of seasonality and trend, and independent of the influence of regression to the mean, there was a significant reduction in the mean monthly accident frequency following the installation of SLECs.

According to Wagenaar and Maldonado-Molina (2007), the majority of studies that analyzed the impacts of licence suspension used one of two analytic approaches: (1) ARIMA interrupted time-series modelling, or (2) pooled cross-sectional time-series regression models.

In work evaluating the impact of demerit points on traffic safety in Spain, Pulido et al. (2010) also used an ARIMA time series analysis, a similar study evaluating the impacts of demerit points in Kuwait also used the same technique (Akhtar and Ziyab, 2013). Moreover, in most of the recent studies evaluating the impacts of vehicle impoundment and excessive speeding legislation, ARIMA interrupted time series analysis was the dominant assessment procedure (Brubacher *et al.*, 2014, Meirambayeva *et al.*, 2014a, Meirambayeva *et al.*, 2014b).

As evident by this preceding review, a variety of statistical techniques have been used to assess legislative impact; nevertheless, it is clear that the majority of the studies used an ARIMA intervention analysis in their modelling, a technique that has been recommended for use in intervention assessment (Biglan et al., 2000). The primary reason most researchers opt for this technique is that, unlike other regression models, ARIMA time series regression modelling accounts for a serial correlation present in longitudinal data (this concept is addressed in more detail in chapter 5 of this thesis).

3. New Legislation

In this chapter, details of the sanctions, which came into effect due to the implementation of the excessive speeding legislation, are provided. As already discussed in the review, excessive speeders are typically targeted with severe sanctions with the aim of achieving both specific and general deterrence impacts. In fact, research has shown that the higher the sanctions and the more severe the punishment is, the lower the violation rates (Davey and Freeman, 2011).

3.1 British Columbia

3.1.1 Law:

British Columbia was the latest of the three provinces to adopt the excessive speeding legislation. The law came into effect on the 20th of September 2010 and was mainly established to counteract excessive speeders; however, street racers and stunt-drivers were also targeted under the new law. Excessive speeding under the motor vehicle act in BC is defined as exceeding the posted speed limit by more than 40km/h (RSBC, 2015).

3.1.2 Sanctions:

Drivers caught under the new laws in BC are subject to fines, demerit points and vehicle impoundment, depending on the violation speed and whether the violation is a repeat offence. Fines and black points are specified as follows:

- ✓ Exceeding the speed limit by more than 40 km/h — $368 fine and three points.
- ✓ Exceeding the speed limit by more than 60 km/h — $483 fine and three points.

Vehicle impoundment period and fees are allocated as follows:

- ✓ **1st offence:** 7 days of vehicle impoundment plus towing and storage costs – at least $210.
- ✓ **2nd offence:** if the offence occurs within two years of the first, the driver is subject to a 30-day vehicle impoundment plus towing and storage costs – approximately $700.
- ✓ **3rd offence:** if the offence occurs within two years of the previous offence, the driver is subject to a 60-day vehicle impoundment plus towing and storage costs – over $1,200.

3.2 Ontario

3.2.1 Law:

In Ontario, the excessive speeding legislation has been in effect since the 30th of September 2007. Ontario was the first Canadian province to adopt the law, named "Ontario's Street Racers, Stunt and Aggressive Drivers Legislation." The law was mainly implemented against drivers who exceed speed limits by margins higher than 50km/h. As evident from the name, the law also targeted stunt driving and aggressive driving activities; however, charges for those offences are laid in cases where excessive speeding occurs (Meirambayeva et al., 2014a).

3.2.2 Sanctions:

The sanctions in Ontario include licence suspension, vehicle impoundment, hefty fines and a potential jail sentence. Penalties are issued before and after conviction and depending on recidivism. The next few points provide a summary of the different sanctions issued at different stages:

- ✓ Pre-conviction – Immediate 7-day licence suspension and 7-day vehicle impoundment.
- ✓ Upon conviction – Fine ranging from $2,000 to $10,000, 6 demerit points, up to 6 months in jail, and up to 2 years of licence suspension for a first conviction
- ✓ Moreover, if a second offence occurs within 10 years of the first, once convicted, the driver faces a 10-year licence suspension.

3.3 Quebec

3.3.1 Law:

Quebec implemented the excessive speeding law on the 1st of April 2008. Unlike Ontario and British Columbia, in Quebec the margin at which the law came into effect was split into the following three levels depending on the speed limit on the road.

- 40 km/h or more over the posted speed limit in zones where the limit is 60 km/h or less.
- 50 km/h or more over the posted speed limit in zones where the limit is more than 60 km/h but less than 90km/h.
- 60 km/h or more over the posted speed limit in zones where the limit is 100 km/h or higher.

These levels were defined based on the risk of getting involved in a collision on different types of roads. Citing outcomes of research work by Kloeden et al. (1997) and Kloeden et al. (2001), the government of Quebec defined the following risk categories (SAAQ, 2013):

The risk of being involved in an accident in a residential area is approximately

- Twice as high for every 5 km/h over the speed limit;
- 4 times higher at 70 km/h than at 60 km/h (the speed limit in Australia in residential areas);
- 32 times higher at 80 km/h than at 60 km/h.

The risk of being involved in an accident in a rural area is approximately

- Twice as high at 10 km/h over the speed limit;
- 6 times higher at 20 km/h over the speed limit;
- 18 times higher at 30 km/h over the speed limit.

3.3.2 Sanctions:

A number of sanctions were included under the law in Quebec, depending on whether it was the driver's first, second, third or fourth offence. The sanctions are summarized in Table 3.

Table 3: Excessive Speeding Sanctions in Quebec

Offence	Penalty
1st Offence	Getting caught under the law for the first time involves the following: ✓ Immediate licence suspension for 7 days; ✓ Fines and demerit points are doubled.
2nd Offence	A second violation of the law within 10 years of the first offence involves the following: ✓ An immediate licence suspension for 30 days; ✓ Doubled fines and demerit points (post-conviction); ✓ Vehicle impoundment for 30 days if the offence was committed in a 60km/h zone.
3rd Offence	If a third violation is recorded within 10 years of the second, the driver is subject to the following penalties: ✓ Immediate licence suspension for 30 days, or ✓ Immediate suspension of driver's licence for 60 days if all offences occurred in a 60 km/h zone or less; ✓ Immediate vehicle impoundment for 30 days if two or more offences were committed in a zone of 60 km/h or less; ✓ Doubled fines and demerit points (post-conviction).
4th Offence or higher	A driver caught with four or more violations within 10 years is subject to the following: ✓ Immediate licence suspension for 30 days, or ✓ Immediate suspension of driver's licence for 60 days if two or more offences occurred in a 60 km/h zone or less; ✓ Immediate vehicle impoundment for 30 days if one or more offence(s) were committed in a zone of 60 km/h or less; ✓ The number of demerit points and amount of the fine is tripled (post-conviction).

3.4 Publicity and Enforcement

The impacts of any legislation are typically affected by the amount of enforcement and publicity it receives. Unfortunately, information about these topics with respect to the excessive speeding legislation was limited, particularly in Quebec and British Columbia. Nonetheless, an attempt was made to obtain as much information as possible for each of the provinces.

In Ontario, the Ministry of Transportation of Ontario (MTO) ran educational campaigns targeting high school students and distributed brochures outlining the consequences of speeding and stunt driving activities. Moreover, road signs on major highways included information about the new legislation; in addition, information was also included in the Driver's Handbook (Meirambayeva et al., 2014a). Due to its controversy, the law also gained some media attention (Daigle et al., 2014).

In Quebec, a brochure providing details about the stiffer penalties was prepared by the Société de l'assurance automobile du Québec (SAAQ). The leaflet also included information about the offences that warranted sanctioning. Information about the new laws is also available on the SAAQ official website (SAAQ, 2014).

In BC, three weeks before the launch of the law (2nd September 2010), a press release was launched by the Ministry of Public Safety and Solicitor General (Solicitor General BC, 2010). Information about the new law was also made available on the official websites of Insurance Corporation of British Columbia (ICBC) the BC Ministry of Justice (MOJ). Moreover, the Office of the Superintendent of Motor Vehicles at the MOJ prepared a vehicle impoundment fact sheet describing the different scenarios in which a vehicle is impounded, the duration of the impoundment and the appeal and retrieval system (BC MOJ, 2014). In terms of media attention to street racing, BC was second only to Ontario in the percentage of articles covering the topic (Daigle et al., 2014).

3.5 Hypotheses

As evident from the information presented in this chapter, there is some variation among provinces in both the offences warranting sanctioning and the severity of the sanctions. Nevertheless, all laws are implemented to target excessive speeders who violate speed limits by certain margins. Since the aim of this thesis is not to compare the effects of the legislation in the different provinces, the differences in sanction severity, publicity and enforcement among the provinces are not a major concern.

The objectives of this thesis involve testing for the effects of the excessive speeding legislation (ESL) at each province on collisions of different severity levels. These objectives are demonstrated in the following hypotheses. Since the ESL targeted speeding, which is a major contributor to severe crashes, the primary hypothesis is that the policy would have effects in reducing those severe collisions (fatal and injury). The secondary hypothesis involves the assumption that the law also had potential effects of the law on reducing property-damage-only (PDO) and total collisions.

4. Dataset Description

4.1 Collision Data

Since the aim of this study was to analyze the effects of excessive speeding legislation on direct safety indicators, monthly collision counts, broken down by severity, for each of the three provinces were collected. The collision data covered a period of time before implementing the law (pre-intervention data) and after the legislation had come into effect (post-intervention data).

The number of data points before and after the intervention varied by province. Ontario data included 73 data points before (≈ 6 years) the law and 52 points after (≈ 4.3 years); for British Columbia, the numbers were 57 before (≈ 4.75 years) and 40 after (≈ 3.3 years); whereas, for Quebec, more data points were provided after the legislation, 70 (≈ 5.8 years), than before, 52 (≈ 4.3 years). In order to avoid potential bias towards any of the time periods (pre or post) an effort was made to ensure that difference between the length of the two time periods did not exceed 20% of the total data, as evident by the numbers in Table 4.

Each data point represented the number of collisions in a particular month, and the data were available for fatal, injury, property-damage-only (PDO) and total collisions. The overall time trends of the data for each province are shown in Figures 8-10 for fatal crashes and Figures 18-26 in Appendix B.1 for the remainder of the data; the figures also show the intervention date marked in red. Moreover, the descriptive statistics of the data are found in Table 4.

The data were gathered from several different sources. BC collision data originated from police reports and were obtained from the Insurance Corporation of British Columbia (ICBC). In ON, the collision data were obtained from Ontario Road Safety Annual Reports (ORSAR) kept by Ontario’s Ministry of Transport (MTO). The QC collision data were obtained from the Société de l'assurance automobile du Québec (SAAQ).

Table 4: Descriptive Statistics of the Data

Province	Severity	N	Pre	Post	Minimum	Maximum	Mean	Std. Deviation
BC	Fatal	97	57	40	11	46	25.57	7.124
	Injury	97	57	40	3482	5450	4345.52	422.946
	PDO	97	57	40	14343	27939	17873.69	1921.431
	Total	97	57	40	18128	32985	22244.78	2166.265
ON	Fatal	125	73	52	19	85	53.79	14.082
	Injury	125	73	52	2758	5580	4026.56	554.188
	PDO	125	73	52	8031	24617	14679.07	3118.453
	Total	125	73	52	10897	30011	18759.43	3419.160
QC	Fatal	122	52	70	18	80	42.03	13.266
	Injury	122	52	70	1762	3758	2768.28	476.337
	PDO	122	52	70	4784	14751	8045.64	2137.685
	Total	122	52	70	6707	18305	10855.96	2290.421

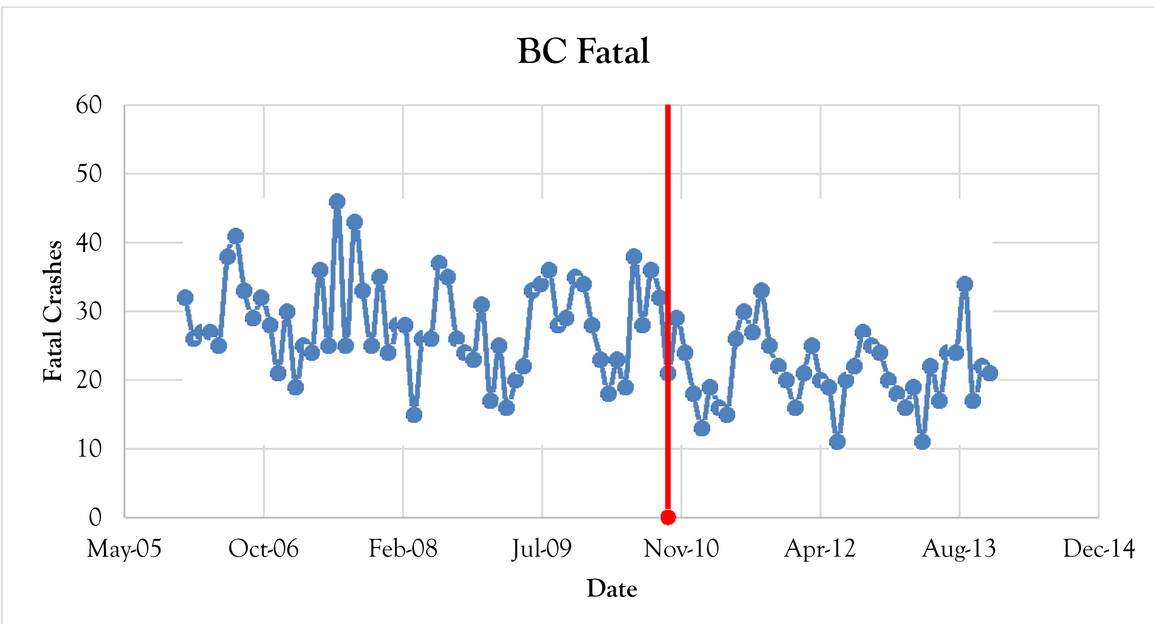

Figure 8: BC Fatal Collision Data Time Trend

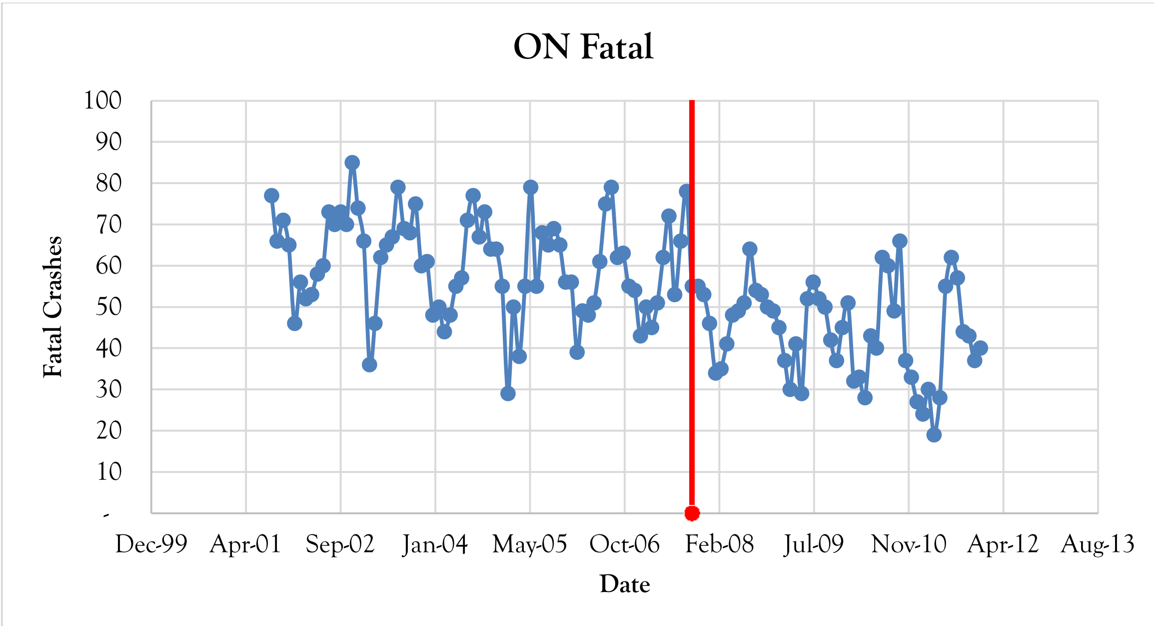

Figure 9: ON Fatal Collision Data Time Trend

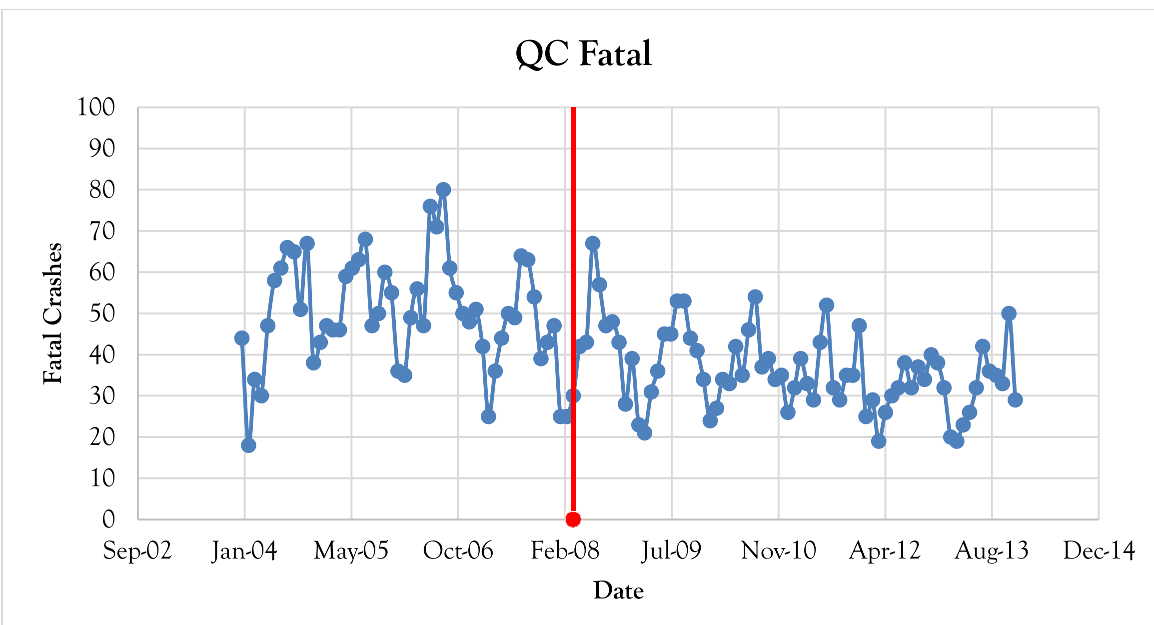

Figure 10: QC Fatal Collision Data Time Trend

4.2 Exposure Measure

Traffic flow is one of the most significant variables that affects collision counts; the higher the exposure to a risk (traffic volume) on a road, the higher the risk of being involved in a crash (crash frequency) (Baruya, 1998, Quddus, 2008). Therefore, in order to avoid potential biases in the results, exposure measures had to be included in the analysis at some stages.

For an aggregate analysis, such as the provincial-level assessment performed in this thesis, traffic volume is often represented through the amount of travel, which is typically measured in vehicle miles/kilometres travelled (VMT/VKT) per month. In cases where VKT are not available, a surrogate measure of exposure, such as fuel sales, can be used. Fuel sales have been used as a measure of traffic exposure in many previous studies (for example, see Fridstrøm, 1999; Fridstrøm et al., 1993).

In this thesis, motor vehicle fuel sales per month, kept by Statistics Canada, were assembled for a similar period of time, during which collision counts were available. Data were available for each of the three provinces separately.

4.3 Other Legislation

In addition to traffic exposure, collision counts are also affected by the implementation or withdrawal of any major traffic laws. As a result, accounting for other legislative changes in the analysis was essential. In each province, information about any province-wide legislation that was enforced or cancelled during the analysis period was obtained. All legislation with potential effects on collisions was then statistically accounted for in the models. Since the analysis dealt with data on a provincial level (aggregate), it was assumed that the effects of any location-specific laws and regulations (disaggregate) would be negligible. A summary of all legislative changes included in the analysis is found in Table 5.

Table 5: Other Legislative Changes during the Study Period

Province	List of Other Major Legislative Changes During the Study Period			
	Type	**Implemented/Cancelled**	**Month**	**Year**
British Columbia	Distracted Driving Law **(DDL)**	Implemented	Feb	2010
	Impaired Driving Law **(IDL)**	Implemented	Sept	2010
	Excessive Speeding Legislation (ESL)	**Implemented**	**Sept**	**2010**
	Impaired Driving Law	Cancelled	Nov	2011
Ontario	**Excessive Speeding Legislation (ESL)**	**Implemented**	**Oct**	**2007**
	Speed Limiter Legislation for Trucks **(Truck)**	Implemented	Jan	2009
	Impaired Driving Law: Drivers with BAC .05-.08 will lose licence. **(IDL-BAC)**	Implemented	May	2009
	Distracted Driving	Implemented	Oct	2009
	Impaired Driving Law: Drivers under 21 will be subject to automatic suspension if any alcohol on breath. **(IDL-u21)**	Implemented	Aug	2010
	Impaired Driving law: Failure to comply with testing **(IDL-test)**	Implemented	Dec	2010
Québec	Distracted Driving Law	Implemented	Apr	2008
	Excessive Speeding Legislation (ESL)	**Implemented**	**Apr**	**2008**
	Impaired Driving Law	Implemented	Dec	2008
	Speed Limiter Legislation for Trucks **(Truck)**	Implemented	Jan	2009

5. Methodology

In this thesis, the Box-Jenkins methodology (Box and Jenkins, 1976) was used in the data analysis; it involved implementing an Autoregressive Integrated Moving Average (ARIMA) analysis in modelling the data. This was then followed by an interrupted time series analysis to assess the magnitude and significance of the effect that the intervention had on the series, if any, as demonstrated by (Box and Tiao, 1975).

After a thorough review of the literature, it was found that the ARIMA interrupted time series analysis (also known as ARIMA intervention analysis) was the most efficient method when it comes to evaluating the effects of an intervention or legislation. This technique has been used in multiple studies, both in the traffic safety field and in other disciplines.

The main advantage of ARIMA time-series analysis is that it accounts for the fact that time series observations are not independent. In other words, this means that for time series data, an observation (e.g. number of collisions) in a given period of time (t) is not independent of the observation in the previous time period (t-1) (Anderson et al., 2013). In statistical terms, this is known as serial correlation or autocorrelation between observations in consecutive time periods and it is a phenomenon that is common with time series (longitudinal) data.

Unlike time series models, regression models describe the relationship between a dependent or response variable and a set of independent or predictor variables where it is usually assumed that the errors are uncorrelated, which in turn, implies that the observations on the response are uncorrelated. In the special case of fitting regression models to time series data, these assumptions are relaxed and the models must be generalized to a class of models that detects serial correlations in the errors and accounts for their consequences. One such model that describes a variety of different autocorrelation structures is the autoregressive model, which represents part of the ARIMA structure.

While taking into account autocorrelations, ARIMA intervention analysis also permits the addition of covariates to the model, such as intervention terms. These terms can then be used to assess the intervention effects or to statistically control for other events that occur during the analysis period and have potential effects on the behaviour of the series. Finally, ARIMA modelling also provides a forecasting model, which could be used to predict future observations (collisions), while taking into account effects of the intervention (new legislation) (Abraham and Ledolter, 2009).

5.1 ARIMA

5.1.1 General Notation

The concept of ARIMA time series analysis is that it attempts to explain as much variation in a series of observations as possible before attributing any variation to exogenous factors, such as the implementation of a new law. As evident from the name, in an ARIMA analysis the time series (Y_t) is assumed to follow an Autoregressive Integrated Moving Average process, which includes three terms (p, d, q):

$$\text{ARIMA } (p, d, q)$$

Where, p represents the number of autoregressive (AR) terms; d represents the number of differences required in the case of a non-stationary series; and q represents the number of moving average (MA) terms.

The autoregressive term AR represents the lasting effects of previous observations on the current and future observations of the series; this implies that, in order to predict future values, an AR process regresses past values of the same variable (i.e. the series is regressed on itself, hence the name) (Cryer and Chan, 2008). The moving average term (MA) represents the lasting effects of random shocks that have occurred in the past on the future values of the series. In other words, the MA process models the lagged effects of a certain random event in the past on future observations.

When the time series data include seasonal variation, the ARIMA model is often extended to account for that variation using additional seasonal terms; in that case, the model becomes the following:

$$\text{ARIMA (p, d, q)(P, D, Q)}_{\text{s}}$$

Where, s represents the number of periods per season and the uppercase terms represent the seasonal part of the model.

The notation of the ARIMA model then proceeds as follows. Let Equation 1 represent the time series behavior, where Y_t is the observation at time t, and let α_t (error term) be a white noise process,

$\alpha_t \sim N(0,\sigma^2)$. If B were to represent the backward shift operator of the period, defined such that $B^k Y_t = Y_{t-k}$, then the ARIMA equation can be written as follows:

$$(1-\varphi_1 B^1 - ....\varphi_p B^p)(1-\phi_1 B^{(s\times 1)} ... - \phi_P B^{Ps})(1-B)^d (1-B)^D Y_t = (1-\vartheta_1 B^1 - ...\vartheta_q B^q)(1-\theta_1 B^{(s\times 1)} ...\theta_Q B^{Qs})\alpha_t \quad \text{------------------------} \quad (1)$$

Where, $\varphi_1 to\ \varphi_p$ are the non-seasonal AR parameters; $\emptyset_1\ to\ \emptyset_P$ are the seasonal AR parameters; $\vartheta_1\ to\ \vartheta_q$ are the non-seasonal MA parameters; and $\theta_1\ to\ \theta_Q$ are the seasonal MA parameters.

5.1.2 Box-Jenkins Procedure

The Box-Jenkins methodology is a four-step iterative procedure. The steps, listed below, are applied to the pre-intervention data to develop the ARIMA model, which is then combined with a transfer function to perform the intervention analysis. Since the methodology works only for a stable dataset, the effects of the seasonal variation within the data as well as long-term trends in the data must be removed before applying any of the steps that follow:

1. **Tentative identification**: In this stage, historical data are used to tentatively identify an appropriate Box-Jenkins model.
2. **Estimation**: The data are then used to estimate the parameters of the tentatively identified model.
3. **Diagnostic checking**: To check the adequacy of the tentatively identified model, various diagnostics are performed at this stage. If needed, an improved model is suggested; this model is then regarded as the new identified model. If a new model is identified, steps 2 and 3 are repeated.
4. **Forecasting**: Once the final model is obtained, it can be used to forecast time series values.

5.2 Intervention Analysis

Intervention can affect the response in several ways. It can either transform the level of a series abruptly or after some delay, change the trend, or have other more complex effects. As first demonstrated by (Box and Tiao, 1975), transfer functions can be used to model an intervention effect and determine whether there is evidence that a change in the series has actually occurred and, if so, its nature and magnitude.

Intervention analysis, which can also be referred to as interrupted time series analysis, involves assessing the effects of an intervention by introducing an intervention term into the ARIMA model. The intervention term is represented through a transfer function, which models the behaviour of the change in the series.

In intervention models, after suitable transformation, the general model for the ARIMA time series Y_t previously shown in Equation 1 becomes the following:

$$\begin{aligned}(1-\varphi_1 B^1 - \ldots \varphi_p B^p)(1-\phi_1 B^{(s\times 1)} \ldots - \phi_P B^{Ps})(1-B)^d (1-B)^D Y_t = \\ (1-\vartheta_1 B^1 - \ldots \vartheta_q B^q)(1-\theta_1 B^{(s\times 1)} \ldots \theta_Q B^{Qs})\alpha_t + \omega I_t\end{aligned} \quad \text{------------------------} \quad (2)$$

Where, ω is the intervention parameter representing an unknown permanent change in the mean due to the intervention; I_t is the function modelling the effect of the intervention on the mean level of the series; and all other parameters are as defined in Equation 1. The combination of ωI_t is also known as the transfer function.

The effect of the intervention on the mean function can often be specified using some parameters. Commonly used functions in this specification are the step and pulse functions. In this project, since the policy was expected to have permanent effects on the mean level of collisions, the intervention was represented using a step function (Equation 3). Due to the limited amount of post-intervention data, the policy was also assumed to have abrupt effects on the response.

$$I_t = \begin{cases} 0 & if \quad t < T \\ 1 & if \quad T \geq t \end{cases} \quad \text{------------------------} \quad (3)$$

Where, T is the time (t) at which the intervention was implemented.

5.3 Outlier Assessment

In any statistical analysis, it is necessary to inspect the data for extreme or unusual observations that may arise due to measurement errors or abrupt short-term changes in the underlying process. Such observations are often called outlier observations. In time series analysis, the first step in the analysis is generally an inspection of plots of the original data against time. Such plots help in defining the nature of the data and are really useful in identifying extreme observations. Nonetheless, statistically testing and accounting for those outliers is still required.

Since the presence of outliers seriously impacts the model selection process, the estimation of parameters, and consequently, forecasts, many iterative strategies for outlier detection exist (for example, see (Hillmer *et al.*, 1983). In practice, in has been observed that many time series are affected by outliers and they are more common than intervention variables, especially when a large heterogeneous set of time series is analyzed.

In a time series data analysis, testing for and accounting for outliers is not as straight forward as with cross-sectional data. The reason here is that, in time series data, autocorrelation exists between consecutive observations. Therefore, deciding whether an observation is an extreme value does not depend on the median of all observations alone, as in the InterQuartile range (IQ) assessment criteria (McGill et al., 1978). Testing for outliers in time series analysis should also take into account the value of observations before and after the data point of interest.

Fox (1972) defined two types of unusual observations in time series data: *additive outliers (AO)* and *innovative outliers (IO)*. An additive outlier occurs at time T if the underlying process is perturbed additively at time T so that the following process is observed:

$$Y_t^{'} = Y_t + \omega_A P_t^{(T)} \quad \text{------------------------} \quad (4)$$

Where, ω_A is the unknown change in the mean due to the outlier, $P_t^{(T)}$ equals 1 at $t=T$ and 0 otherwise. This is the indicator dummy variable flagging the time at which the outlier takes place (pulse dummy variable); $Y^{'}$ denotes the observed process that may be affected by some outliers and Y is the unperturbed process should there be no outliers. Thus, $Y_T^{'} = Y_T + \omega_A$ but $Y_T^{'} = Y_T$

otherwise, so the time series is only affected at time *T* if it has an additive outlier at *T*. An additive outlier can also be treated as an intervention that has a pulse response at *T* so that $m_t = \omega_A P_t^{(T)}$.

On the other hand, an innovative outlier occurs at time *t* so that the perturbed process can be written as in the following equation:

$$Y' = Y_t + \Psi_{t-T}\omega_I \qquad \text{------------------------} \qquad (5)$$

Where, $\Psi_0 = 1$ and $\Psi j = 0$ for negative *j*. Thus, an innovative outlier at *T* perturbs all observations on and after *T*, although with diminishing effect, as the observations is farther away from the origin of the outlier. The time *T* as well as the time series parameters are unknown and have to be replaced by estimates.

Detecting and correcting the effect of outliers is important because they can bias the parameter estimation, forecasts and seasonal adjustments. Significance tests for outliers can be performed based on standardized estimates. Automatic procedures to detect and adjust the series for outliers have been implemented in multiple packages of the statistical analysis software *R*; these include TSA, tseries and tsoutliers.

For the data analysis carried out in this thesis, testing for outliers was performed for all models using the TSA package in *R*; however, outliers were only accounted for when they were found to affect the model outcomes (Andrews and Pregibon, 1978).

6. Modelling

6.1 ARIMA Modelling:

As already mentioned, developing ARIMA models for time series data is an iterative process. In this thesis, the aim was to develop models for fatal, injury, PDO and total collision data from each of the three provinces. Consequently, the process described in the next few paragraphs and illustrated in Figure 11 was repeated for each response variable. Moreover, the process was also repeated while accounting for exposure.

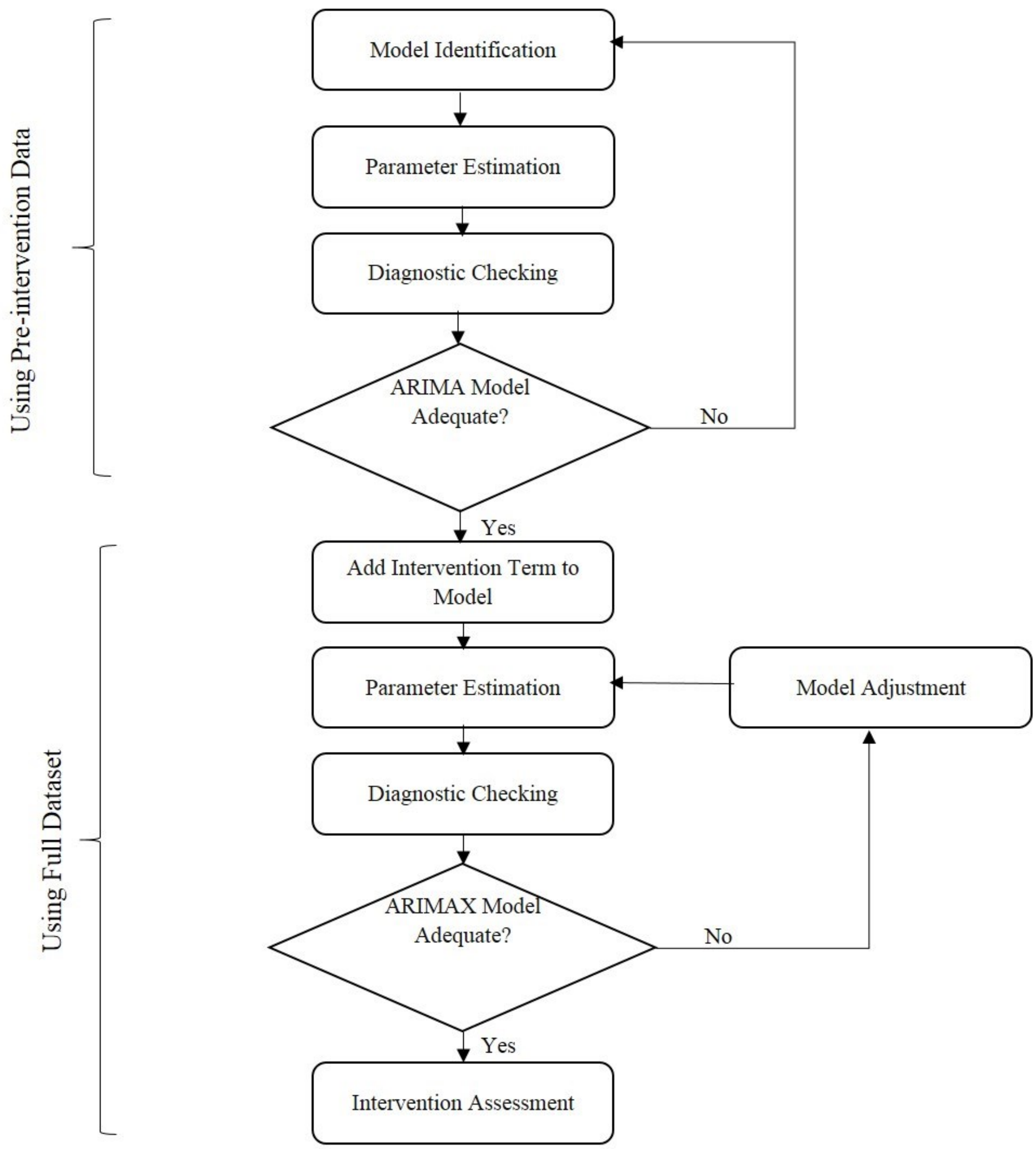

Figure 11: Modelling Framework

The dataset was first split into pre-intervention and post-intervention data. The pre-intervention data includes the observations, which were recorded before the legislation was implemented; this is also known as the baseline period. The post-intervention data, on the other hand, includes the observations after the policy was implemented.

The time trends of the pre-intervention data (Appendix B.6, figures 75-86) were first observed, in order to ensure that the data to be analyzed was stationary. In the case of a non-stationary series, the effects of random shock are permanent, and hence must be treated by differencing or transforming the series before performing the Box-Jenkins procedure. In addition to checking for non-stationarity by inspection, the Augmented Dickey-Fuller (ADF) test was run for each of the datasets, as seen in Table 6. The ADF test checks for the stationarity of a high-order AR process, in which a unit root indicates non-stationarity of the series. This test is available as part of the tseries package in *R* statistical software used in the analysis.

Table 6: Augmented Dickey-Fuller Test Results

Data	Augmented Dickey-Fuller Test (*p*-value)*
BC Fatal	0.01
BC Injury	0.01
BC PDO	0.015
BC Total	0.01
ON Fatal	0.01
ON Injury	0.014
ON PDO	0.01
ON Total	0.01
QC Fatal	0.09
QC Injury	0.195
QC PDO	0.046
QC Total	0.055

**p*-value <0.05 implies stationarity.

The alternative hypothesis was set as "stationarity," and hence, *p*-values less than 0.05 provide enough evidence to reject the null hypothesis, accepting the alternative hypothesis and indicating a stationary series. The test results show that all the data from BC and ON were stationary, and thus, no transformations were required for these provinces. In the case of QC, the fatal collision and injury collision data were both non-stationary in mean; this implied that the data had to be differenced before using it in the analysis. For the injury data, first differencing resolved the situation, while for the fatal data first differencing had to be combined with seasonal differencing for the data to become stationary. The variance was constant for all datasets; therefore, no transformations were required and the analysis was performed using the actual collision counts.

After the stationarity issues were resolved, correlation structures were explored. In each case, the plots of the ACF (autocorrelation) and the PACF (partial autocorrelation) functions, found in Appendix B, Figures 51-74, were observed for potential patterns. The ACF plot is a bar graph between the correlation coefficients of the series and its lags; whereas, the PACF plot displays partial-correlation coefficients of the series on its lags (i.e. the correlation between two variables unexplained by mutual correlation with other variables).

Exploring the plots helps identify an appropriate order for the tentative ARIMA model (i.e. it helps identify the number of AR and MA terms required in the baseline model). It is worth noting here that these models were updated in the diagnostic stage; hence, they only represented a starting point for the iterative process.

After identifying the order of the tentative model, the parameters of the model were estimated using only the pre-intervention data, with the reason being that the analysis aims to capture the trend in the data without the effects of the intervention. The analysis then attempts to replicate this trend in the post-intervention period while introducing a covariate, which models the effects of the interruption caused by the intervention (new legislation).

Diagnosis of the tentative model was then performed; this includes a number of steps:

1. **Ensuring that the residuals of the model represent white noise (i.e. the residuals are random with no patterns).** This was done by checking the ACF plots of the residuals and by running the Box-Ljung test. The Box-Ljung test is a portmanteau test that tests the overall randomness of the series based on a number of lags. A large p-value (≥ 0.1) indicates randomness, which was the case in all models developed in this thesis, as seen in Table 7.
2. **Checking the significance of the parameters in the selected model.** Insignificant parameters were dropped from the model only when it was seen that this improved the model quality.
3. **Comparing the Akaike information criterion (AIC) of different models.** Model selection is based on AIC minimization; hence, when comparing different models, the model with the lowest AIC was selected since it represented the best fit.

If the model did not satisfy the requirements, a different model was estimated and assessed. After several iterations, the ARIMA model that best satisfied the diagnostic checks for the pre-intervention data was identified. The order of the model selected in each case is shown in Table 7.

After finalizing the ARIMA model for the pre-intervention data, it was possible to advance to the next stage, which involved assessing the intervention effects. However, before performing intervention modelling using transfer functions, a preliminary analysis of the data was conducted by running a simple before-after comparison between the forecasted and the actual trends of the data in the post-intervention period.

Table 7: ARIMA Models Selected for Pre-Intervention Data

Province	Data	ARIMA Model Order	AIC	Box-Ljung *p*-value
ON	Fatal	$(0,0,0)(1,1,2)_6$	500	0.27
	Injury	$(0,0,0)(2,1,1)_{12}$	872	0.71
	PDO	$(0,1,1)(0,1,1)_{12}$	1079	0.10
	Total	$(0,1,1)(0,1,1)_{12}$	1097	0.13
BC	Fatal	$(0,1,2)(0,1,1)_{12}$	296	0.47
	Injury	$(1,1,1)(1,0,1)_{12}$	799	0.15
	PDO	$(0,1,1)(0,1,1)_{12}$	789	0.83
	Total	$(0,1,1)(0,1,1)_{12}$	794	0.82
QC	Fatal	$(3,1,1)(1,1,0)_{12}$	296	0.63
	Injury	$(0,1,1)(0,1,0)_{12}$	517	0.14
	PDO	$(1,1,1)(0,1,0)_{12}$	638	0.60
	Total	$(1,1,1)(0,1,0)_{12}$	645	0.86

6.2 Preliminary Investigation

At this stage of the analysis, the effects of the intervention were assessed by comparing the actual collision observations after the intervention had occurred with those forecasted using the ARIMA models developed for the pre-intervention data (i.e. the predicted observations if the policy had not been implemented). A paired sample t-test was used to determine whether the differences between the levels of the actual and predicted observations were statistically significant.

The results of the comparison for each case are found in Table 8. The plots seen in figures 27-38, Appendix B, illustrate the differences between the two levels. As evident from the results, a significant drop in all types of collisions was observed for Ontario. For BC, similar outcomes were observed, except that for injury collisions there was an insignificant increase. Finally, for Quebec, there was a significant drop in PDO and injury collisions only, while the comparison revealed that there was an increase in the mean level of fatal and injury crashes at the province, with the former being statistically significant.

Although the analysis provides some insight into the behaviour of the series in the post-intervention period, it remains oversimplified and fails to account for many confounding factors including, but not limited to, the effects other legislative changes could have on the series. Due to these limitations, intervention modelling was required to ensure rigorous analysis of the data is achieved.

Table 8: Mean Comparison Using t-Test

Province	Severity	Change in Mean	Actual Mean	Predicted Mean	*p*-value*
ON	***Fatal***	-15.64	44.18	59.82	<0.001
	Injury	-345.11	3703.31	4048.43	<0.001
	PDO	-1248.03	14018.08	15266.11	<0.001
	Total	-1181.28	17765.57	18946.85	<0.001
BC	***Fatal***	-5.58	21.36	26.94	<0.001
	Injury	+22.76	4474.69	4451.92	0.5644
	PDO	-1224.88	17323.85	18548.72	<0.001
	Total	-842.08	21819.90	22661.98	<0.001
QC	Fatal	+6.56	36.22	29.66	<0.001
	Injury	+12.30	2576.38	2564.08	0.6707
	PDO	-6974.20	7262.54	14236.73	<0.001
	Total	-5799.49	9875.13	15674.62	<0.001

**p*-value<0.05 indicates significance; significant drops shown in bold

6.3 Intervention Modelling

6.3.1 Procedure

In the process of ARIMA intervention analysis, the ARIMA model developed for the pre-intervention data is combined with a transfer function, which best captures the hypothesized change that occurred due to the intervention. This combined model is known as an ARIMAX model, where X denotes the addition of a transfer function to the ARIMA model. As already mentioned, it was assumed that the change was rapid and permanent in each case; hence, it was possible to model the behaviour using a step function.

After deciding on the behaviour of the intervention, the next stage was to estimate the parameters of a combined model (ARIMAX model) using the full dataset (pre- and post-intervention data). The same diagnostic checks of the Box-Jenkins procedure were also applied to the ARIMAX model and adjustments were made to the model when required. Other policies, which took place during the study period, were also integrated into the ARIMAX model. After finalizing the models, the significance of the model parameters, including the intervention term, were assessed.

All stages of analysis were carried out using statistical analysis software *R* v3.1.1, in which the TSA, tseries and lmtest packages were all used. In order to account for exposure, the number of collisions per million litres of gasoline sold was computed. The gasoline sale estimates represented the sales of fuel used by road motor vehicles only. The analysis was repeated twice, once using the number of collisions and then once using the number of collisions per million litres of gasoline.

6.3.2 Models

In this section, the intervention models developed for the data from all three provinces are presented. The orders of the ARIMAX models selected, along with the AIC estimate and the Box-Ljung test results, are presented in Table 9. Table 10 seen below and Tables 12-14 in Appendix A show the parameter estimates for each model, in addition to the standard error associated with each estimate. This also includes the estimates computed for the intervention terms in every model. Abbreviations used to represent the policy names, and more information about these policies can be found in Table 5. It is worth noting here that the models developed can be used to predict collisions of different severity levels in the three provinces, while taking into account the effects of the new policy.

Table 9: ARIMAX Models Selected

Province	Data	ARIMAX Model Order	AIC	Box-Ljung *p*-value
ON	Fatal	$(0,0,0)(1,1,2)_6$	852	0.718
	Injury	$(0,1,1)(2,1,1)_{12}$	1584	0.978
	PDO	$(0,0,1)(0,1,1)_{12}$	1970	0.781
	Total	$(0,1,1)(0,1,1)_{12}$	2008	0.637
BC	Fatal	$(0,0,2)(0,1,1)_{12}$	539	0.461
	Injury	$(1,1,1)(0,1,1)_{12}$	1152	0.461
	PDO	$(0,1,1)(0,1,1)_{12}$	1436	0.689
	Total	$(2,1,1)(0,1,1)_{12}$	1449	0.573
QC	Fatal	$(1,1,1)(0,1,1)_{12}$	1420	0.246
	Injury	$(0,1,1)(0,1,1)_{12}$	1418	0.726
	PDO	$(1,1,1)(0,1,1)_{12}$	1764	0.496
	Total	$(1,1,1)(0,1,1)_{12}$	1789	0.809

Table 10: Parameter Estimates for Developed Models

Model	Par	Est	S.E.	Model	Par	Est	S.E.	Model	Par	Est	S.E.	Model	Par	Est	S.E.
ON Fatal	sar1	-0.9999	0.001	**ON Injury**	ma1	-0.761	0.078	**ON PDO**	ma1	-0.997	0.048	**ON Total**	ma1	-1	0.065
	sma1	0.1306	0.095		sar1	0.193	0.105		sma1	-0.876	0.088		sma1	-1	0.127
	sma2	-0.8375	0.090		sar2	-0.257	0.107		IO-53	-5740.795	1587.036		**ESL-**	**1120.0265**	**616.188**
	ESL-	**-11.1188**	**2.239**		sma1	-1.000	0.178		**ESL-**	**947.935**	**514.619**		IDL-BAC-	-153.6688	1154.868
	IDL-BAC-	-7.7041	4.846		**ESL-**	**-96.023**	**165.450**		IDL-BAC-	-191.542	966.483		DDL-	-333.9928	927.111
	DDL-	2.1747	3.871		IDL-BAC-	-47.652	176.788		DDL-	-391.133	772.065		IDL-u21-	802.8618	1003.497
	IDL-u21-	2.5638	4.239		DDL-	-96.439	175.143		IDL-u21-	635.787	836.571		IDL-Test-	-3073.4316	963.526
	IDL-Test-	-7.7211	4.075		IDL-u21-	20.847	181.302		IDL-Test-	-3166.424	802.167		Truck	-472.0124	955.670
	Truck	0.4953	4.010		IDL-Test-	-93.029	175.539		Truck	-670.651	794.787				
					Truck	134.359	172.899								
BC Fatal	ma1	-0.0435	0.107	**BC Injury**	ar1	-0.0537	0.11	**BC PDO**	ma1	-0.7278	0.12	**BC Total**	ar1	0.1274	0.13
	ma2	0.3036	0.139		ma1	-0.9884	0.05		sma1	-0.6701	0.13		ar2	0.3335	0.12
	sma1	-0.6945	0.159		sma1	-0.7217	0.11		IO-36	6755.017	1101.13		ma1	-1	0.09
	ESL-	**-6.2786**	**2.394**		IO*-37	-879.512	230.66		IO-48	868.7397	1198.36		sma1	-0.6941	0.13
	IDL-	2.5322	1.946		**ESL-**	**357.6849**	**93.38**		**ESL-**	**-318.821**	**1245.12**		IO-36	7638.152	1140.96
	DDL-	-1.9927	2.220		IDL-	-314.036	71.36		IDL-	45.9295	816.11		IO-48	969.6554	1242.90
					DDL-	154.5838	85.34		DDL-	678.7431	948.25		**ESL-**	**-166.322**	**925.75**
													IDL-	-239.776	670.16
													DDL-	269.316	884.38
QC Fatal	ar1	0.196	0.162	**QC Injury**	ma1	-0.882	0.062	**QC PDO**	ar1	0.505	0.201	**QC Total**	ar1	0.422	0.180
	ma1	-0.929	0.143		sma1	-0.658	0.100		ma1	-0.779	0.129		ma1	-0.800	0.103
	sma1	-0.764	0.122		**ESL-**	**-325.148**	**79.751**		sma1	-0.794	0.120		sma1	-0.778	0.118
	ESL-	**-2.736**	**5.529**		IDL-	18.014	160.377		**ESL-**	**-2659.057**	**896.480**		**ESL-**	**-2670.688**	**968.310**
	IDL-	-14.079	7.950		Truck	109.722	158.522		IDL-	1208.964	804.291		IDL-	928.413	890.457
	Truck	11.370	7.779						Truck	858.213	967.196		Truck	807.939	1078.537

6.3.3 Goodness of Fit

For further verification of the model's fit, the fitted plots for each of the estimated models are presented; a sample of these plots for injury collisions is provided in Figures 12-14. The rest of the plots are supplemented in Appendix B.3, Figures 39-50. It is clear from the plots that the models are a good fit for the original data and that the behaviour of the series is captured in the models. The *p*-values for the Box-Ljung test, recorded in Table 9, also indicate that the residuals of each model are random; this behaviour is also reflected in the ACF plot of the residuals (not shown in the thesis).

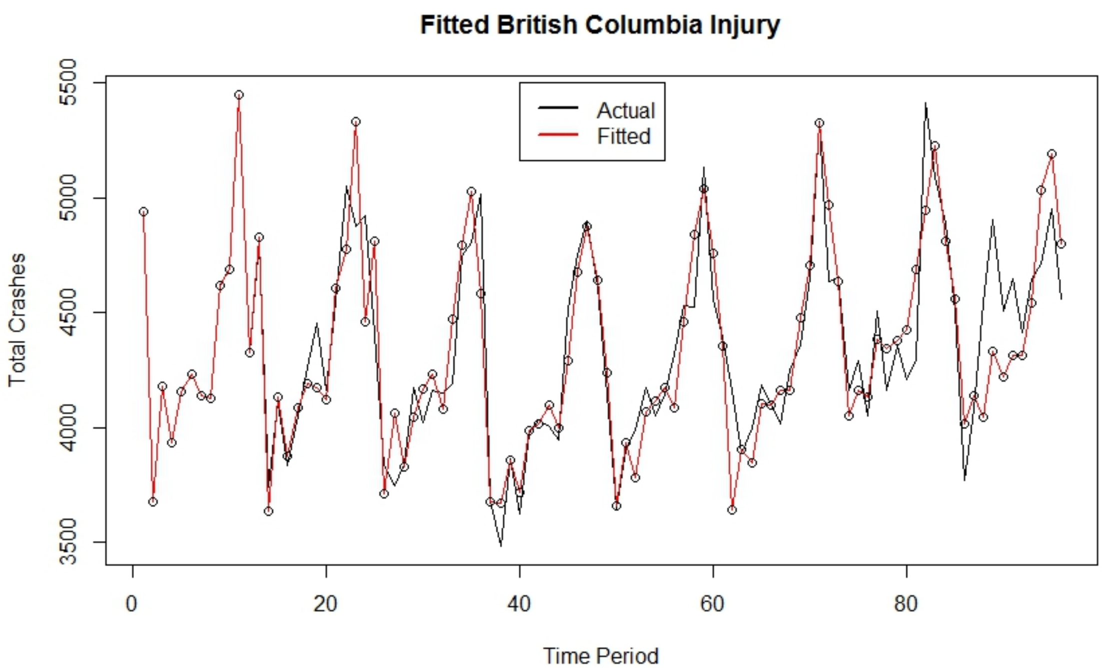

Figure 12: Fitted Plot (Injury Data BC)

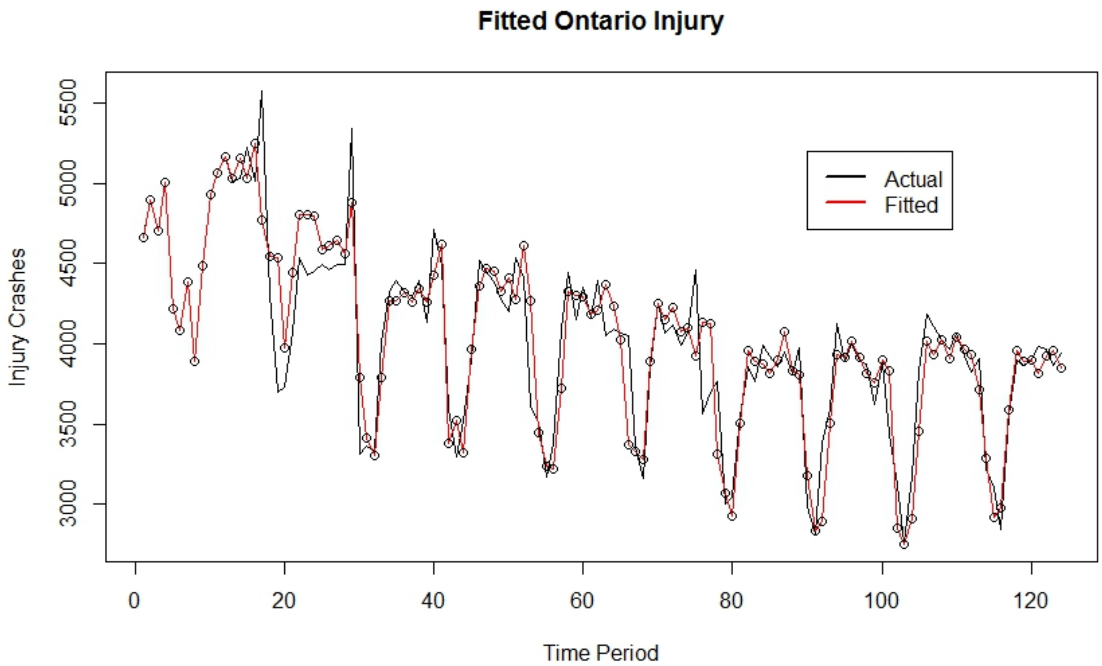

Figure 13: Fitted Plot (Injury Data ON)

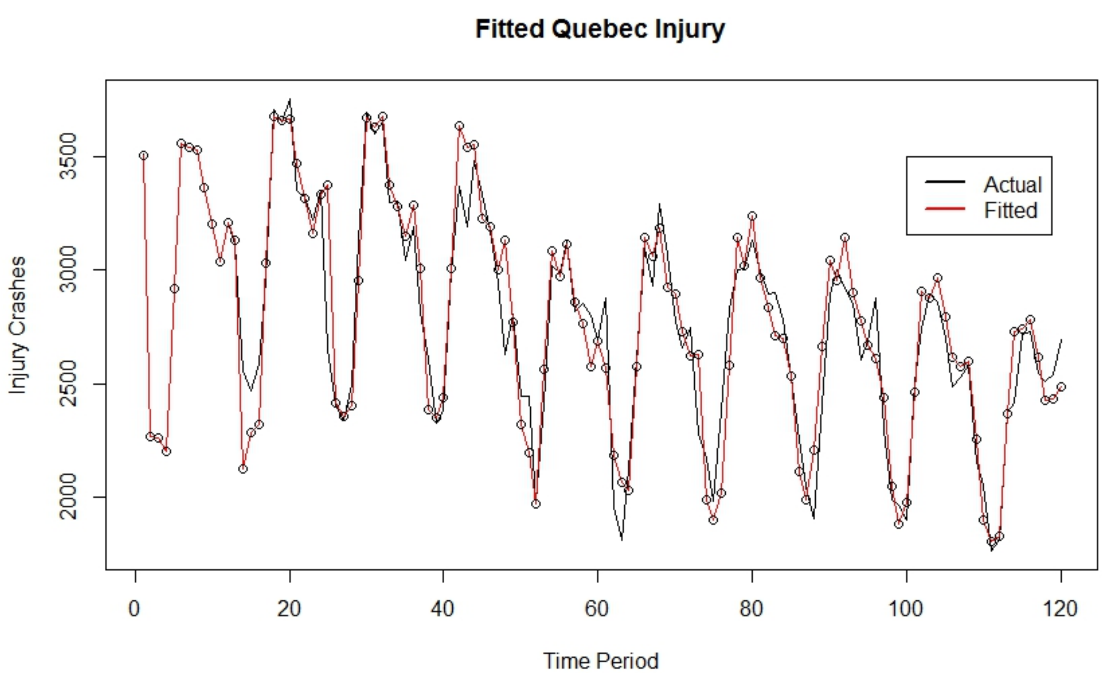

Figure 14: Fitted Plot (Injury Data QC)

7. Results & Discussion

In this section, the results for each collision severity level and at each of the three provinces are presented. The results were obtained using the models presented in the modelling section, shown in Tables 9 and 10. The outcomes varied among provinces and for different severity levels. The variation between the outcomes was in terms of the statistical significance of the intervention term, its magnitude and its direction. A summary of the effects is provided in Table 11 and illustrated through the bar charts seen in Figure 15, and Figures 87 and 88 (Appendix B). Datasets where the policy caused a significant reduction in collisions are marked with an asterisk and shown in italics. All other significant changes are marked with an asterisk only. In section 7.1, further elaboration on the results is provided; in addition, section 7.2 involves a thorough discussion of the findings.

7.1 Results

Table 11: Intervention Parameter Estimates and Significance

	Variable	Effect	*p*-value
Ontario			
	*Fatal**	*-11.12*	*<0.01*
	Injury	-96.06	0.561
	PDO	947.94	0.07
	Total	1120.03	0.07
British Columbia			
	*Fatal**	*-6.28*	*<0.01*
	Injury*	357.68	<0.01
	PDO	-318.82	0.798
	Total	-166.32	0.857
Quebec			
	Fatal	-2.736	0.621
	*Injury**	*-325.15*	*<0.01*
	*PDO**	*-2659.06*	*<0.01*
	*Total**	*-2670.69*	*<0.01*

*p-value<0.05 indicates significant effect

7.1.1 Ontario

In Ontario, the legislative change related to excessive speeding was associated with a statistically significant drop in fatal collisions; this observation did not change when the exposure-based analysis was conducted. The mean number of fatal collisions for the post-intervention period decreased by 11 fatal collisions when compared to the pre-intervention time period, as evident in Table 11.

A drop in the mean number of injury collisions was also observed in Ontario; however, further testing showed that this decrease was not statistically significant. The reduction was quantified to be around 96 injury collisions. The analysis, while accounting for exposure, confirmed the findings.

For PDO collisions in Ontario, the post-intervention period coincided with an increase in the number of collisions. Although this increase was not statistically significant at the 95% confidence level, the *p*-value of 0.07 indicates slight significance at a 90% confidence level. These findings did not change when the analysis was run for PDO collisions per million fuel litres sold. The increase was measured to be around 948 PDO collisions.

The results for total collisions did not differ much from the findings when analyzing PDO collisions only. For total collisions, the models showed that there was a slight increase in collisions, which was estimated to be around 1120.

7.1.2 British Columbia

In British Columbia, the effects of the excessive speeding policy on fatal collisions were similar to those observed in Ontario. The trend dropped by around six fatal collisions in the post-intervention period, a decrease that was deemed statistically significant, as can be inferred from the *p*-value shown in Table 11.

The findings with respect to injury collisions in BC suggest that the mean number of collisions increased in the period after the intervention. The increase was estimated at around 357, which was a statistically significant change.

It is worth mentioning here that the Impaired Driving Law (IDL), which was implemented in BC at the same time as the excessive speeding legislation but later discontinued, was associated with a significant drop in the mean number of injury collisions. This drop was similar, in magnitude, to the increase that was attributed to the excessive speeding law (see the IDL parameter estimate for BC Injury, Table 10). Thus, the drop in the number of injury collisions was attributed to the IDL. The trend seen in Figure 18, Appendix B, does indeed indicate that after the IDL was cancelled in November 2011, a slight increase in the level of injury collisions occurred.

Unlike injury crashes, the average number of PDO collisions in BC experienced a slight decrease during the post-intervention period. While the drop was insignificant, a reduction of around 318 crashes was observed. Similarly, the mean total accident counts decreased after the intervention, by about 166 crashes, a decrease that was also insignificant.

In each case, analysis using exposure-factored collision counts yielded the same results in terms of significance and the directional behaviour of the series after the intervention.

7.1.3 Quebec

Before presenting the results for Quebec, it is important to note that the excessive speeding legislation and a new distracted driving legislation (DDL) were enforced at the same time. Since it is impossible, statistically, to separate the effects of the two legislative changes on collision counts, the effects described in the next few paragraphs, and displayed in Table 11, cannot be fully accredited to the excessive speeding legislation alone.

After modelling fatal collision data for Quebec, it was observed that the post-intervention data had a slightly lower mean number of fatal accidents when compared to pre-intervention. The drop was quantified to be almost three collisions; however, unlike what was observed in Ontario and BC, the change was not statistically significant.

In contrast, an analysis of injury crashes showed a statistically significant fall in the mean number of accidents for the post-intervention period. The decrease was estimated to be around 325 collisions. Moreover, accounting for exposure did not change the conclusions.

As with injury collisions, the average number of PDO collisions also plummeted post-intervention. The drop was statistically significant and was quantified at about 2659. The significance of the decrease was confirmed after running the analysis while accounting for exposure. Similar behaviour was also observed for total collisions counts, where a significant decrease was also detected and valued at around 2670.

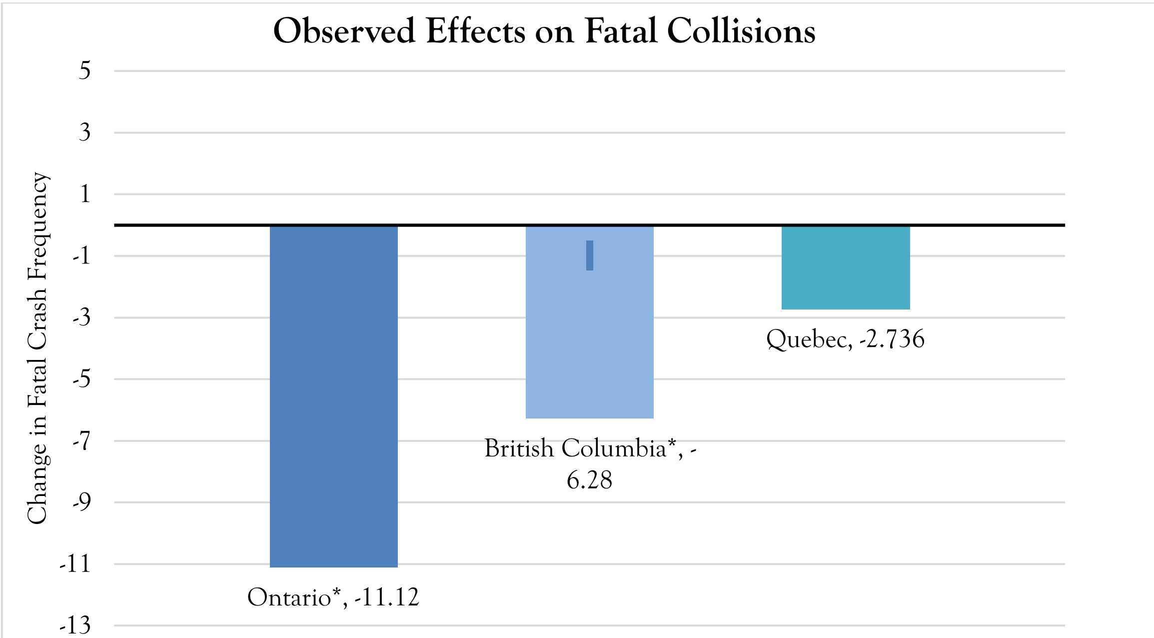

Figure 15: Change in Fatal Collisions in Post-Intervention Period

7.2 Discussion:

As evident from the findings listed in the previous section, the primary hypothesis that the excessive speeding legislation was effective in reducing fatal collisions is validated. The introduction of the policy was associated with a statistically significant drop in the mean number of fatal crashes in both British Columbia and Ontario.

In Quebec, a decrease in the fatal collisions was also present; however, the change was not significant. The failure to observe a statistically significant drop could be related to different publicity or enforcement rates in the province, although data are not available to verify this, and the fact that violations decreased in the province since the introduction of the law indicates otherwise (see Figure 17). Another reason could be related to the severity of the sanctions in Quebec. As already noted in the thesis, unlike Ontario and BC, in Quebec vehicle impoundment only takes place against re-offenders; hence, there is a difference in the severity of the legislation which could have impacted deterrence rates.

In the case of injury collisions, the results were not as consistent as for fatal collisions. The mean number of injury crashes dropped in Ontario, but the drop was not statistically significant. A drop was also observed in Quebec, and it was a significant one. Nonetheless, as already discussed in the previous section, this decrease cannot be fully accredited to the excessive speeding policy alone, and neither can the drops in fatal or PDO accidents observed in the province. Even though the decreasing trend in the number of licence suspensions in Quebec, seen in Figure 17, points towards the encouraging effect of the severe sanctions introduced as part of the excessive speeding law, an observation could not be made for BC suspension data, shown in Figure 16.

Though, as mentioned in the previous section, a statistically significant increase in injury collisions was accredited to the policy in BC, this finding must be interpreted with caution, as the excessive speeding policy was enforced at the same time as the Impaired Driving Law. In this case, it is challenging to isolate the effects of the two policies; nevertheless, due to the fact that the Impaired Driving Law was discontinued, the model was able to estimate separate effects for the two policies. This was done using the portion of the post-intervention period in which the impaired driving law was cancelled (26 observations). The issue here is that this is a relatively short period, which may not be sufficient to capture the full effects of the excessive speeding policy; thus, further analysis may be required to validate the finding.

The effects of the policy on PDO collisions were similar to those on total accidents. There were drops in the levels of those accidents in British Columbia and Quebec, the latter of which was statistically significant. On the other hand, in Ontario, the new law was associated with a slightly significant increase (at the 90% confidence level) in PDO crashes. Since the new legislation targets excessive speeders, who are more likely to contribute to severe collisions, it is reasonable for its effects on PDO collisions be minimal.

Another interesting outcome of the analysis is that combining the excessive speeding sanctioning program with other legislation seems to produce better results in terms of reducing PDO and injury crashes. The indicator here is that, in the case of Quebec, since April 2008, there was a significant drop in injury, PDO and total collisions; this did not occur in the other two provinces. These drops coincide with the enforcement of the excessive speeding policy and the distracted driving policy. Although it is statistically impossible to separate the effects of the two laws in Quebec, it could be the combination of the two policies that caused the drops.

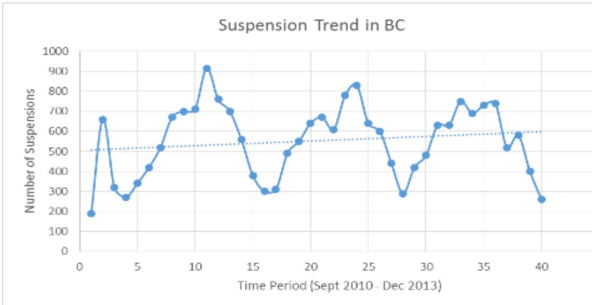

Figure 16: Suspensions in BC

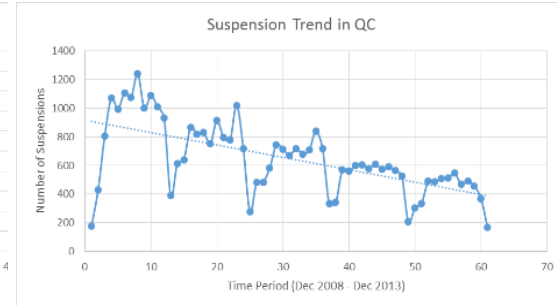

Figure 17: Suspensions in QC

7.3 ARIMA Intervention Modelling vs Analysis Using ARIMA Forecasts

When the outcomes of the two analysis techniques used in this thesis are compared, the outcomes vary significantly. The preliminary analysis, which included a simple comparison of ARIMA forecasted collision counts (without the legislation) and observed collision data (including the effects of the legislation), revealed that the excessive speeding legislation had a statistically significant effect in reducing all collisions in Ontario, only PDO and total collisions in Quebec, and fatal, PDO, and total collisions in British Columbia.

On the other hand, the more rigorous ARIMA intervention analysis found that in Ontario and British Columbia, only fatal collisions experienced a statistically significant drop after the implementation of the new legislation, while in Quebec, a drop in injury and PDO collisions was observed.

Comparing the findings of the two techniques from a traffic safety perspective, one can observe that the results of the simple comparative analysis using the ARIMA model forecasts seems to be less rational than the ARIMAX modelling. Since the policy changes target a specific group of speeding violators (excessive speeders), a reasonable outcome would be that the policy had a significant effect on reducing severe collisions; however, in the simple comparative analysis it is the PDO and total collision counts were observed to consistently drop across the three provinces, which indicates the limitations of the analysis. Moreover, the results in the preliminary analysis seem to exaggerate the effects of the policy, with significant drops observed in all but three of the datasets analyzed.

Therefore, it would be appropriate to conclude that, despite some research showing that forecasting using the simple univariate ARIMA model and the advanced ARIMAX model produce similar results (Ďurka and Pastoreková, 2012), ARIMAX modelling seems to be more effective when using the different models to test intervention effects.

8. Conclusions and Future Research

8.1 Concluding Remarks

The primary goal of this thesis was to analyze the effects of the excessive speeding legislation on collision frequency at varying severity levels in Canadian provinces that adopted the law. The dates at which the legislation was adopted varied for each province, as did the sanctions imposed against offenders. Moreover, the definition of excessive speeding also differed by province; in BC, it was 40km/h over the speed limit, in ON, it was 50km/h and in QC, the margin ranged from 40 to 60 km/h depending on the road class.

In Ontario, the law came into effect in September 2007 and involved immediate licence suspension and 7-day vehicle impoundment; after conviction the driver was also subject to a hefty fine of up to $10,000, demerit points and possible imprisonment. BC enforced the excessive speeding law in September 2010 and was the latest province in Canada to adopt the legislation; the penalties associated with the law included mandatory licence suspension and 7 to 60 days of vehicle impoundment (depending on recidivism). The offender was also responsible for storage and towing costs in addition to fines and demerit points.

Quebec implemented the law in April 2008, and under the law, offenders were subject to an immediate 7-day licence suspension and a doubled speed fine and doubled demerit points after conviction. Unlike the other two provinces, only repeat offenders were subject to vehicle impoundment for 30 days.

In this thesis, the intervention's effects on fatal, injury, property-damage-only (PDO) and total collision data from the three provinces were analyzed. In order to account for exposure, collision counts per million litres of fuel sold were also analyzed at each severity level and in every province. ARIMA intervention analysis was used to analyze the data, through which, a total number of 24 intervention models were developed (i.e., for 3 provinces, at 4 severity levels, with and without a proxy for exposure). In each model, the significance of the intervention was tested and the magnitude of the change was evaluated.

The findings revealed a statistically significant drop in fatal crashes in British Columbia and Ontario since the inception of the law; the decrease was quantified to be 22% and 18.3% respectively. The findings in this respect seem consistent with the few studies that looked at the safety effects of the policy. Brubacher et al. (2014) also found a statistically significant drop in fatal collisions for BC, quantified to be around 21%, while Meirambayeva et al. (2014a) concluded that the legislation in Ontario was associated with a significant drop in young male fatality rates. In Quebec, an insignificant drop of 5.5% was observed in fatal collisions, which could be due to the lower severity of the sanctions compared to the other two provinces.

In Ontario and Quebec, the law was also associated with a drop in injury collisions by 2.2% and 10.7% respectively, only the latter of which was significant. PDO and total collisions only saw a statistically significant drop in Quebec, but again, it is important to emphasize that all observations in Quebec shall not be attributed to the excessive speeding legislation alone.

In general, the outcomes of the analysis seem fairly reasonable, especially when considering that the legislative changes, which introduced the severe sanctions, were imposed against aggressive acts such as excessive speeding and stunt driving activities. Since (Nilsson, 1982) introduced the power models, it has been well accepted that, as speed increases, collision severity increases exponentially. As a result, even if the total number of collisions did not change after the introduction of the policy, it would be reasonable to say that the severity of these collisions has dropped.

Overall, the findings indicate a general deterrence effect of the excessive speeding legislation in Canadian provinces. This implies that the introduction of the new legislation seems to have affected the choice of speed among a large portion of road users (not only the excessive speeders) which, in turn, resulted in a reduction in collisions (fatal in particular). In other words, the threat of being caught under the new law seems to have caused speeders in general to change their speeding behaviour.

8.2 Research Contribution

This thesis contributes to the traffic safety field from a number of perspectives. From a research perspective, the thesis thoroughly analyzes the safety impacts of imposing severe sanctions on excessive speeders, an area that is clearly lacking in the literature. The work also supplements the literature with a new study assessing the safety effects of using severe sanctions (including vehicle-related sanctions) in general. Most studies that have assessed the impacts of severe sanctions are relatively old and in most cases were performed using limited post-intervention data.

In terms of practical contributions, the research provides decision makers with valuable information that enables responsible organizations and legislators to make educated decisions regarding whether or not to adopt the excessive speeding legislation. Furthermore, the thesis developed time series models that can be used to forecast collisions of different severity levels for the three provinces of interest. These models would enable interested parties to predict future collisions, while taking into account the effects of the new legislation. Finally, the thesis also details a comprehensive statistical framework, which could be used in the analysis of any intervention.

8.3 Limitations

As with any research work, this thesis has a few limitations, some of which could be addressed in future research. One important limitation of the analysis is that it was not performed on speed-related collisions only. With the legislation targeting excessive speeders, it would have been ideal to assess the effect of the policy on speed-related collisions alone, but this was not possible since the data was not readily accessible to the author at the time of analysis. Nonetheless, since speed is a factor in a large portion of severe collisions (Road Safety Canada Consulting, 2011, NHTSA, 2012), analyzing each severity level individually should have addressed this limitation to some extent.

In addition, the lack of information about the publicity and enforcement of the legislation meant that the effects of these factors could not be evaluated in this thesis. There is no doubt that publicity and enforcement have significant effects on the deterrence theory. The more publicity and the higher the enforcement that a legislative change receives, the more likely it is that drivers will change their behaviour in response to the new laws. Nevertheless, since the assessment was not actually carried out to compare the outcomes from the three provinces, this could be seen as a tolerable limitation of the study.

Another factor, which could be seen as a limitation of the study, is the inability to separate the impacts of the excessive speeding legislation and the distracted driving law in Quebec due to their enforcement on the exact same date. Unfortunately, this is something that is statistically impossible provided the analysis techniques available at the time of this research.

8.4 Future Research

Assessing the effects of the excessive speeding legislation only on speed-related collisions could be an opportunity for future research. Even though it has been found to have significant effects on collisions of all causes, a policy that targets a certain category of speeders would be expected to have more effects on speed-related collisions in particular. This would also reduce the number of confounding factors that could interfere with the assessment. For instance, when analyzing speed-related collisions only, it would be sufficient if only legislative changes with potential effects on speed are included in the modelling, and there would be no need to account for all other legislative changes.

Moreover, future work might also consider analyzing the specific deterrent effect of the legislative changes (i.e. understanding how the policy affects the behaviour of those who have already been caught under the new law). This is an extremely important yet challenging assessment, since it would require tracking the records of offenders who have been sanctioned under the new laws. The data could then be used to compare their records before and after being sanctioned, or compare their records with drivers who violated the law in the past but were not sanctioned. The main issue with performing such an analysis is that data are fairly difficult to obtain. (DeYoung (1999), Voas *et al.* (2000)) recommend that, in order to facilitate such an analysis in the future, vehicle-related sanctions should be linked instantly to the driver's record.

Another opportunity for future research would be including the effects of publicity and enforcement in the analysis; as already noted in the limitations, this would enable researchers to compare the effects of the policy between different provinces. Given the slight differences observed in this thesis, a comparative analysis might deliver interesting outcomes.

Finally, future research might also work on performing an aggregate analysis of the data for all provinces combined. This would involve compiling the data from all three provinces at each severity level and analyzing the impact of the intervention on collision data from the three provinces. Although such analysis would be subject to many confounding factors, the combined data set, which would include more observations per month, could provide further insight into the effects of the policy.

A more general approach for time series modelling, namely, the state-space time series analysis may be adopted as a methodology for further research. This includes the ARIMA time series models, Bayesian forecasting and models with time-varying coefficients as special cases. State space models of random processes are based on the so-called Markov Property, this could be used to model the effects of the policy while assuming the legislation, not only affected the level of collisions, but also caused drastic change in their behavior.

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Appendices Contents:

APPENDIX A (Supplementary Tables):

A.1 ARIMAX Model Parameter Estimates:

Table 12: British Columbia ARIMAX Model Estimates

	Par	Est	SE	Pval
Fatal	ma1	-0.044	0.107	0.684
	ma2	0.304	0.139	0.029
	sma1	-0.695	0.159	0.000
	ESL-	-6.279	2.394	0.009
	IDL-	2.532	1.946	0.193
	DDL-	-1.993	2.220	0.369
Injury	ar1	-0.054	0.106	0.611
	ma1	-0.988	0.049	<0.001
	sma1	-0.722	0.107	<0.001
	IO-37	-879.512	230.661	<0.001
	ESL-	357.685	93.382	<0.001
	IDL-	-314.036	71.364	<0.001
	DDL-	154.584	85.337	0.070
PDO	ma1	-0.728	0.124	<0.001
	sma1	-0.670	0.128	<0.001
	IO-36	6755.017	1101.133	<0.001
	IO-48	868.740	1198.358	0.469
	ESL-	-318.821	1245.121	0.798
	IDL-	45.930	816.112	0.955
	DDL-	678.743	948.246	0.474
Total	ar1	0.127	0.130	0.326
	ar2	0.334	0.120	0.005
	ma1	-1.000	0.089	<0.001
	sma1	-0.694	0.135	<0.001
	IO-36	7638.152	1140.962	<0.001
	IO-48	969.655	1242.904	0.435
	ESL-	-166.322	925.748	0.857
	IDL-	-239.776	670.165	0.721
	DDL-	269.316	884.377	0.761

Table 13: Ontario ARIMAX Model Estimates

	Par	Est	SE	Pval
Fatal	sar1	-1.000	0.001	<0.001
	sma1	0.131	0.095	0.169
	sma2	-0.838	0.090	<0.001
	ESL-	-11.119	2.239	<0.001
	IDL-BAC-	-7.704	4.846	0.112
	DDL-	2.175	3.871	0.574
	u21-	2.564	4.239	0.545
	IDL-Test-	-7.721	4.075	0.058
	truck-	0.495	4.010	0.902
Injury	ma1	-0.761	0.078	<0.001
	sar1	0.193	0.105	0.065
	sar2	-0.257	0.107	0.016
	sma1	-1.000	0.178	<0.001
	ESL-	-96.023	165.450	0.562
	IDL-BAC-	-47.652	176.788	0.788
	DDL-	-96.439	175.143	0.582
	u21-	20.847	181.302	0.908
	IDL-Test-	-93.029	175.539	0.596
	truck-	134.359	172.899	0.437
PDO	ma1	-0.997	0.048	0.053
	sma1	-0.876	0.088	<0.001
	IO-53	-5740.795	1587.036	<0.001
	ESL-	947.935	514.619	0.490
	IDL-BAC-	-191.542	966.483	0.646
	DDL-	-391.133	772.065	0.613
	u21-	635.787	836.571	0.717
	IDL-Test-	-3166.424	802.167	0.001
	truck-	-670.651	794.787	0.537
Total	ma1	-1.000	0.065	<0.001
	sma1	-1.000	0.127	<0.001
	ESL-	1120.027	616.188	0.069
	IDL-BAC-	-153.669	1154.868	0.894
	DDL-	-333.993	927.111	0.719
	u21-	802.862	1003.497	0.424
	IDL-Test-	-3073.432	963.526	0.001
	truck-	-472.012	955.670	0.621

Table 14: Quebec ARIMAX Model Estimates

	Par	Est	SE	Pval
Fatal	ar1	0.1958	0.1624	0.2279
	ma1	-0.9285	0.1429	<0.001
	sma1	-0.7642	0.1216	<0.001
	ESL-	-2.7357	5.5289	0.6208
	IDL-	-14.0789	7.9503	0.0766
	truck-	11.3696	7.7786	0.1438
Injury	ma1	-0.882	0.062	<0.001
	sma1	-0.658	0.100	<0.001
	ESL-	-325.148	79.751	<0.001
	IDL-	18.014	160.377	0.911
	truck-	109.722	158.522	0.489
PDO	ar1	0.505	0.201	0.012
	ma1	-0.779	0.129	<0.001
	sma1	-0.794	0.120	<0.001
	ESL-	-2659.057	896.480	0.003
	IDL-	1208.964	804.291	0.133
	truck-	858.213	967.196	0.375
Total	ar1	0.422	0.180	0.019
	ma1	-0.800	0.103	<0.001
	sma1	-0.778	0.118	<0.001
	ESL-	-2670.688	968.310	0.006
	IDL-	928.413	890.457	0.297
	truck-	807.939	1078.537	0.454

APPENDIX B (Supplementary Figures):

B.1 Time Plots:

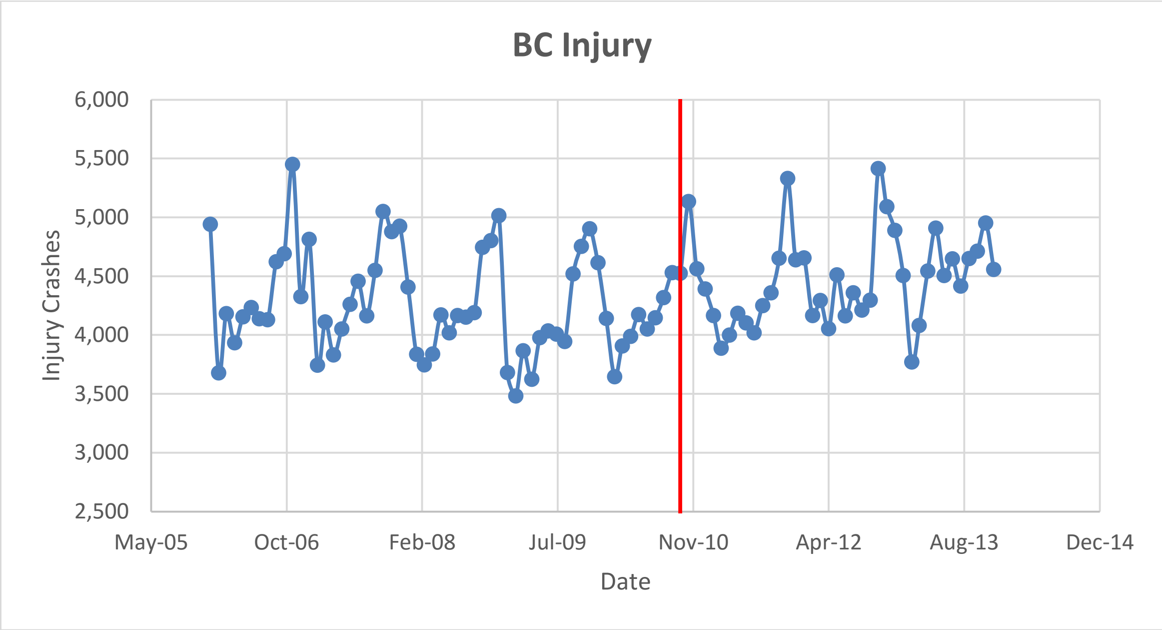

Figure 18: BC Injury Data Time Trend

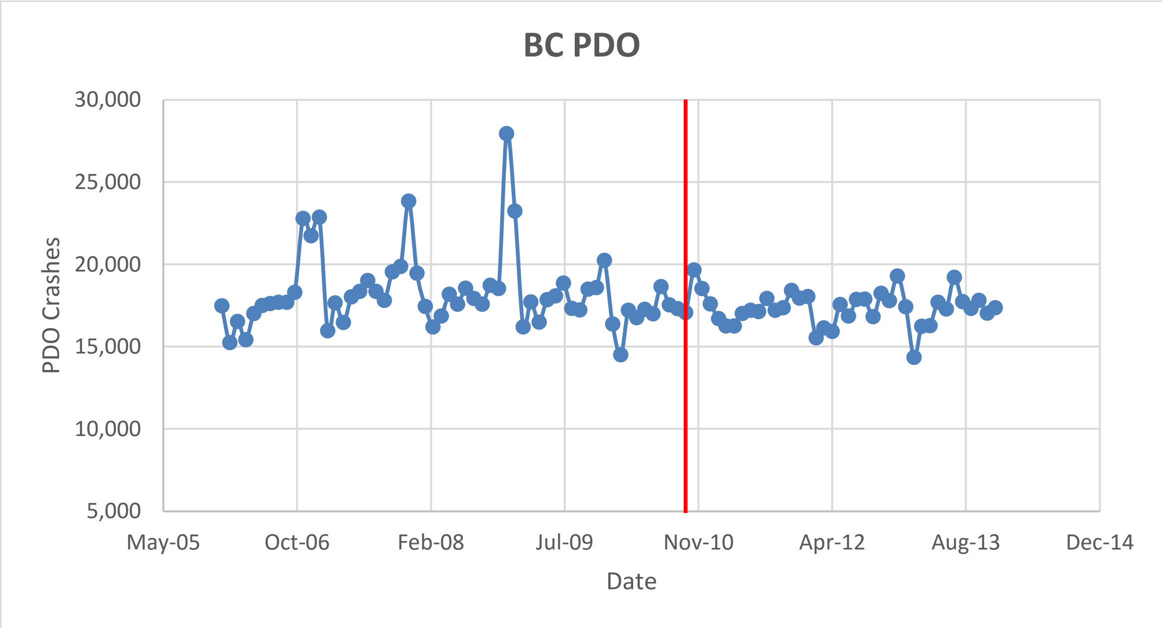

Figure 19: BC PDO Data Time Trend

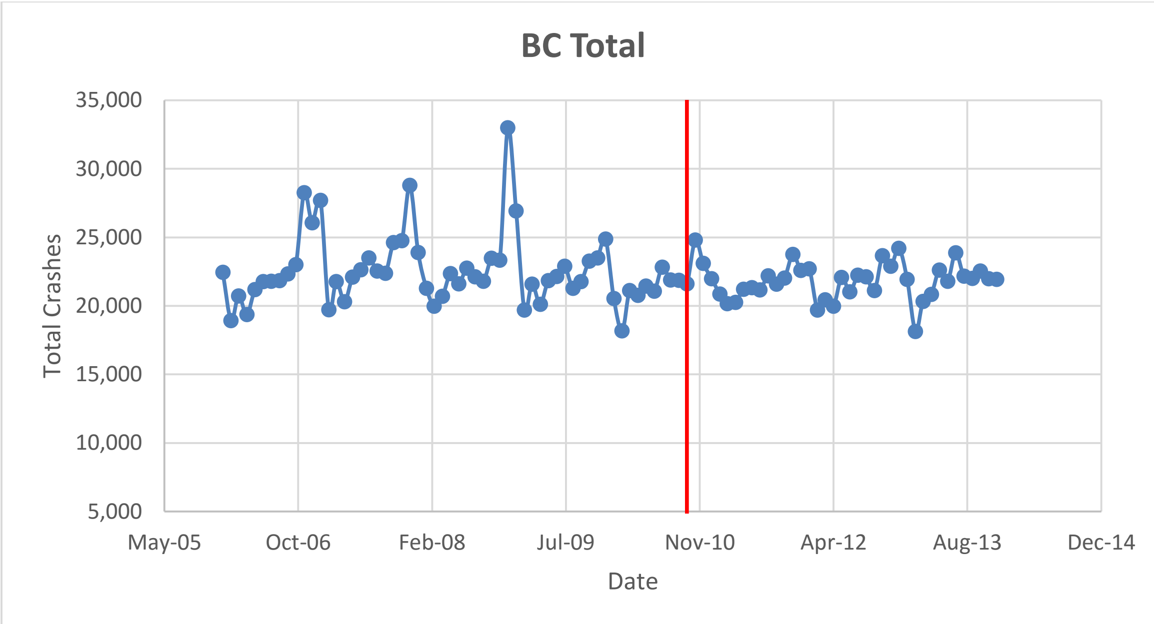

Figure 20: BC Total Data Time Trend

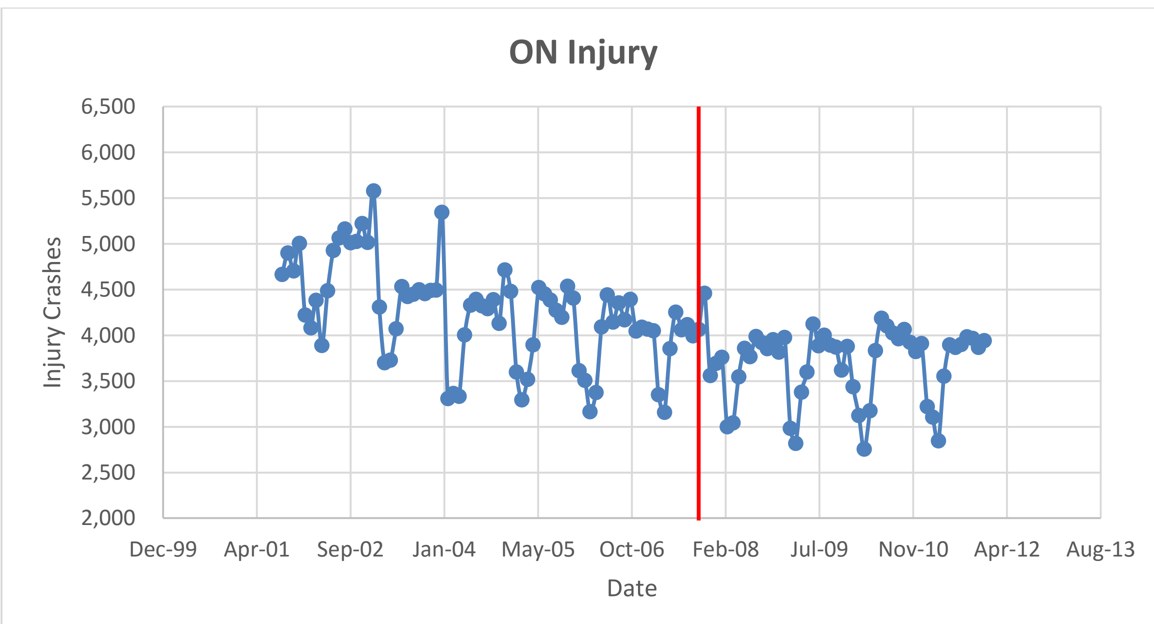

Figure 21: ON Injury Data Time Trend

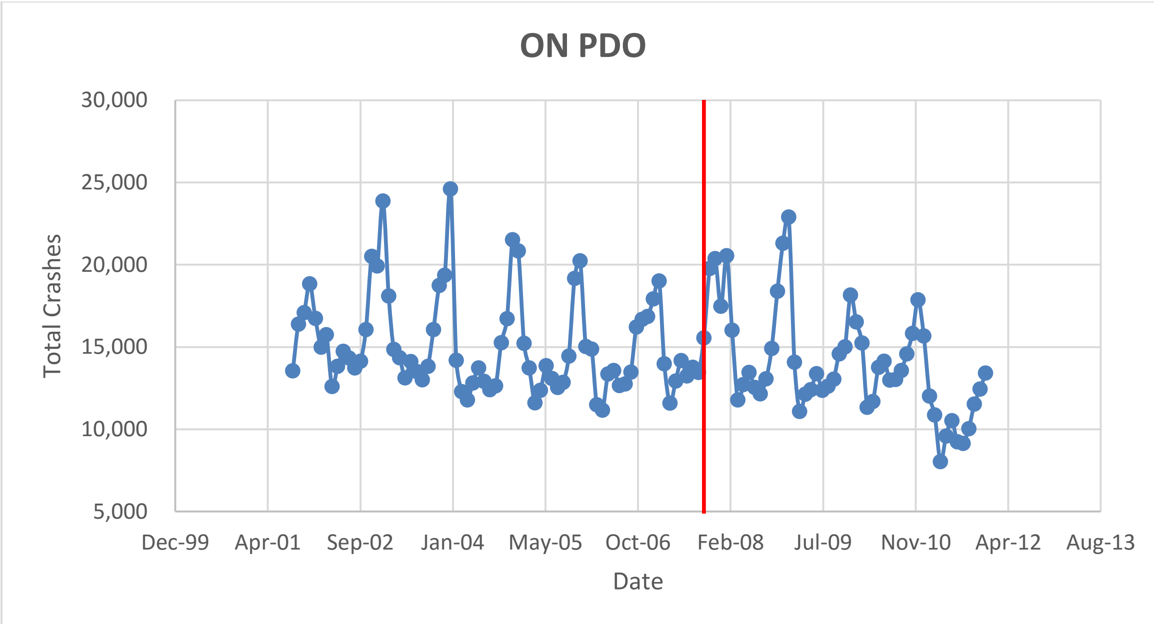

Figure 22: ON PDO Data Time Trend

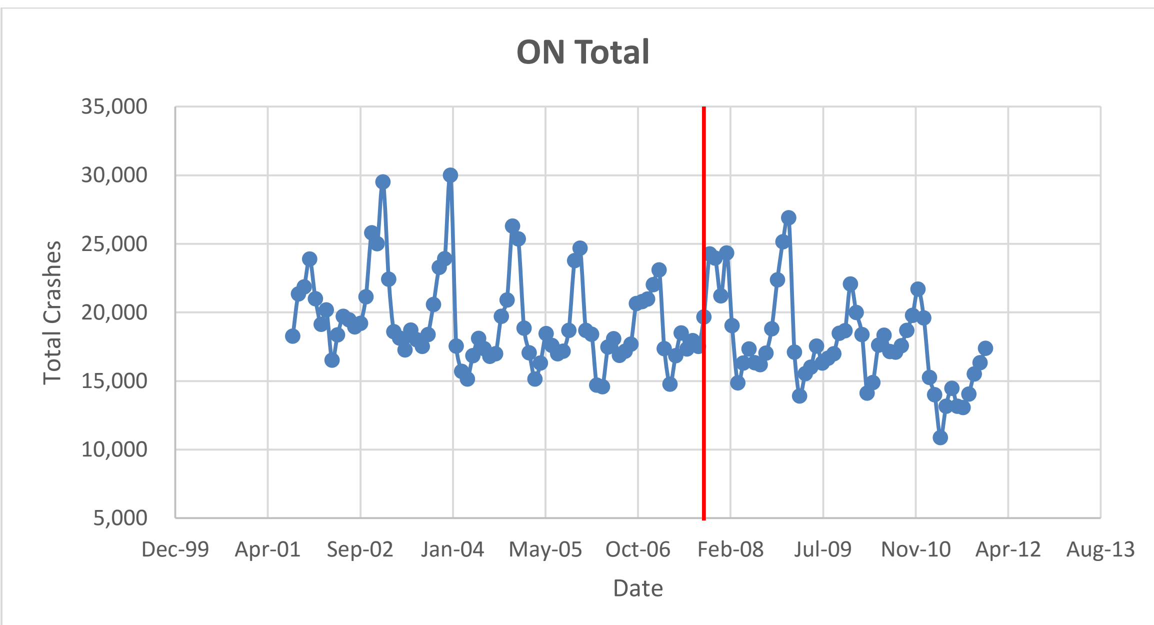

Figure 23: ON Total Data Time Trend

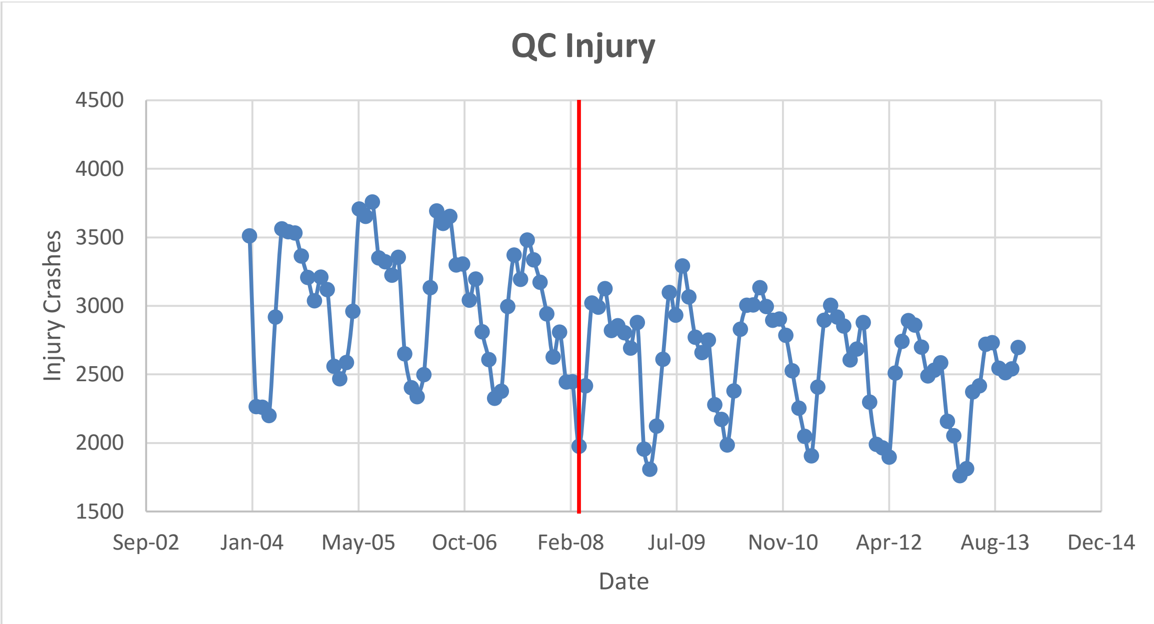

Figure 24: QC Injury Data Time Trend

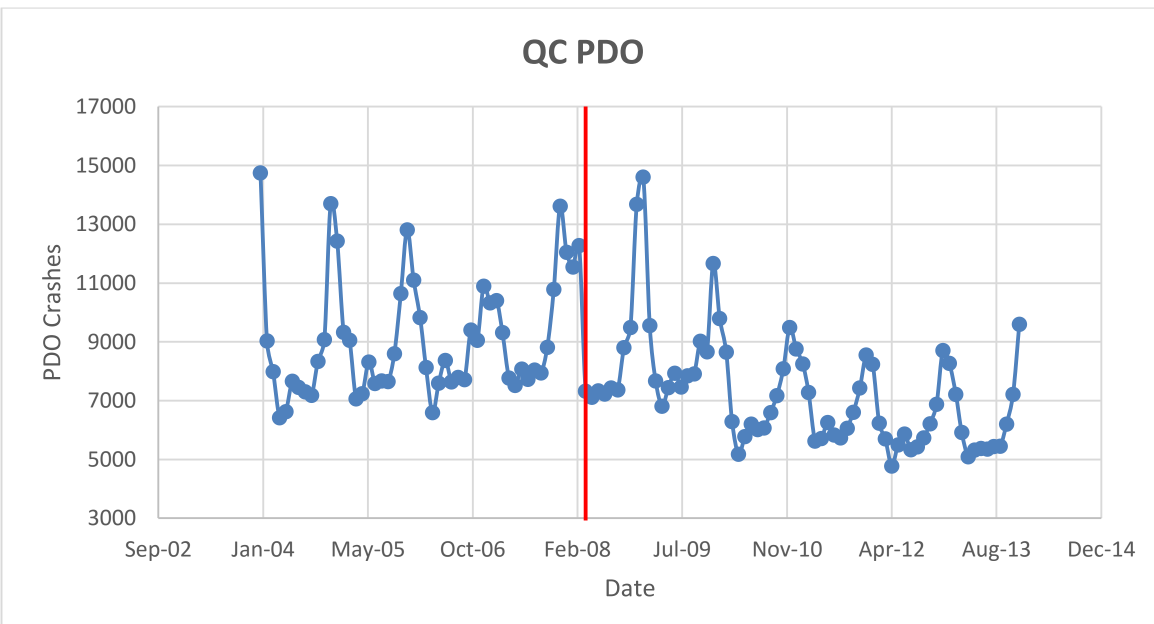

Figure 25: QC PDO Data Time Trend

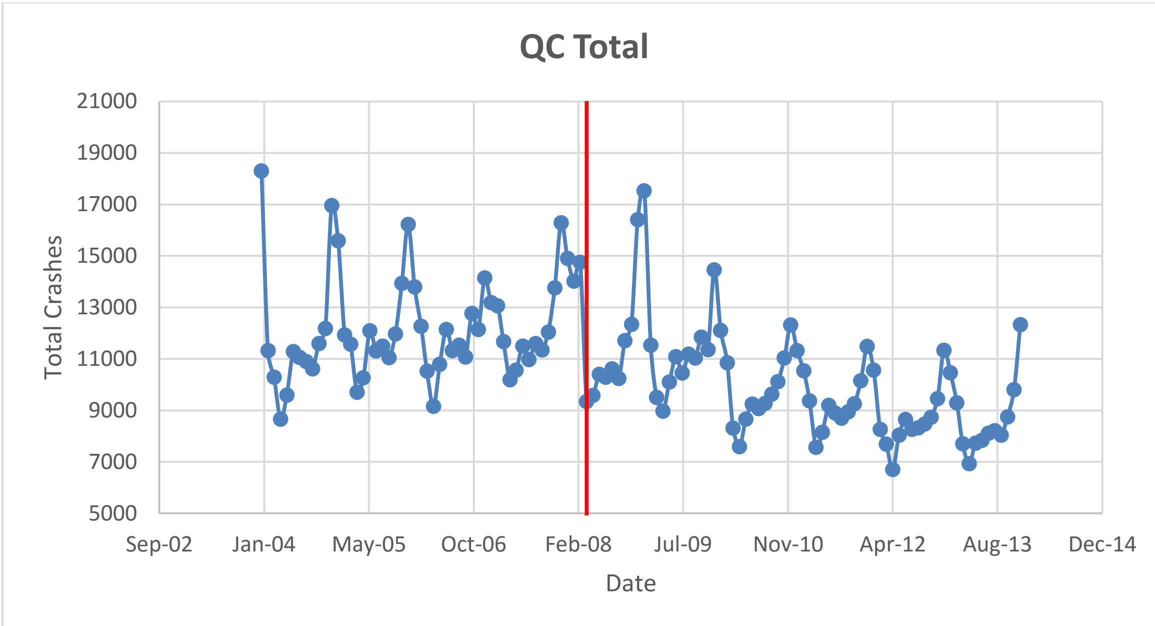

Figure 26: QC Total Data Time Trend

B.2 Mean (Predicted vs. Actual):

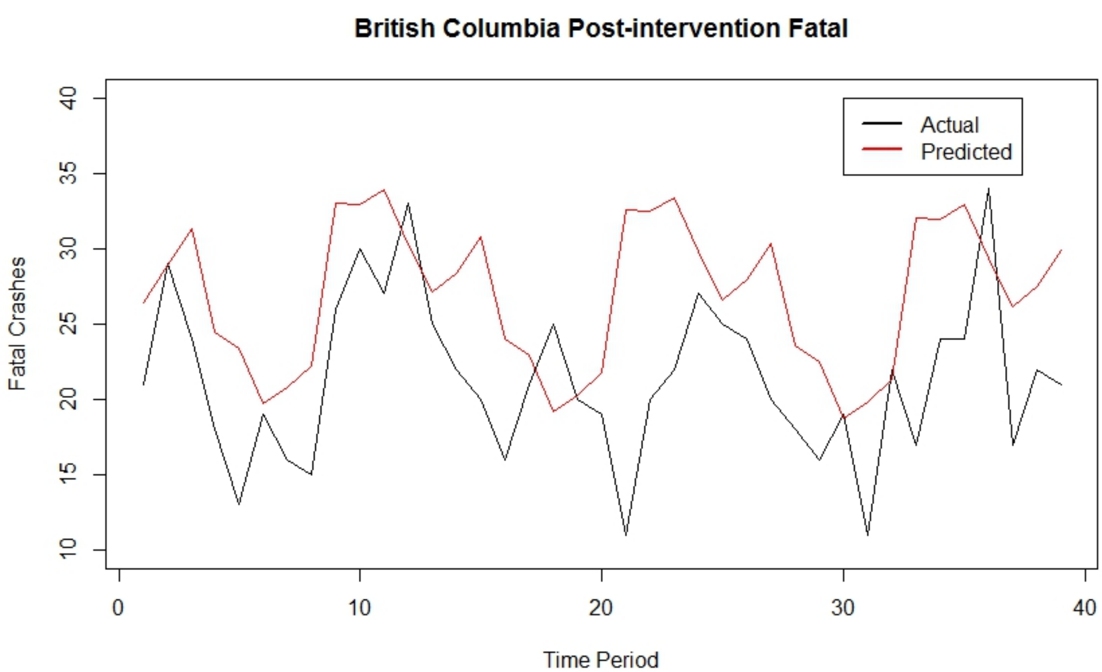

Figure 27: Mean Comparison (BC Fatal)

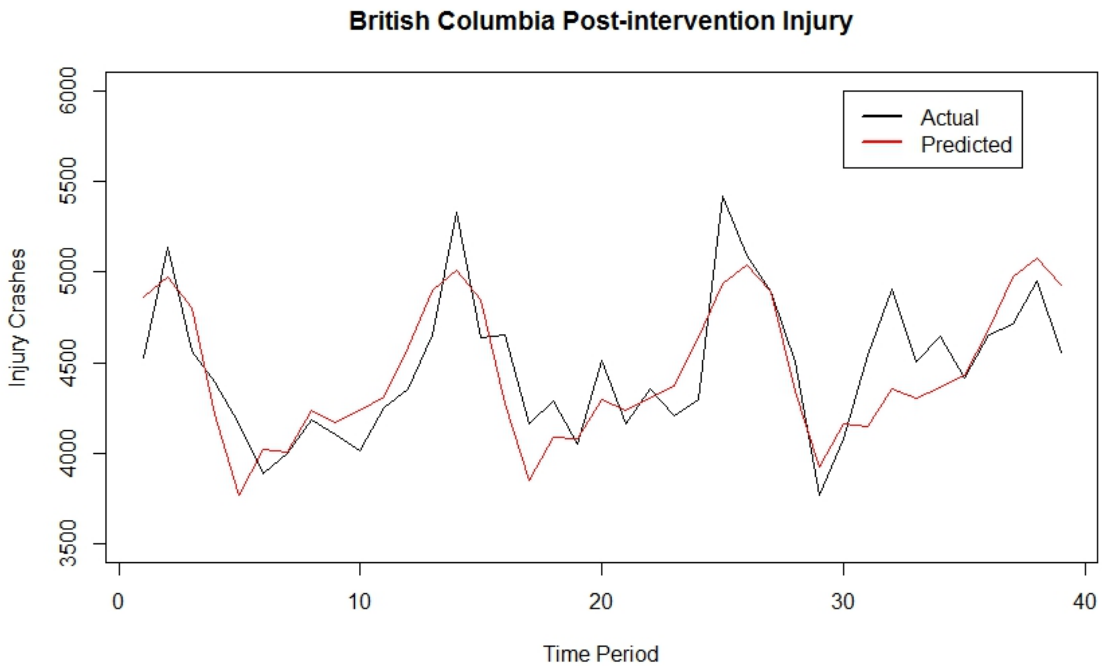

Figure 28: Mean Comparison (BC Injury)

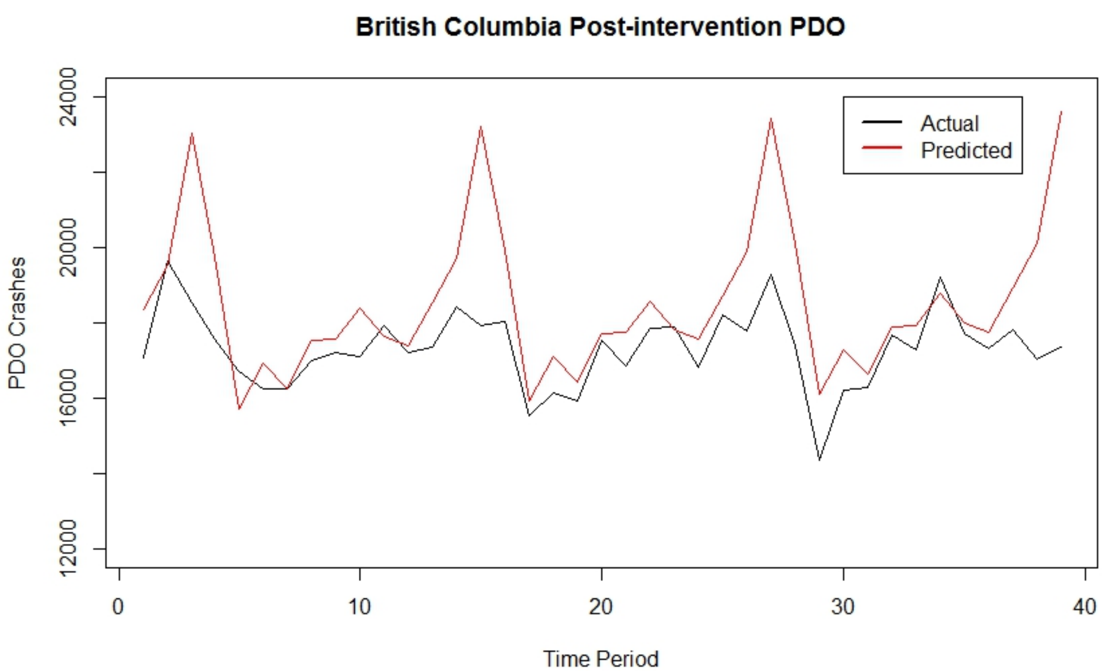

Figure 29: Mean Comparison (BC PDO)

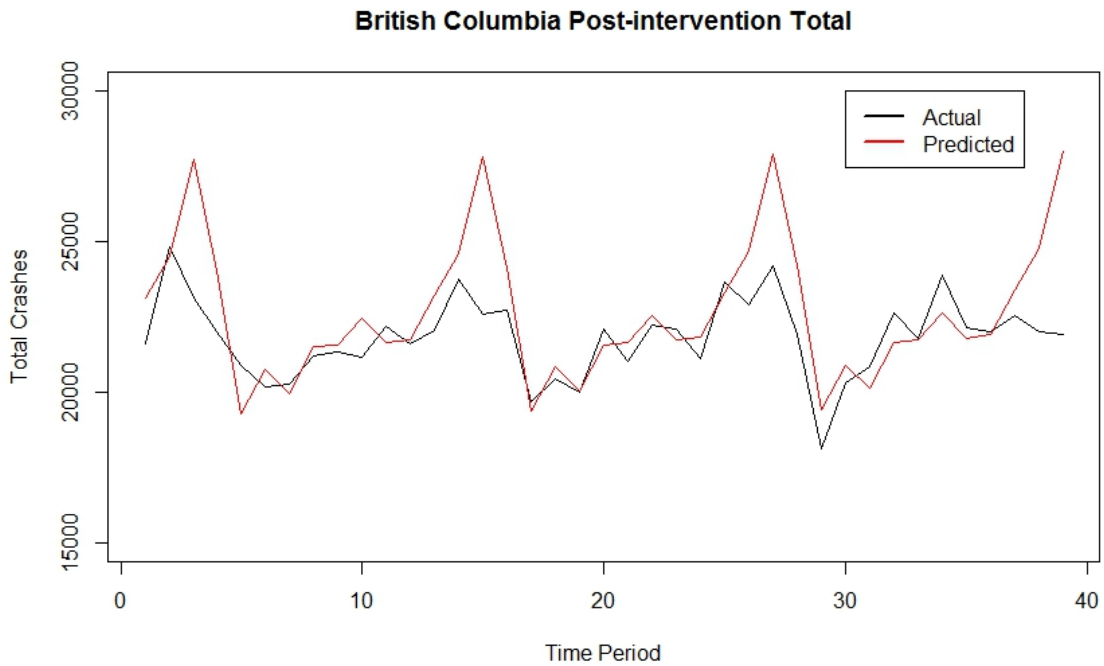

Figure 30: Mean Comparison (BC Total)

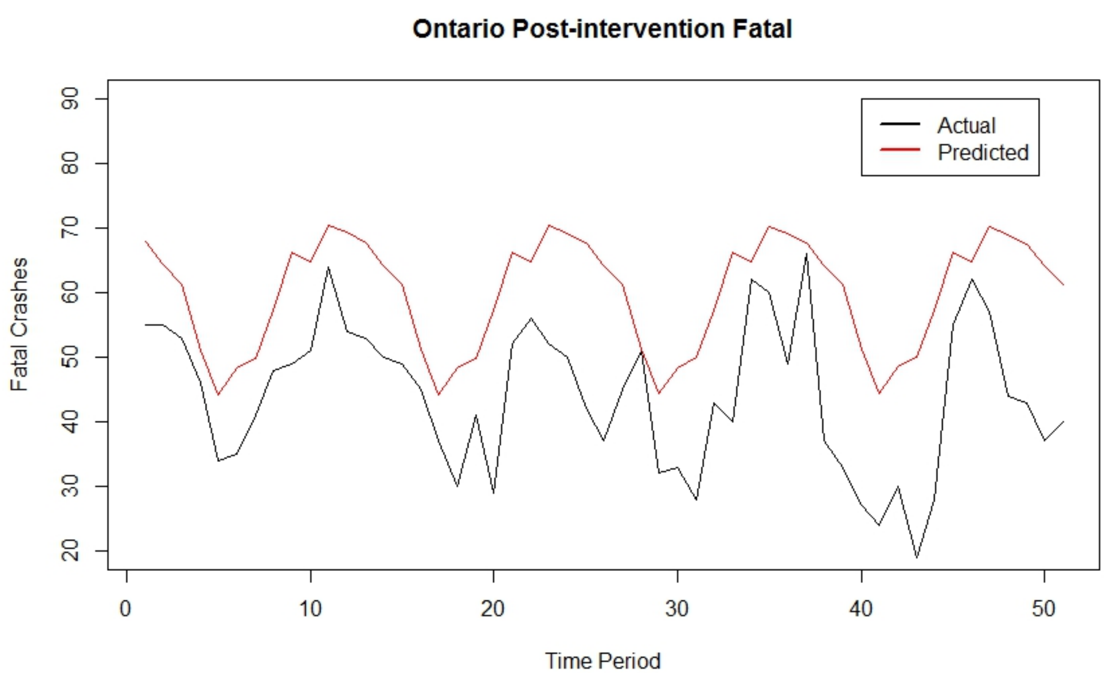

Figure 31: Mean Comparison (ON Fatal)

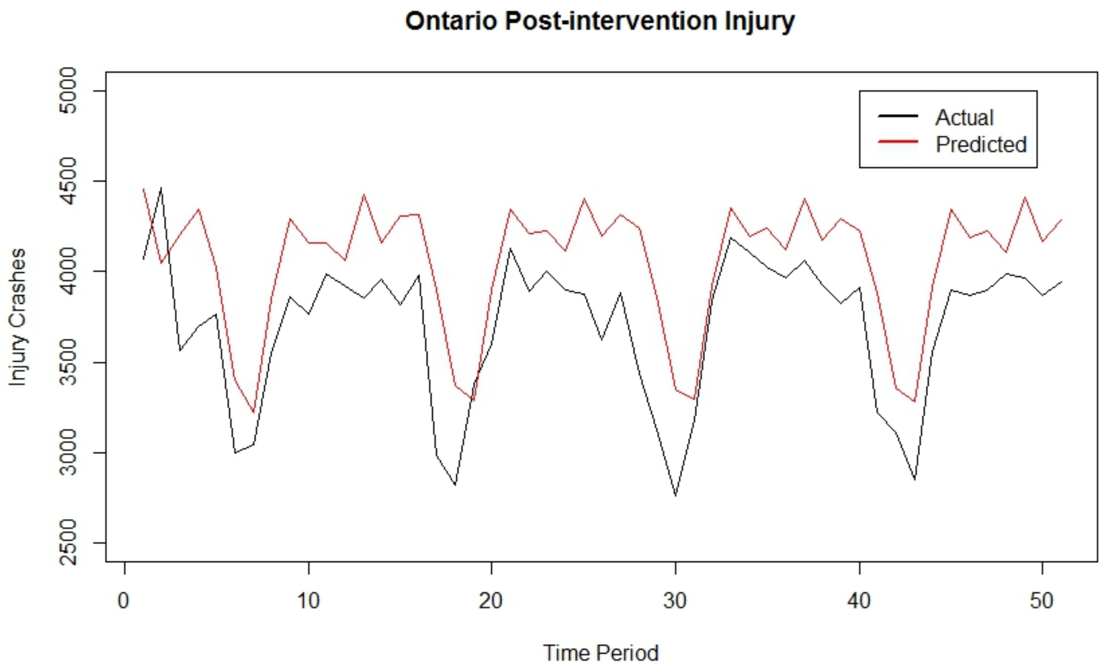

Figure 32: Mean Comparison (ON Injury)

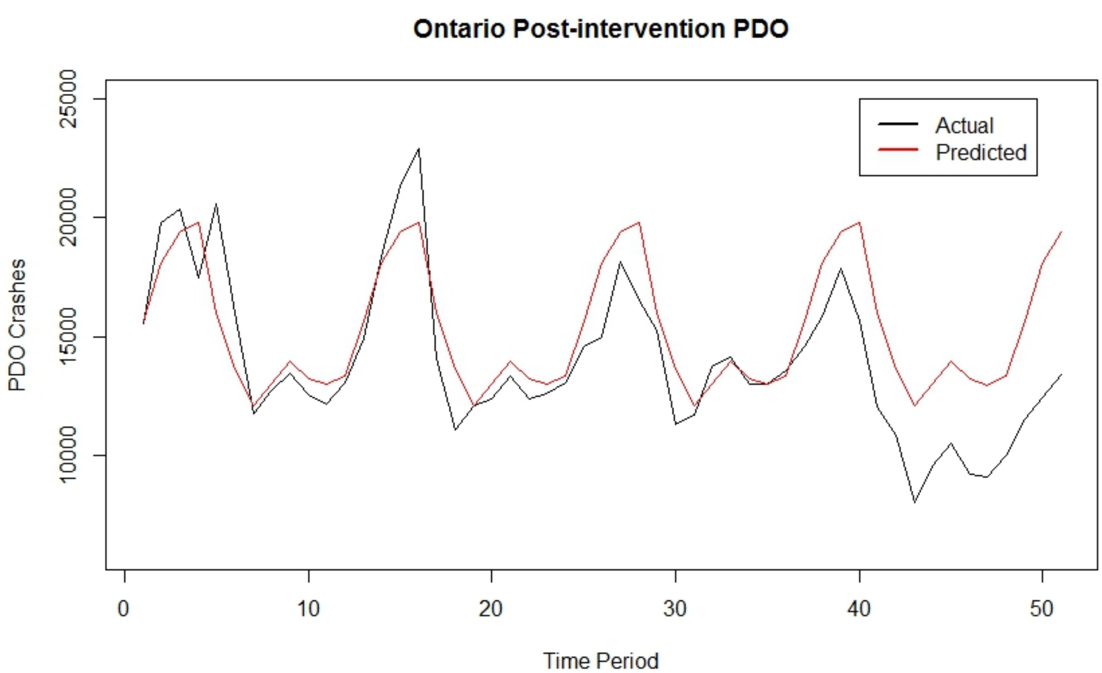

Figure 33: Mean Comparison (ON PDO)

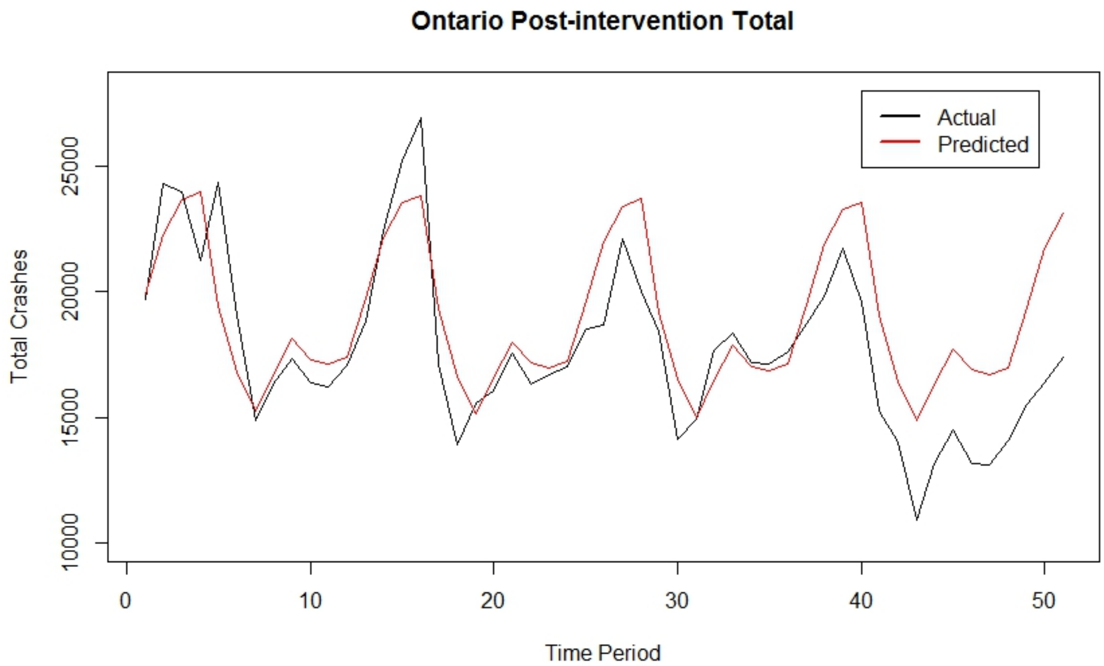

Figure 34: Mean Comparison (ON Total)

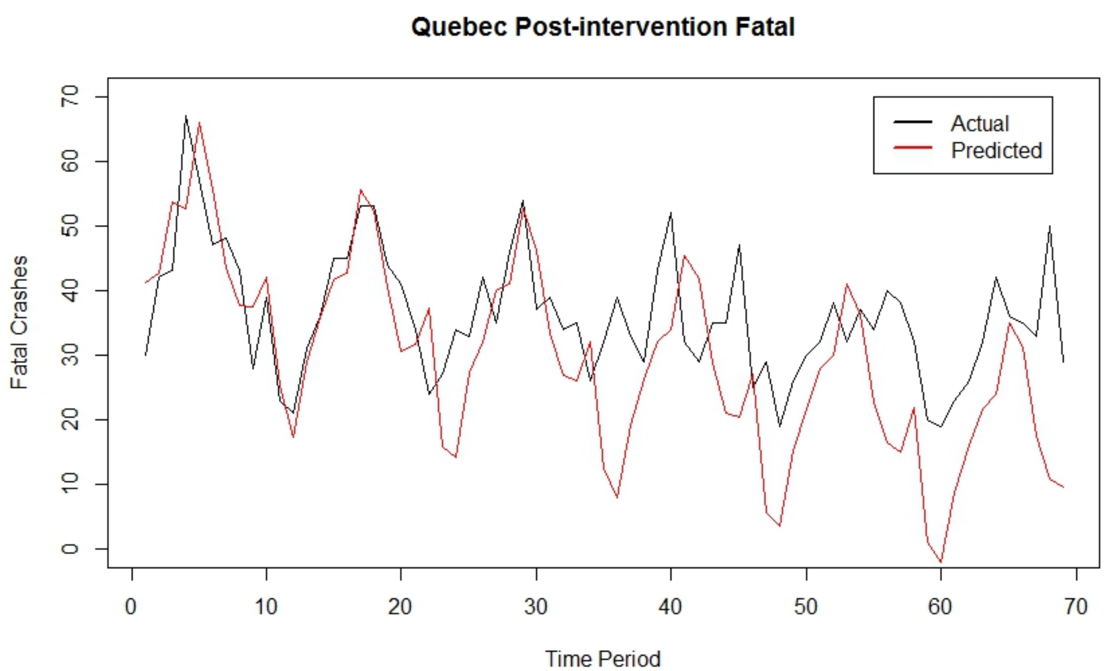

Figure 35: Mean Comparison (QC Fatal)

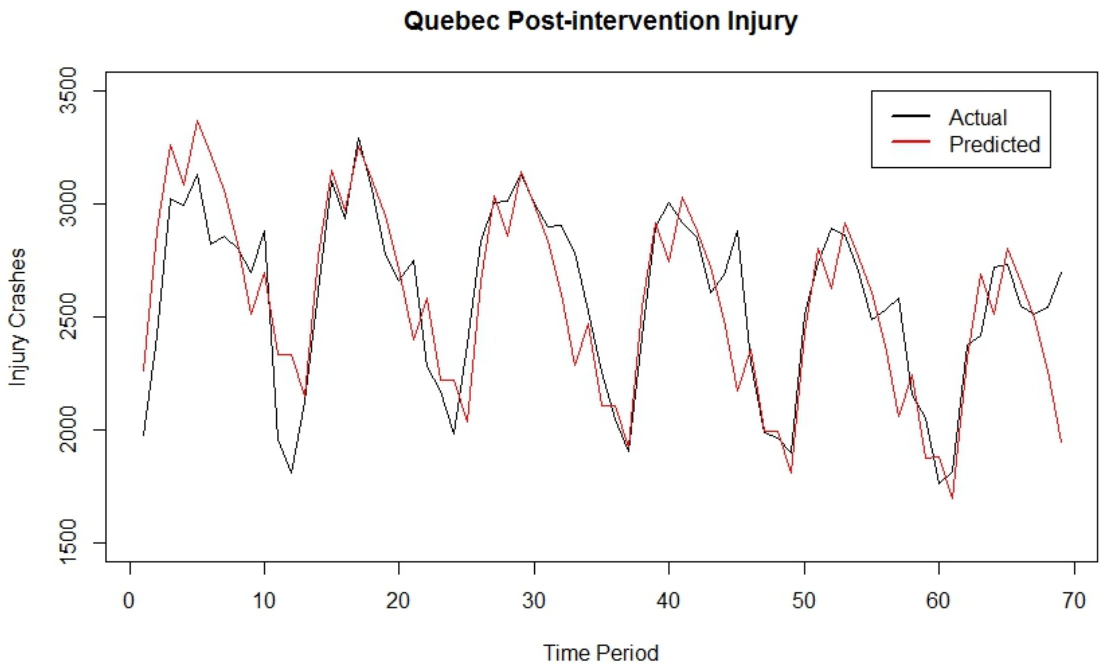

Figure 36: Mean Comparison (QC Injury)

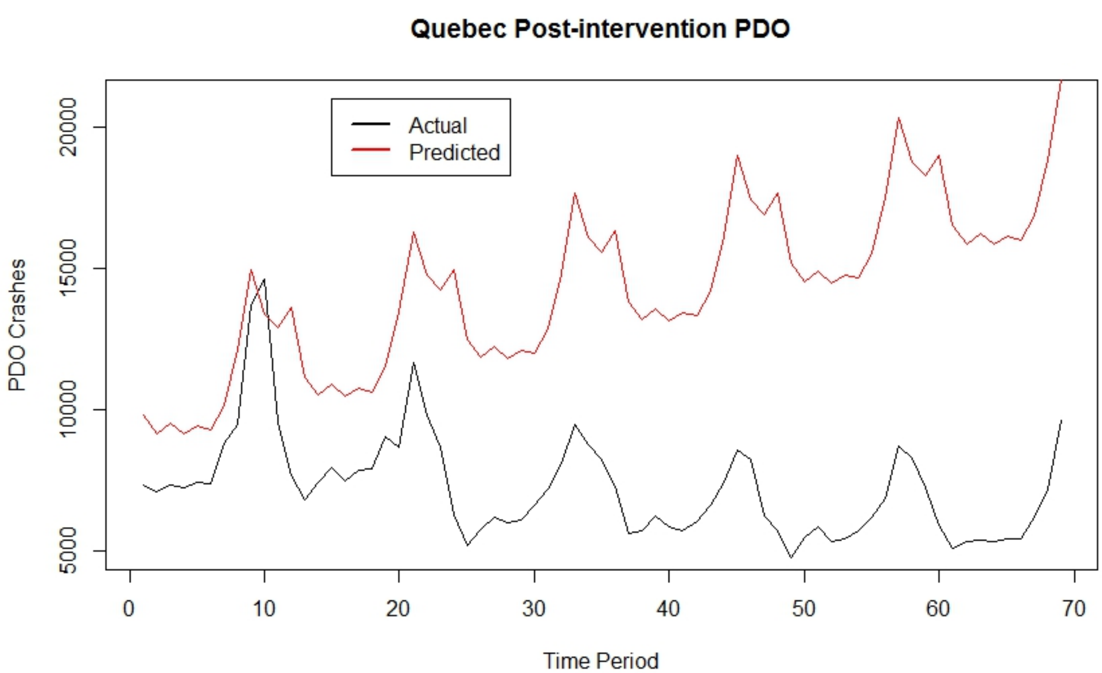

Figure 37: Mean Comparison (QC PDO)

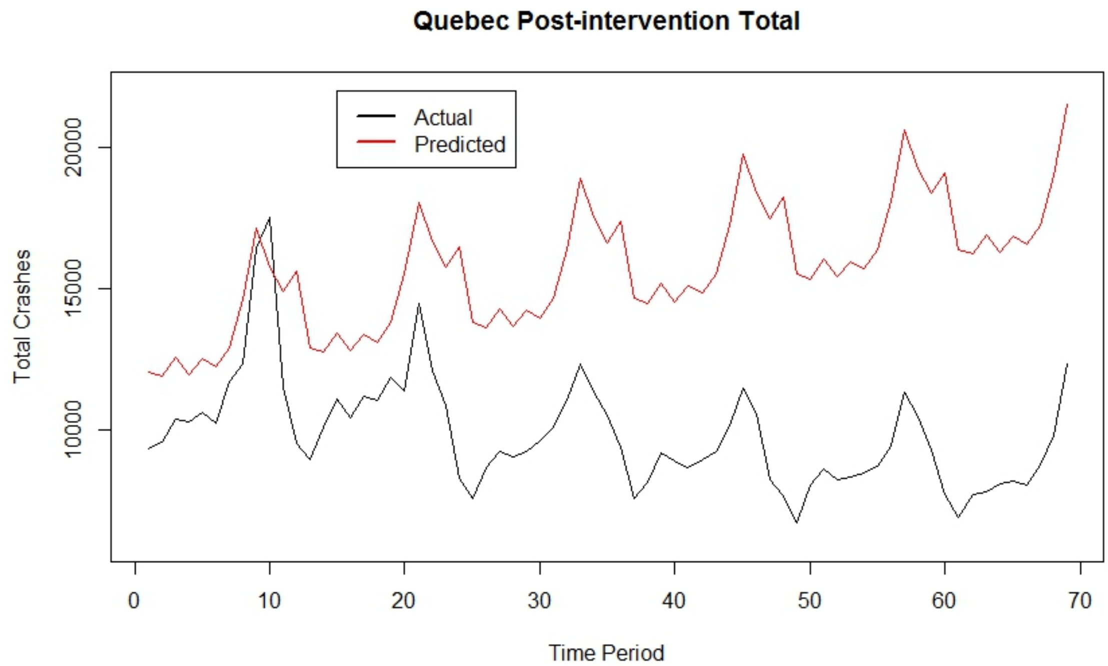

Figure 38: Mean Comparison (QC Total)

B.3 Fitted:

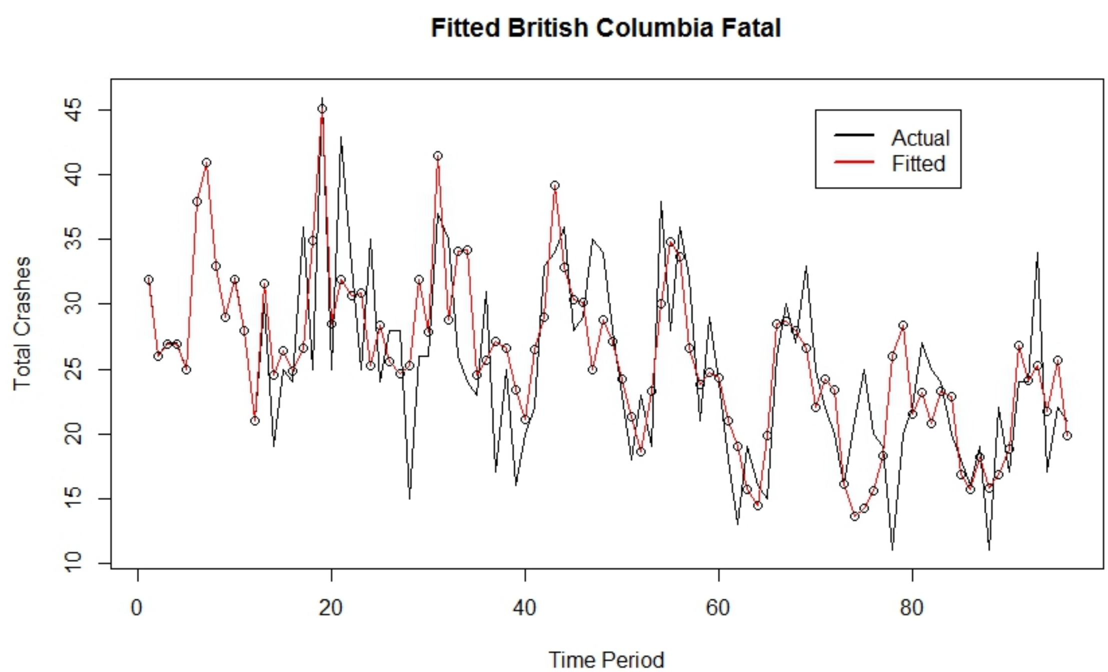

Figure 39: Fitted BC Fatal

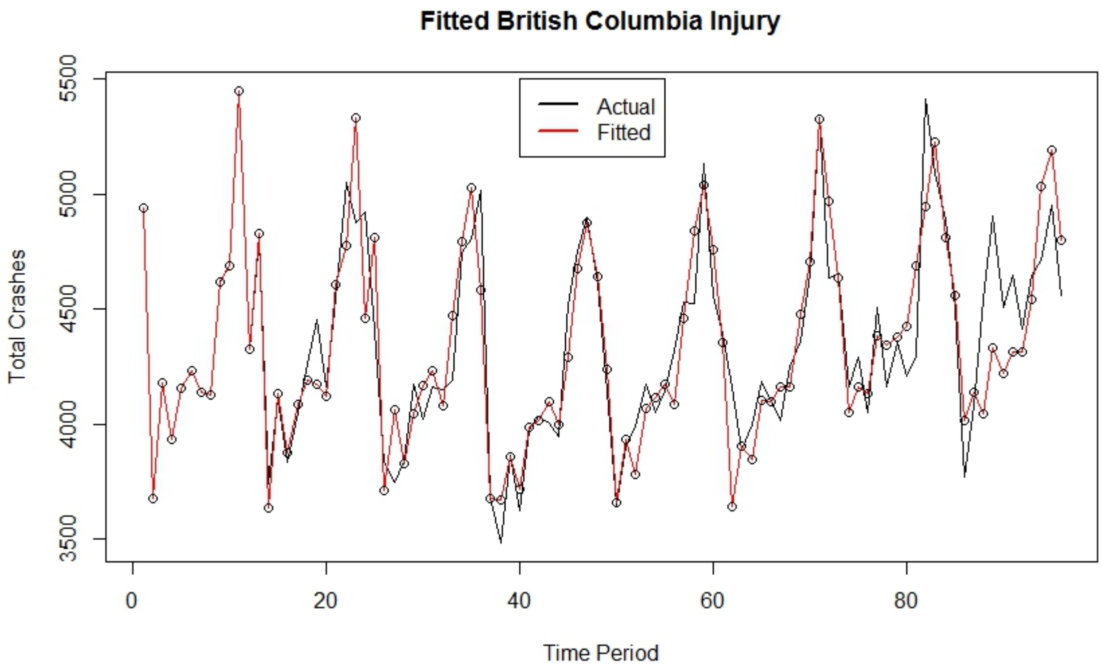

Figure 40: Fitted BC Injury

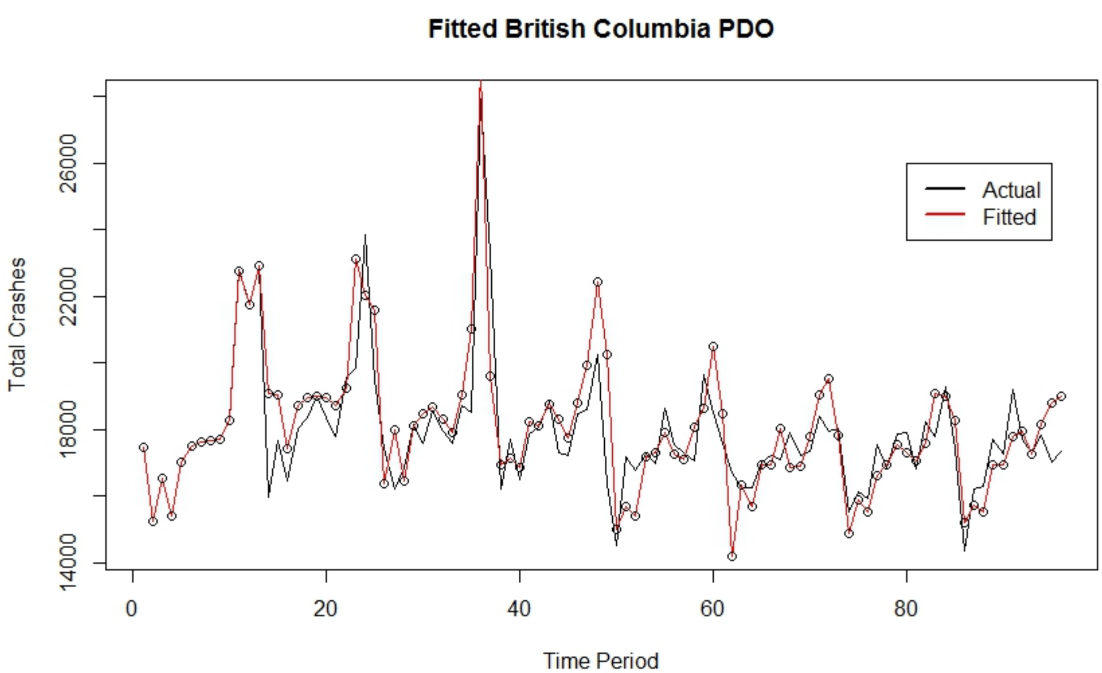

Figure 41: Fitted BC PDO

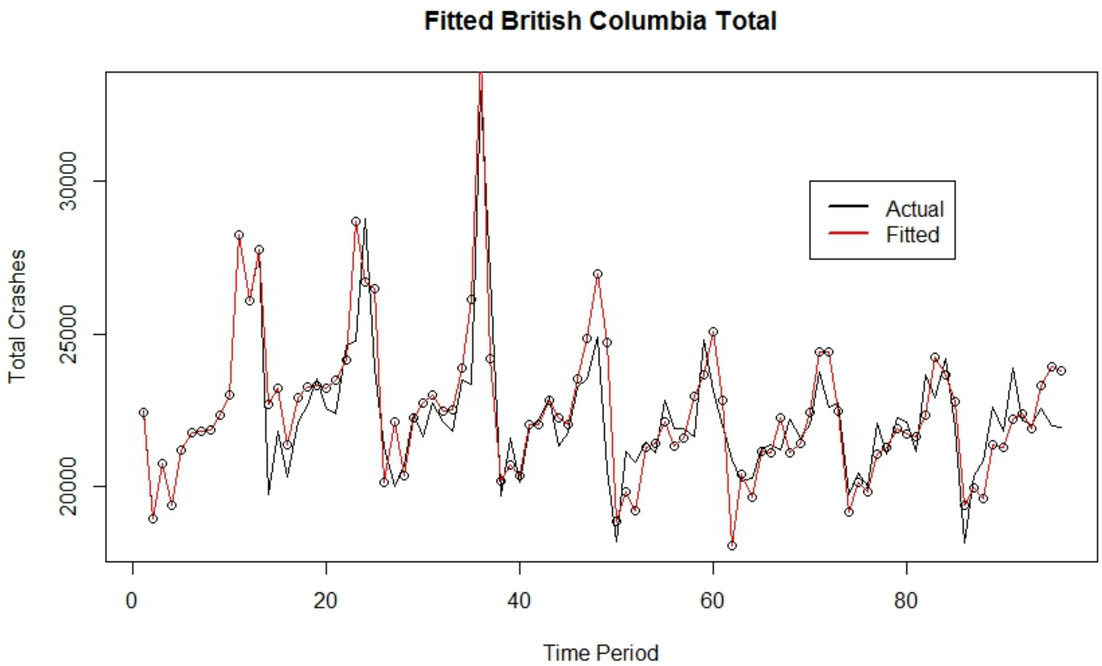

Figure 42: Fitted BC Total

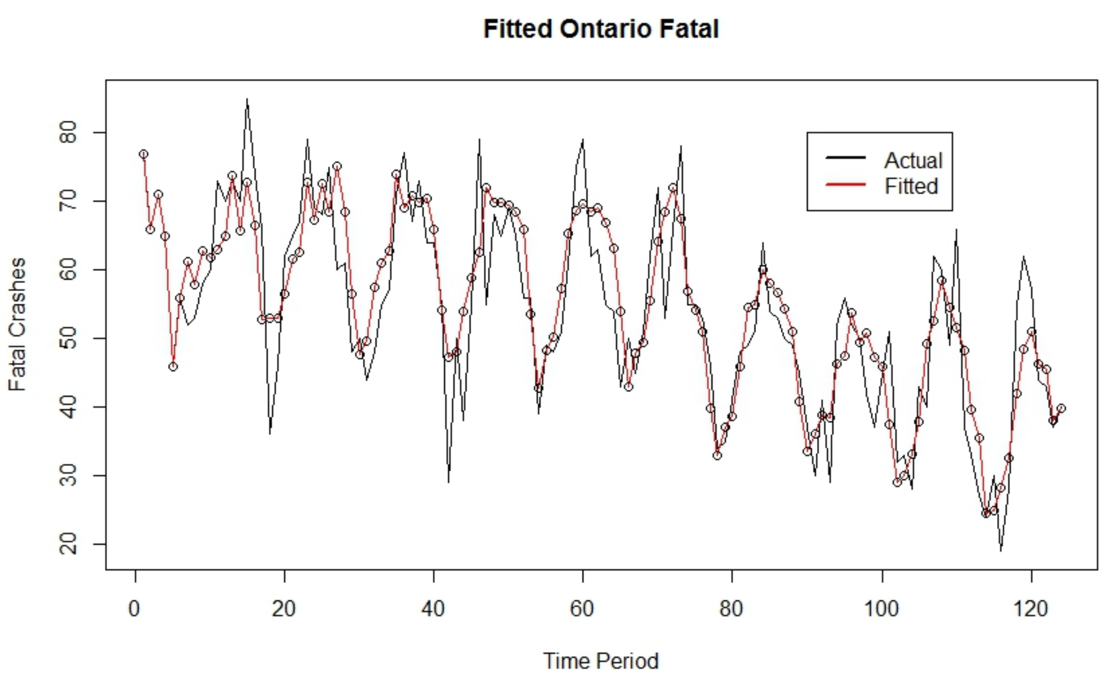

Figure 43: Fitted ON Fatal

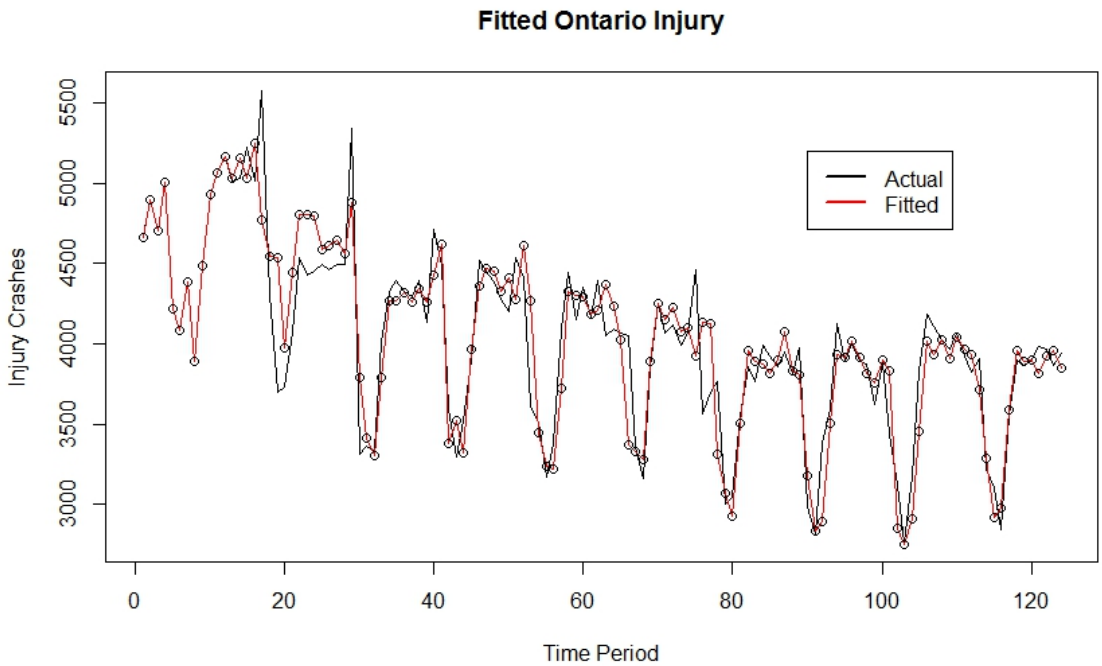

Figure 44: Fitted ON Injury

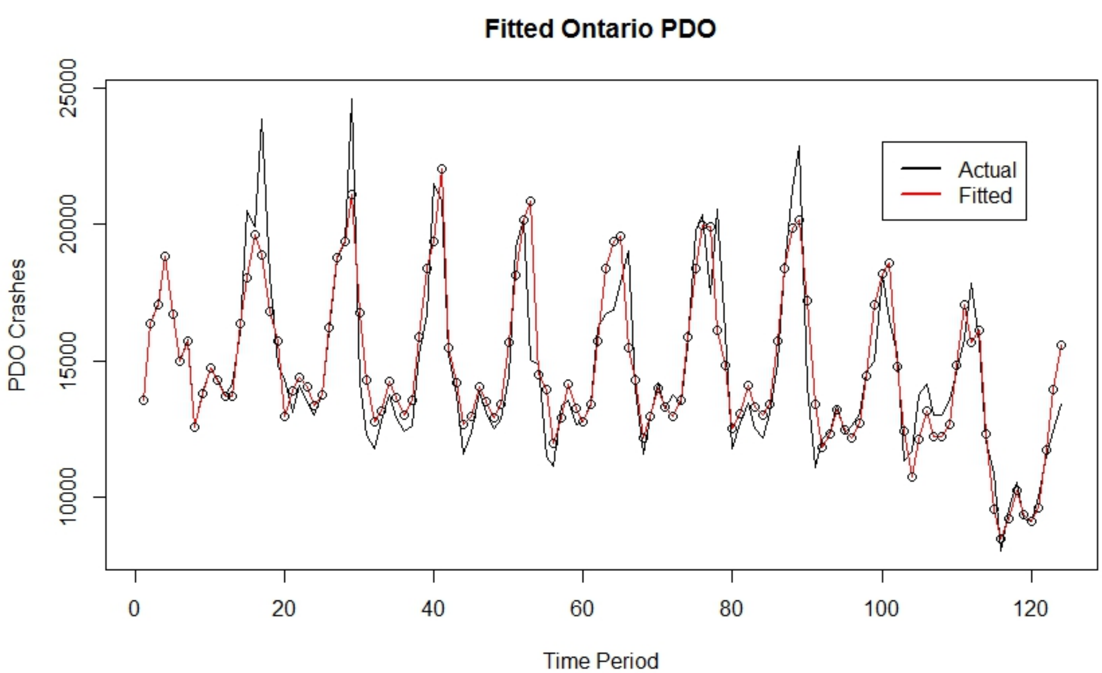

Figure 45: Fitted ON PDO

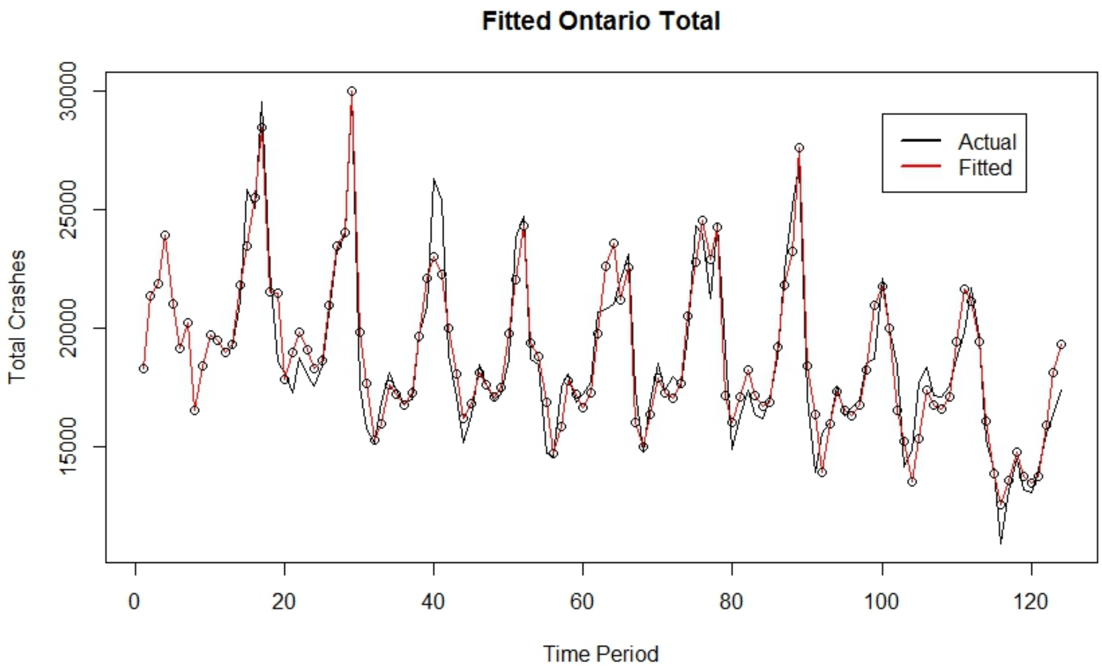

Figure 46: Fitted ON Total

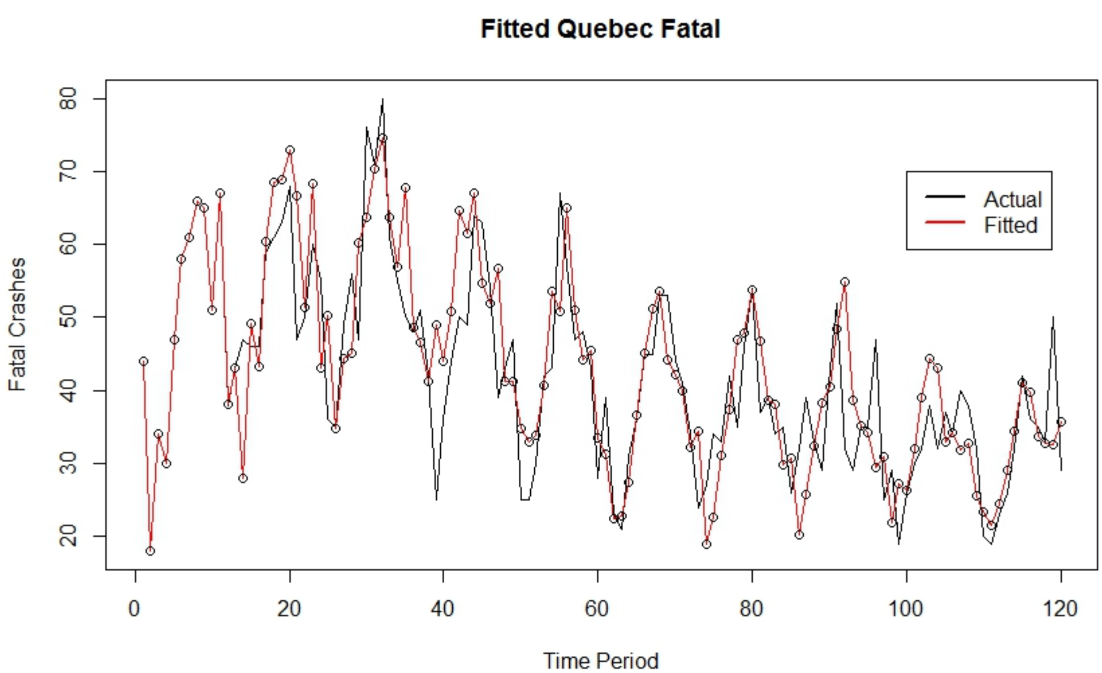

Figure 47: Fitted QC Fatal

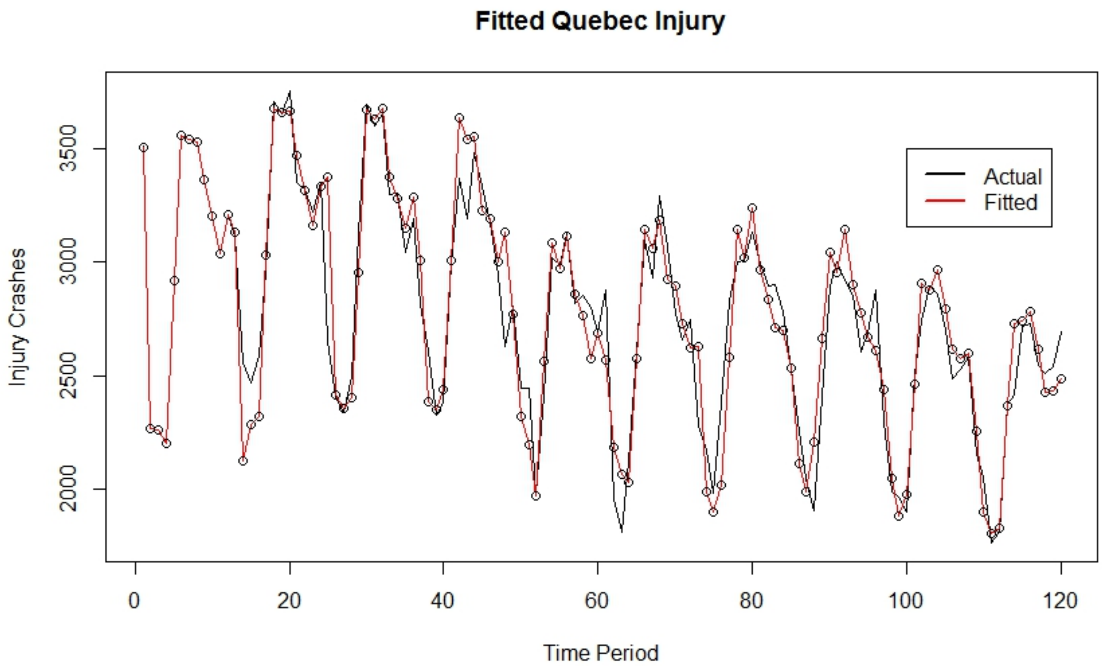

Figure 48: Fitted QC Injury

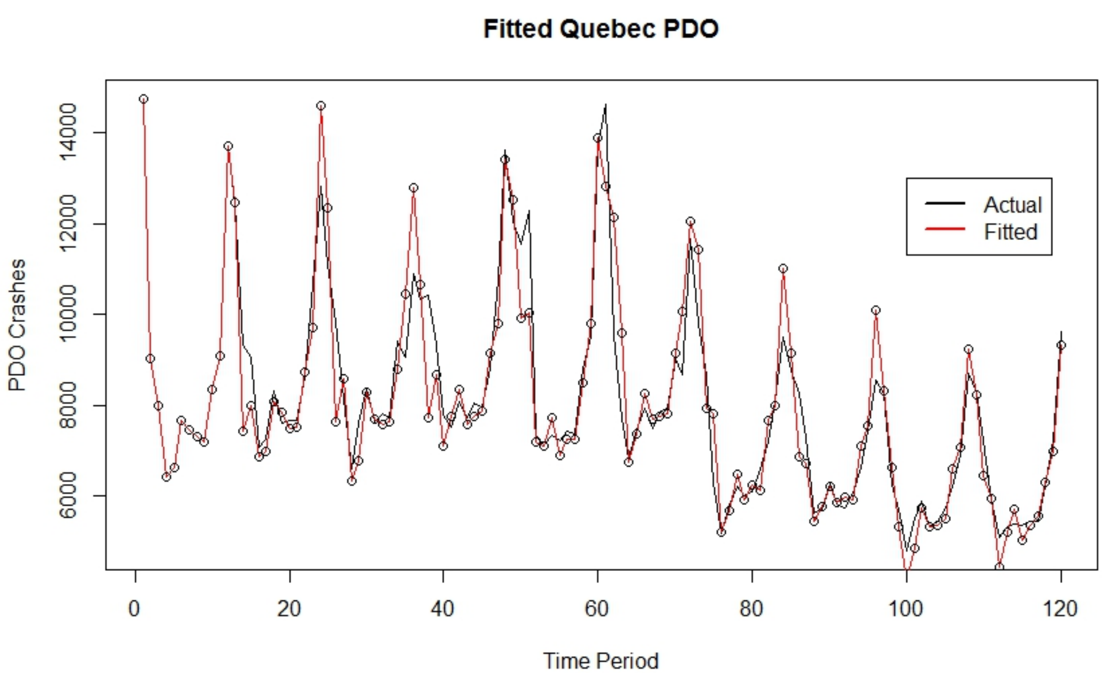

Figure 49: Fitted QC PDO

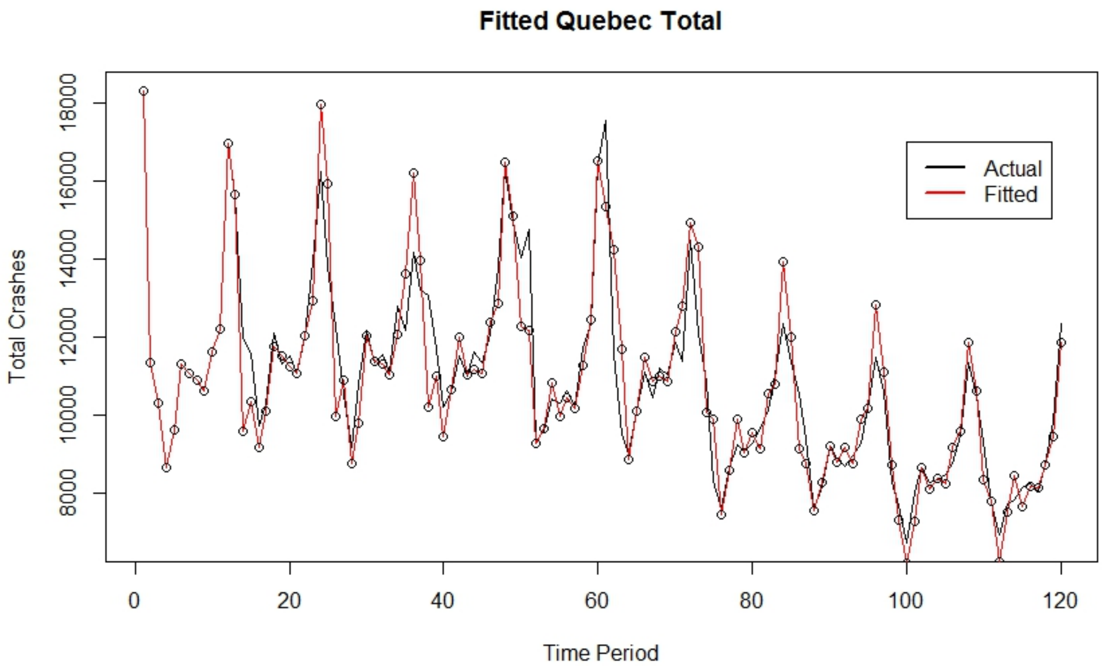

Figure 50: Fitted QC Total

B.4 ACF Plots:

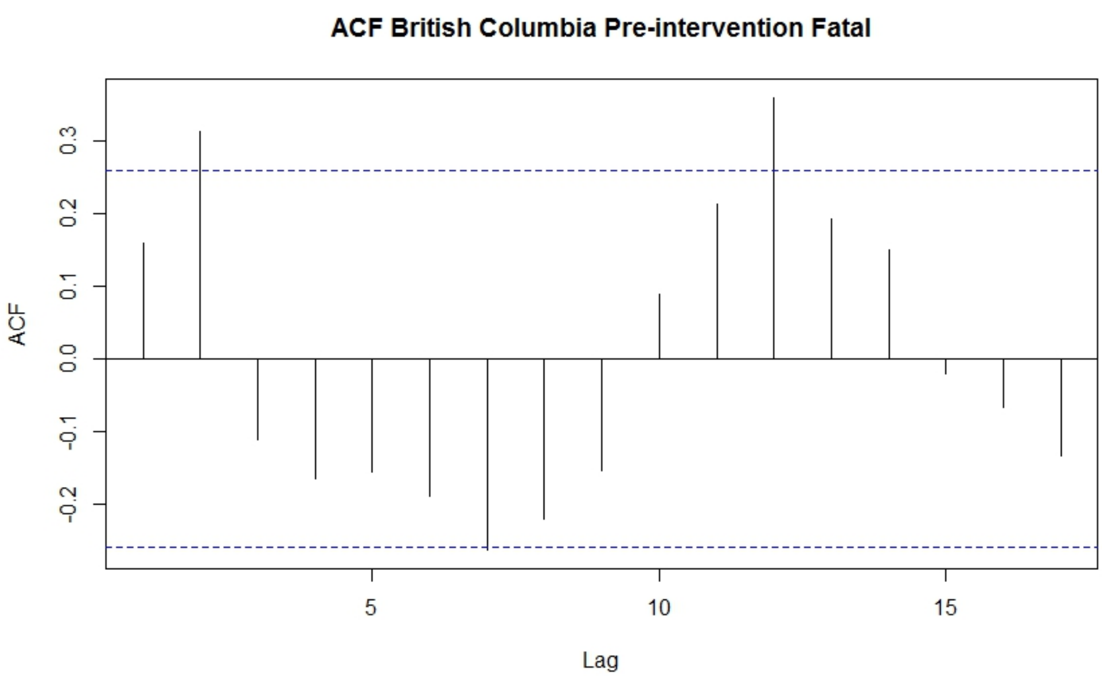

Figure 51: ACF BC Fatal

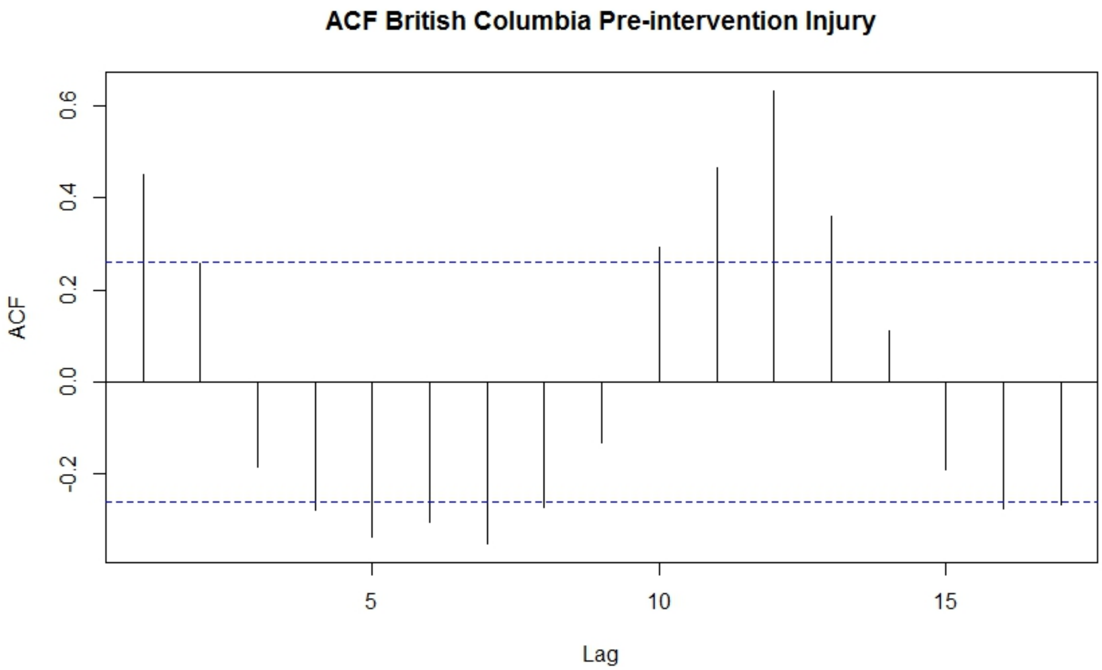

Figure 52: ACF BC Injury

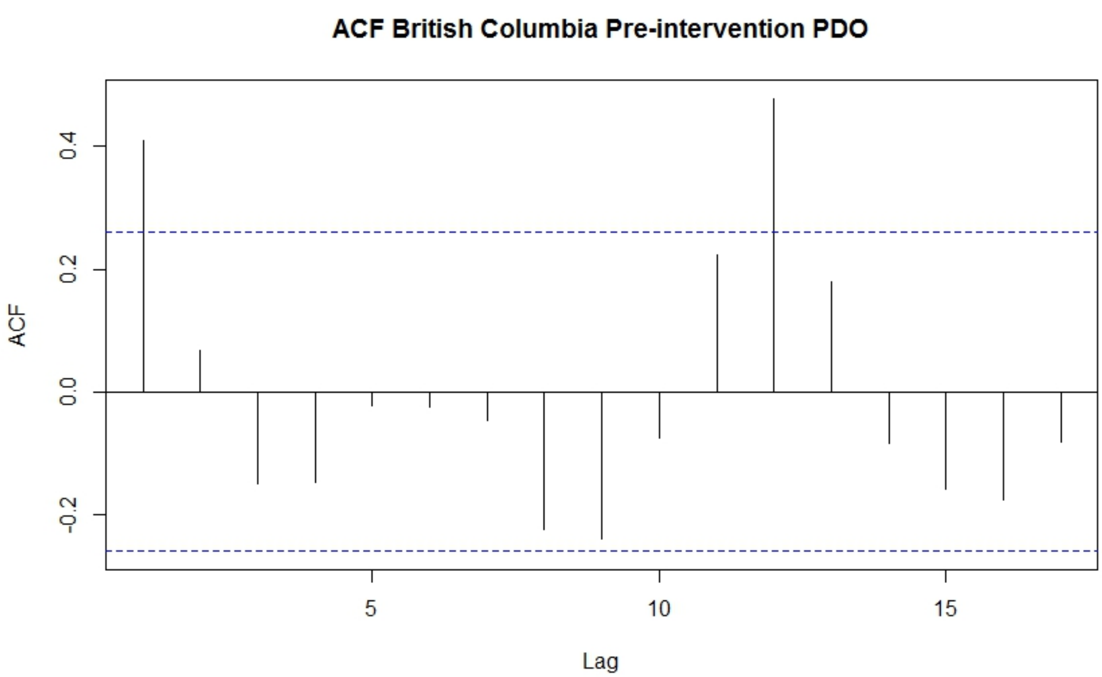

Figure 53: ACF BC PDO

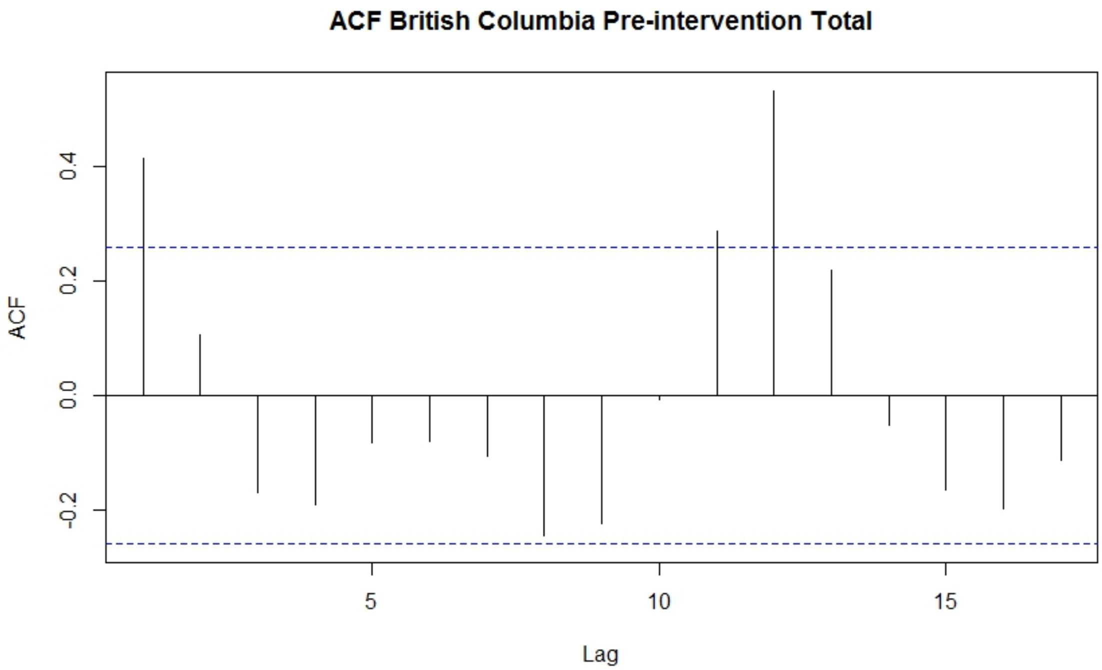

Figure 54: ACF BC Total

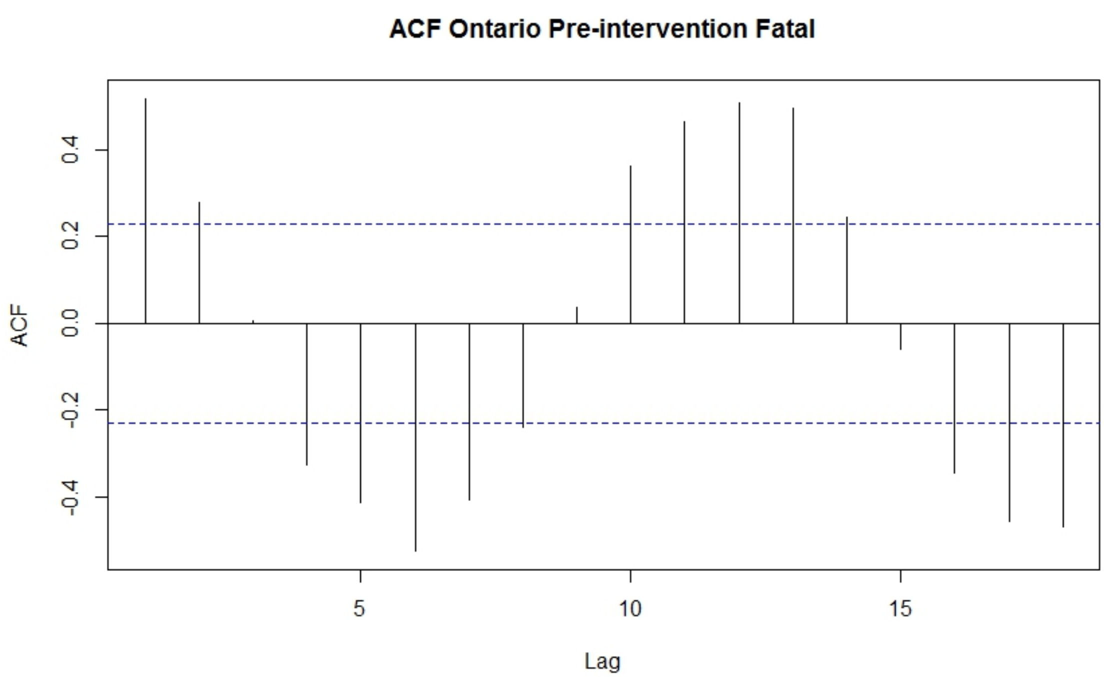

Figure 55: ACF ON Fatal

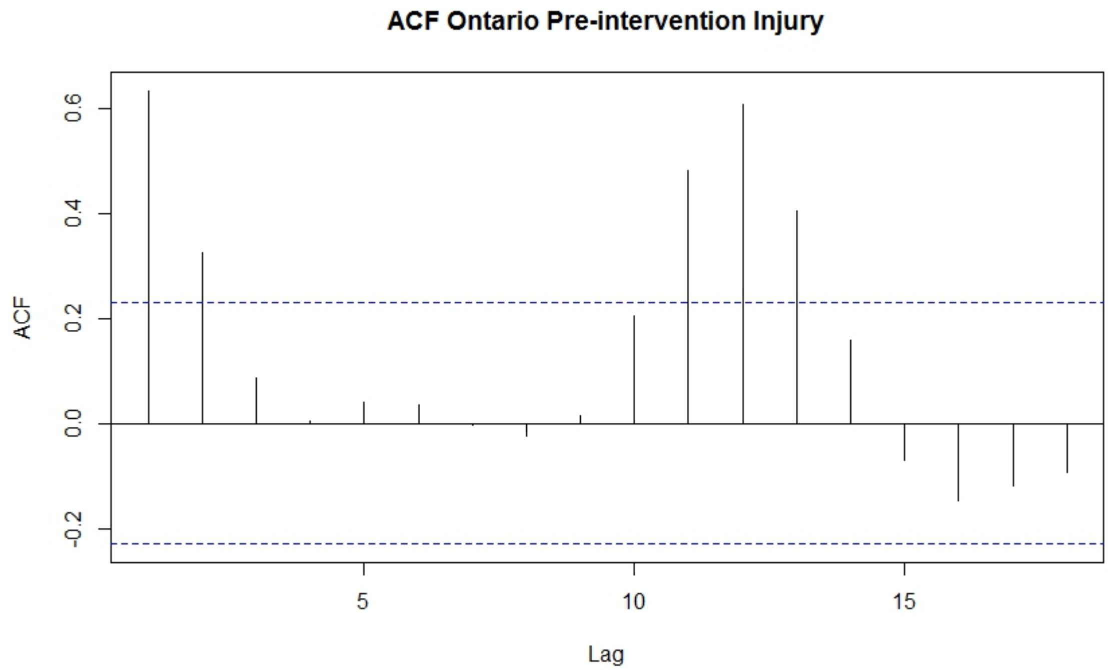

Figure 56: ACF ON Injury

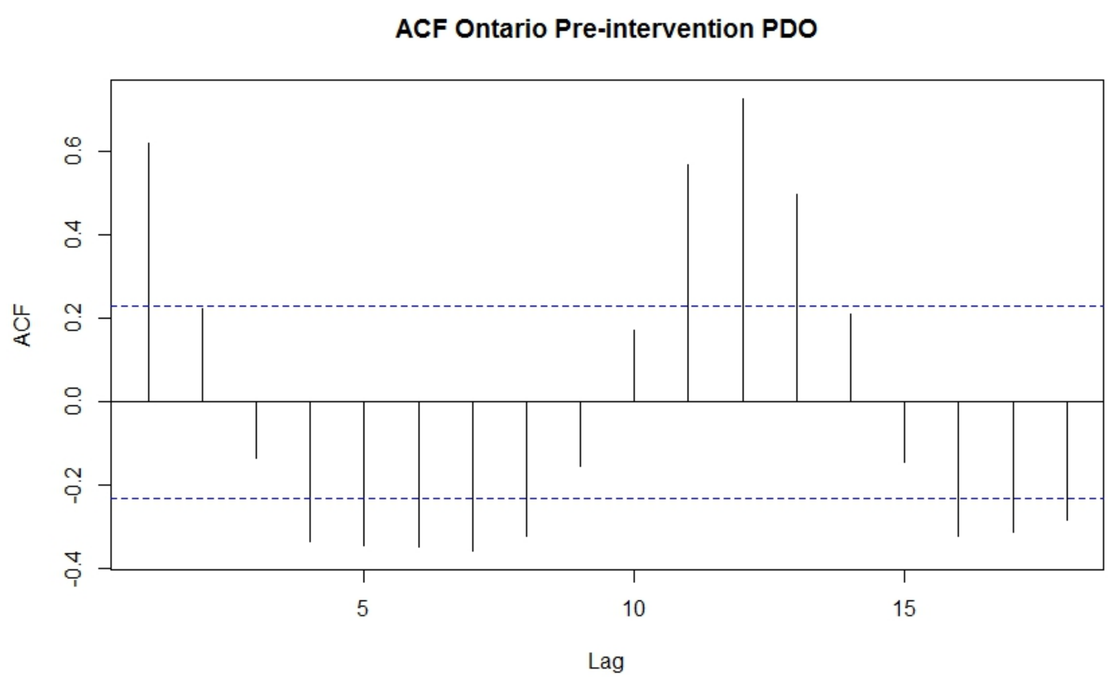

Figure 57: ACF ON PDO

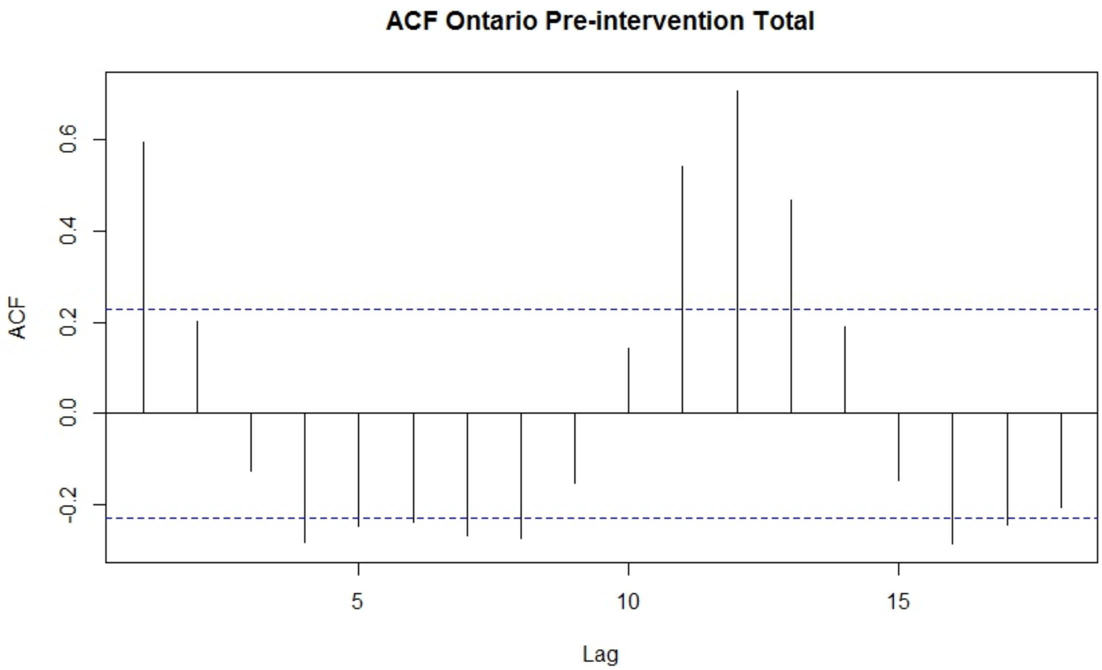

Figure 58: ACF ON Total

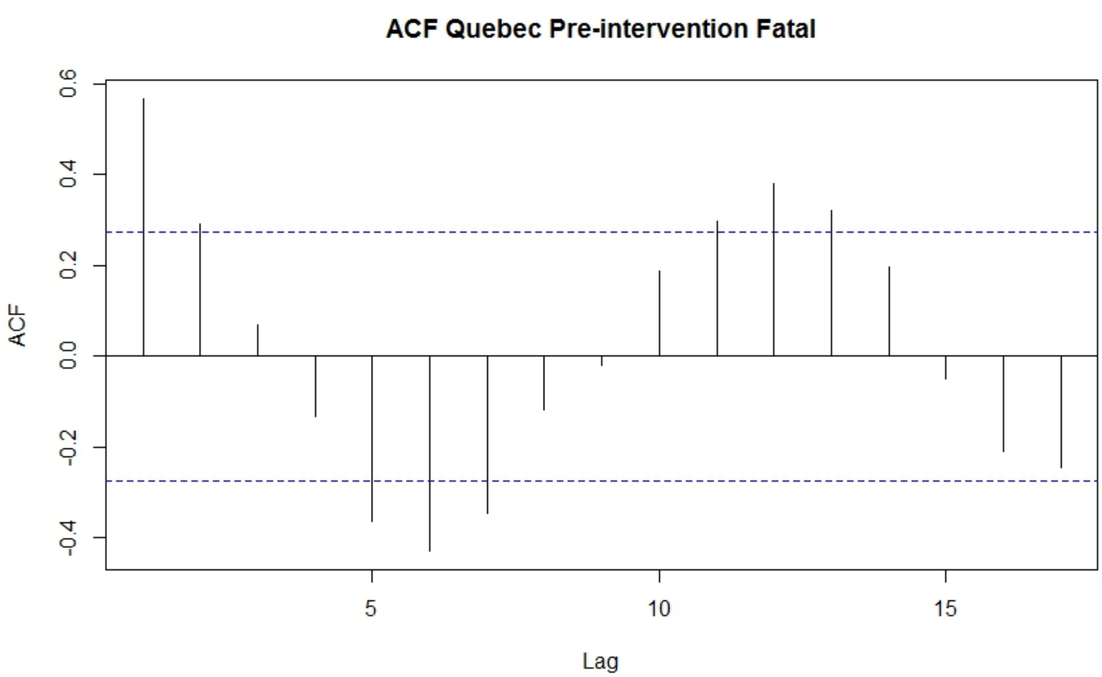

Figure 59: ACF QC Fatal

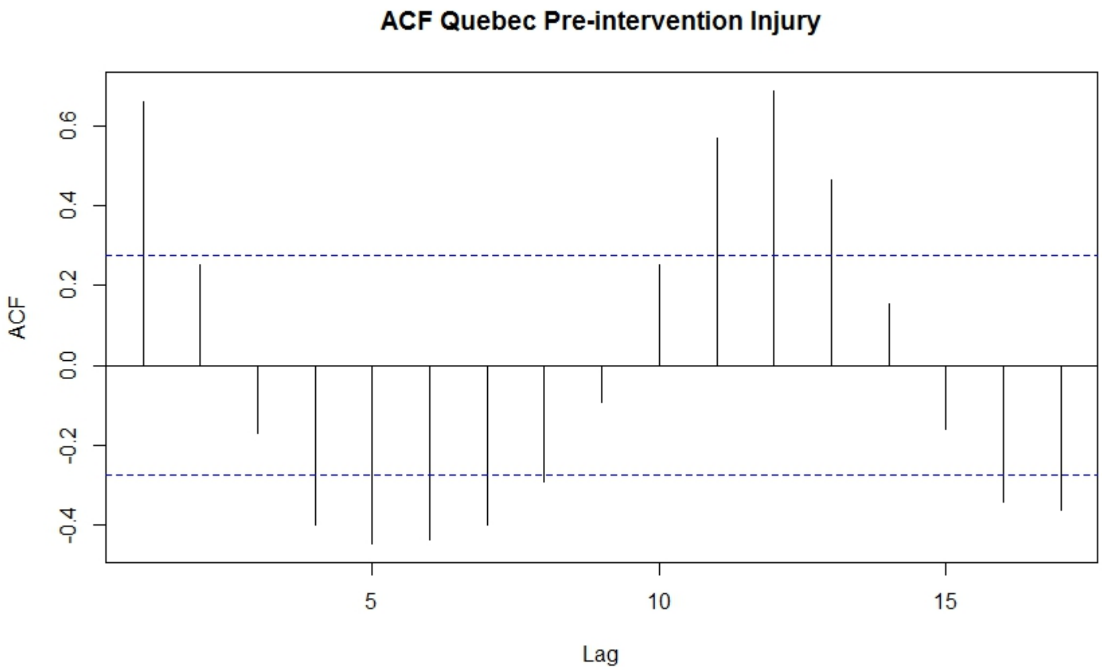

Figure 60: ACF QC Injury

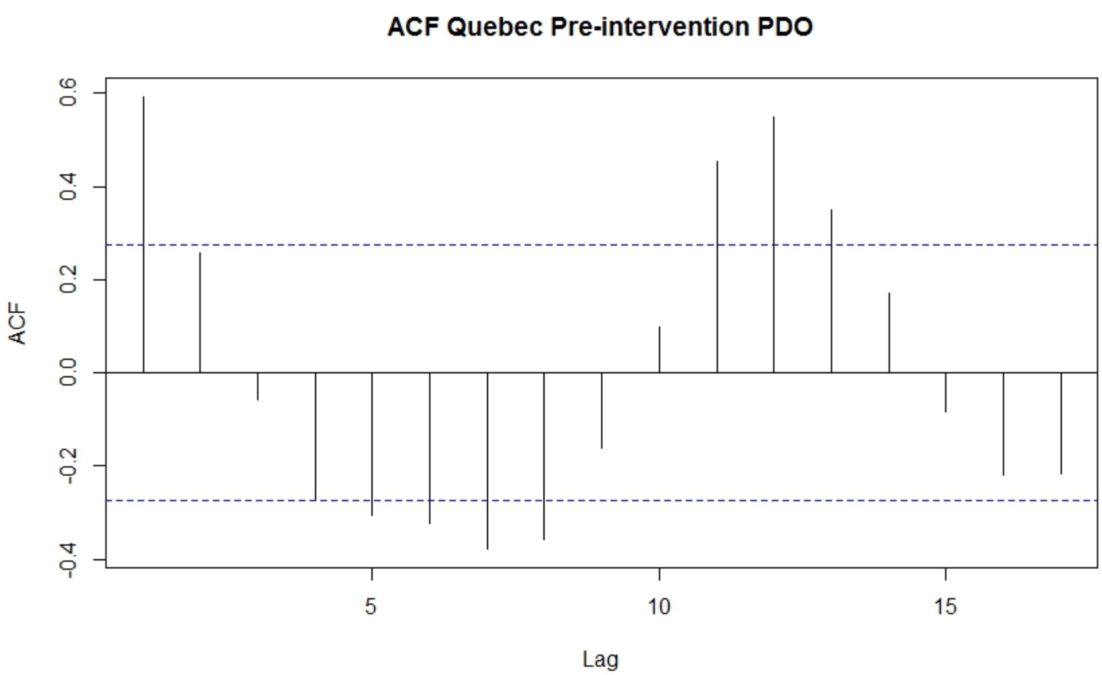

Figure 61: ACF QC PDO

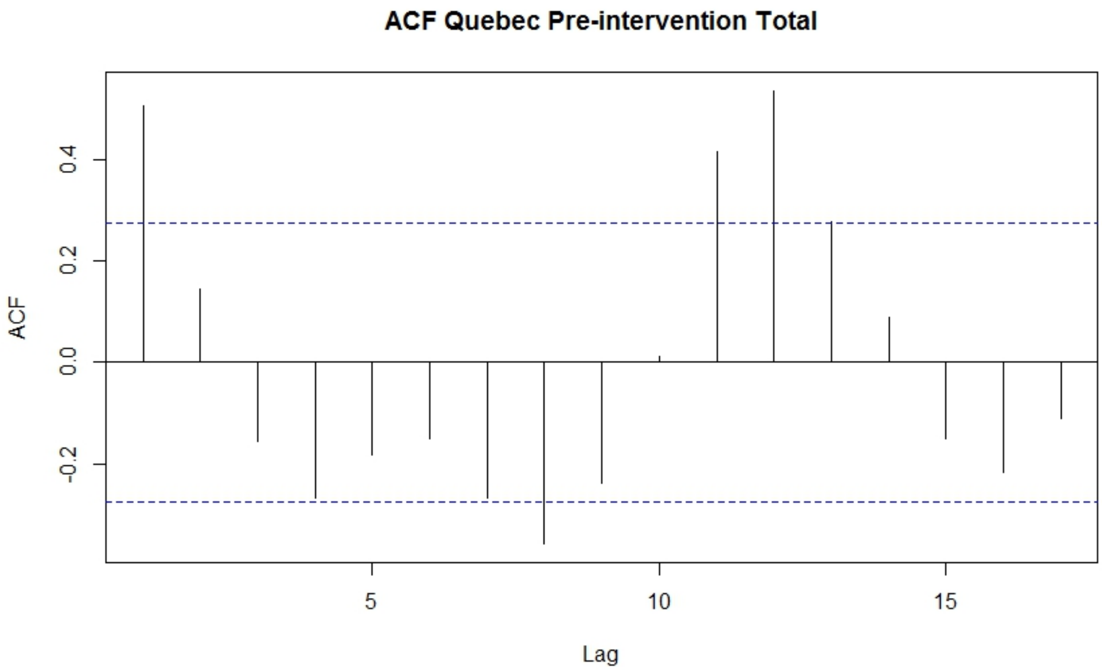

Figure 62: ACF QC Total

B.5 PACF Plots:

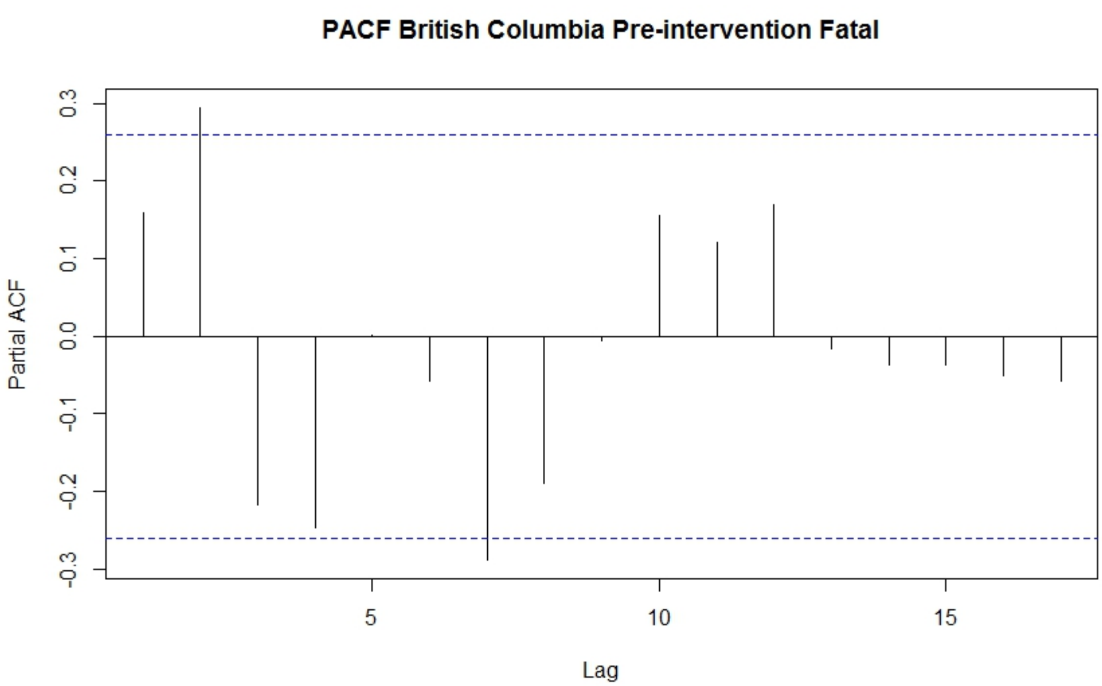

Figure 63: PACF BC Fatal

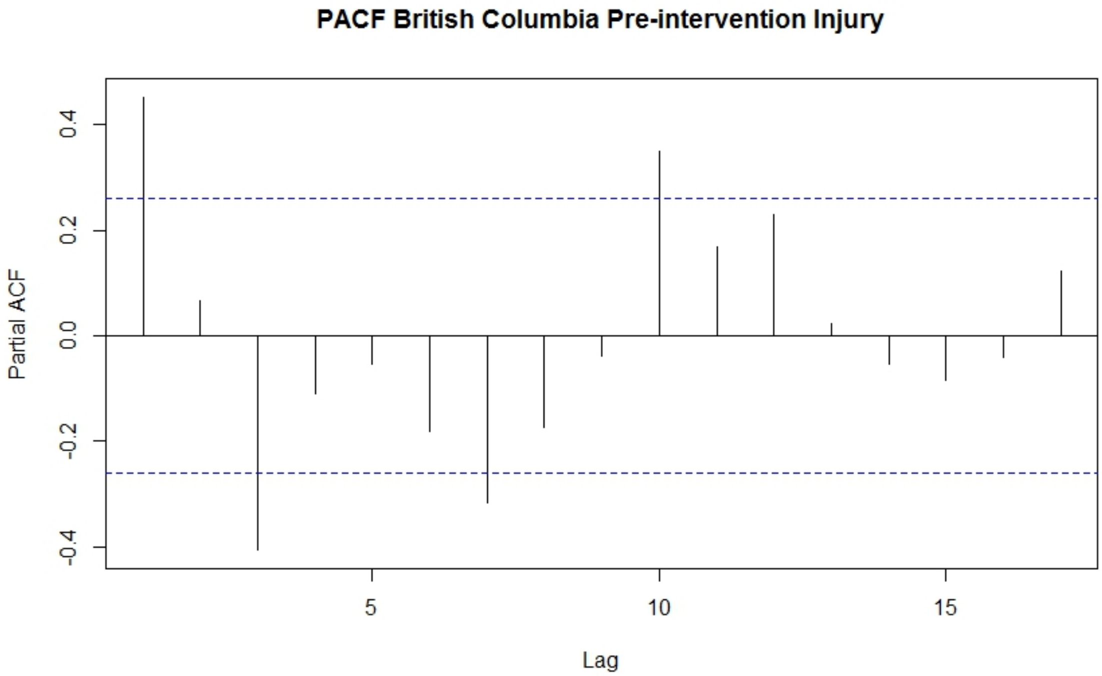

Figure 64: PACF BC Injury

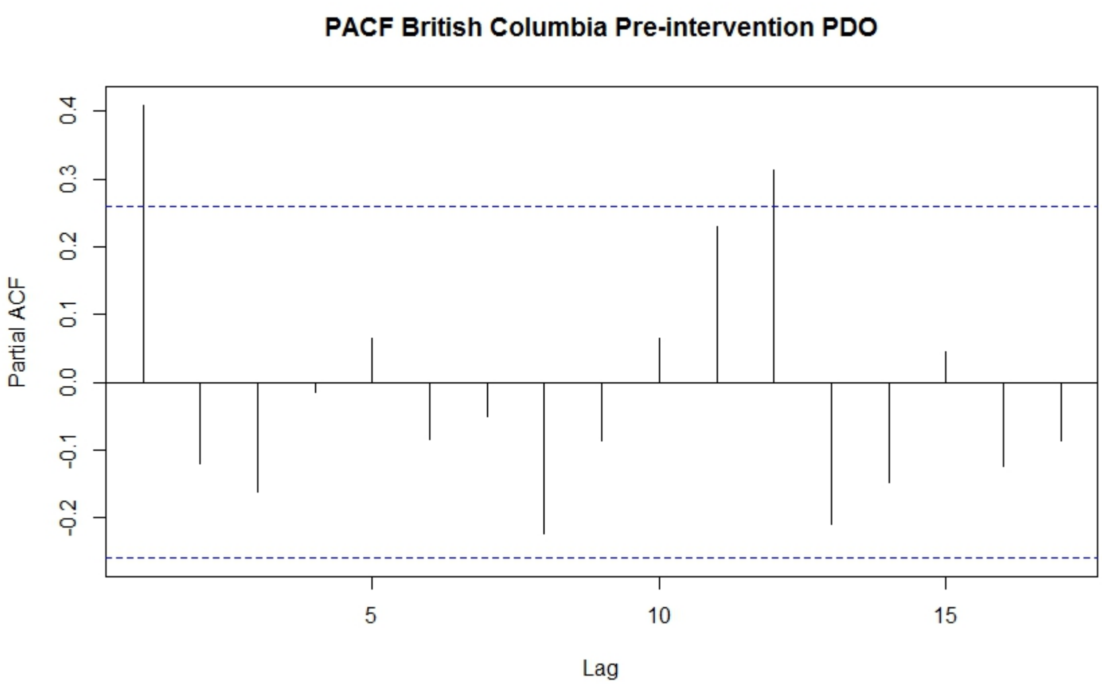

Figure 65: PACF BC PDO

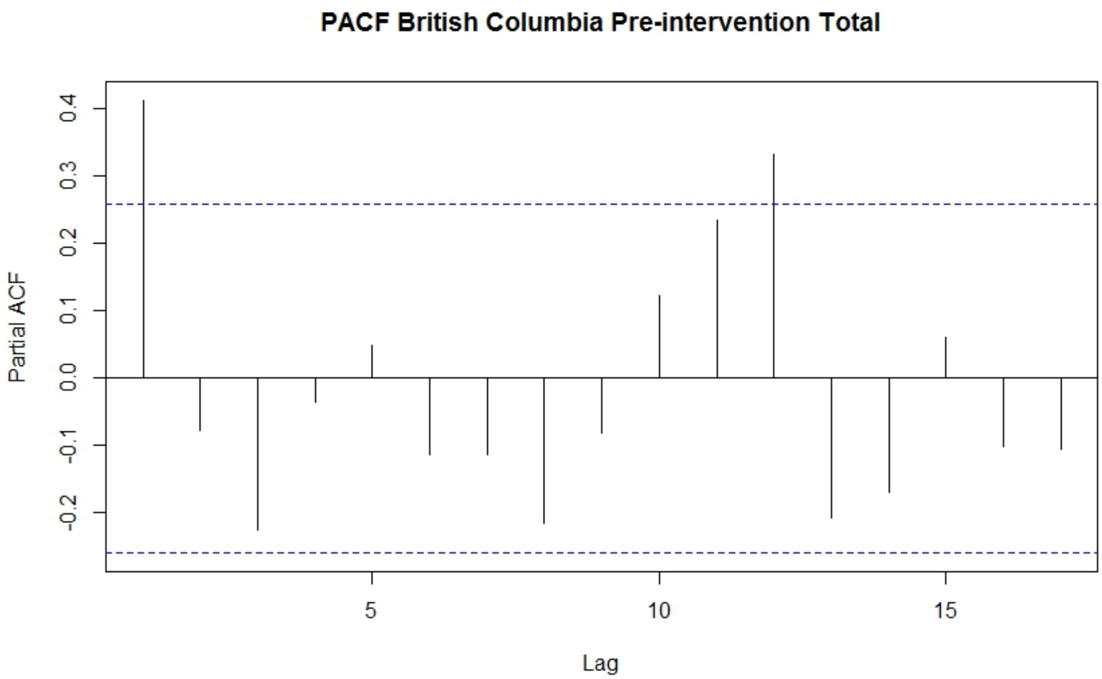

Figure 66: PACF BC Total

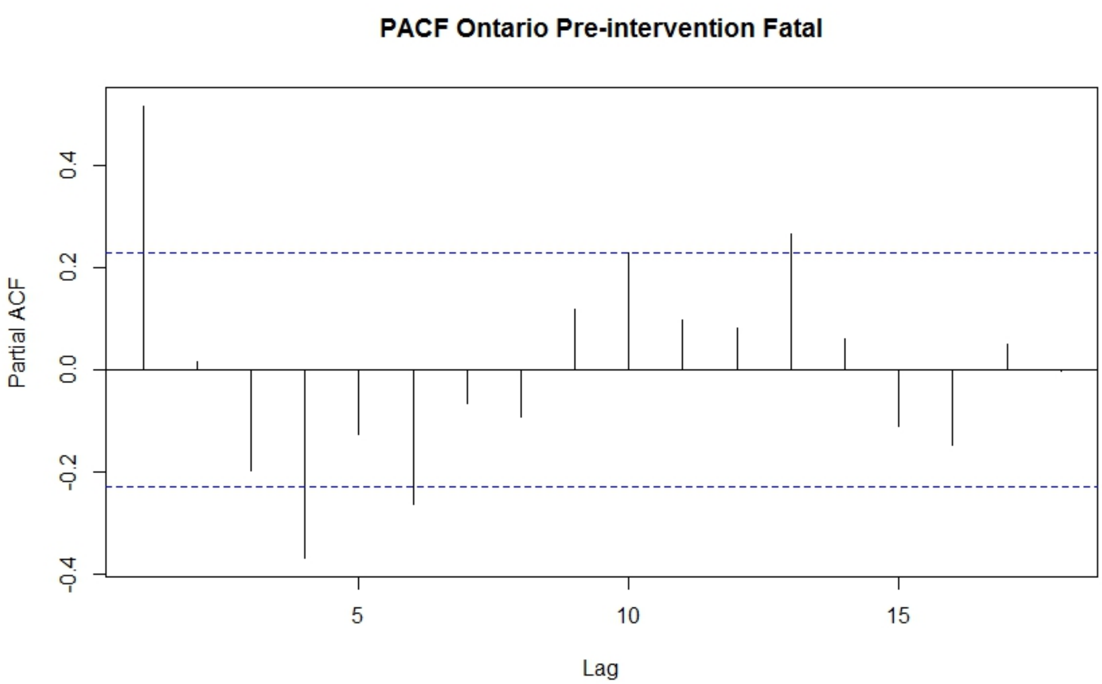

Figure 67: PACF ON Fatal

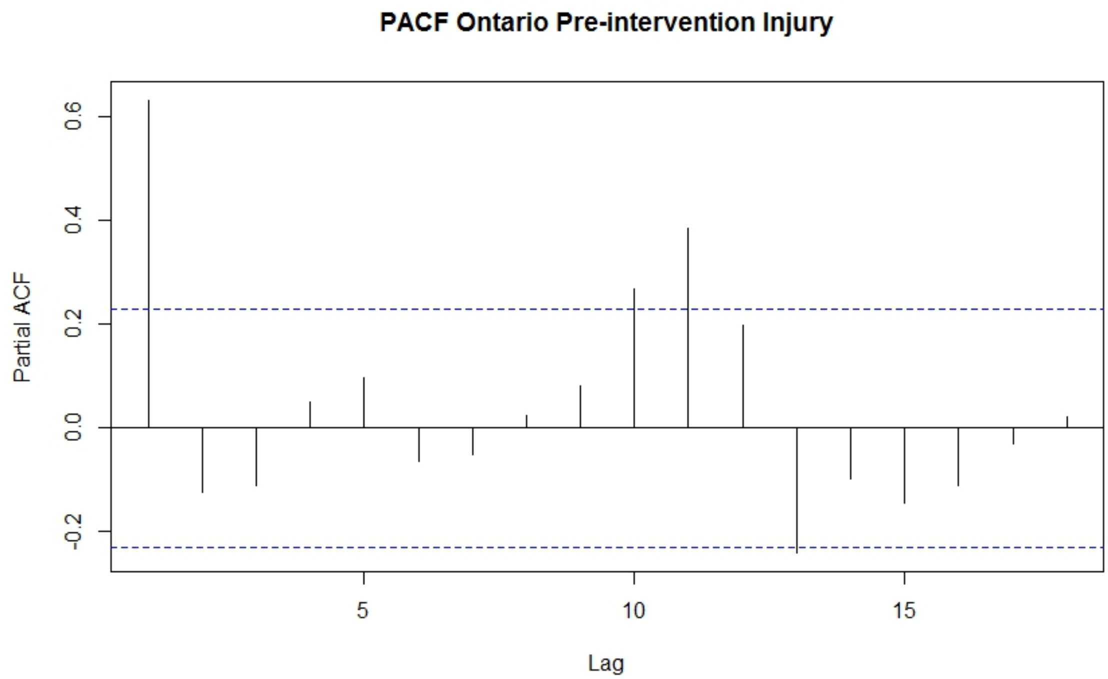

Figure 68: PACF ON Injury

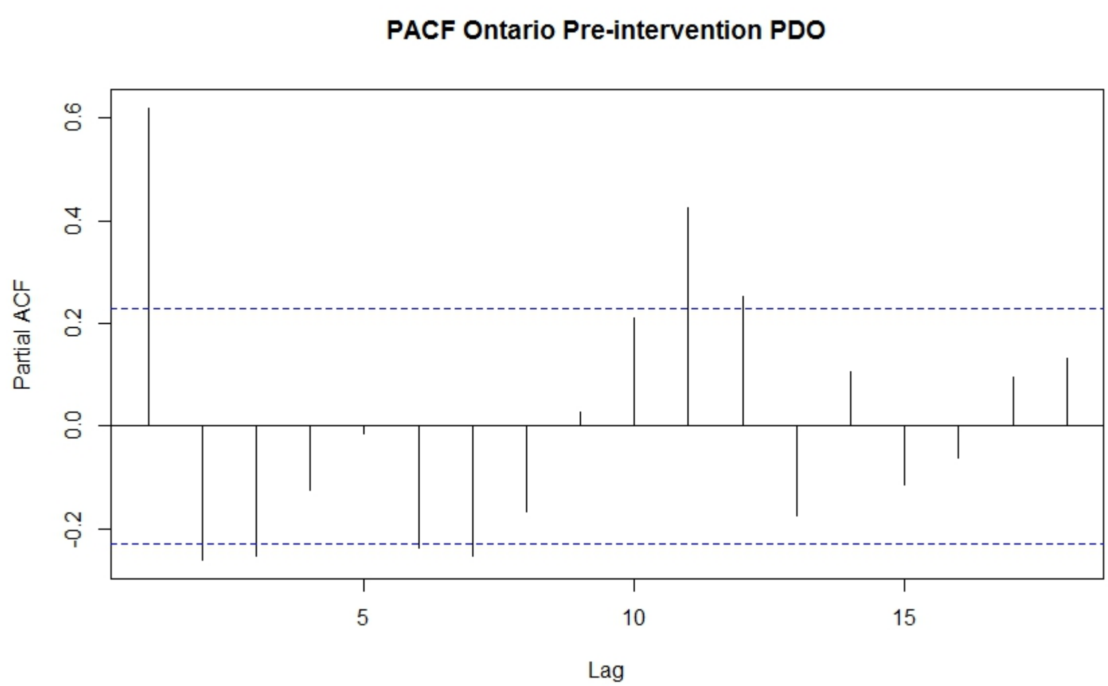

Figure 69: PACF ON PDO

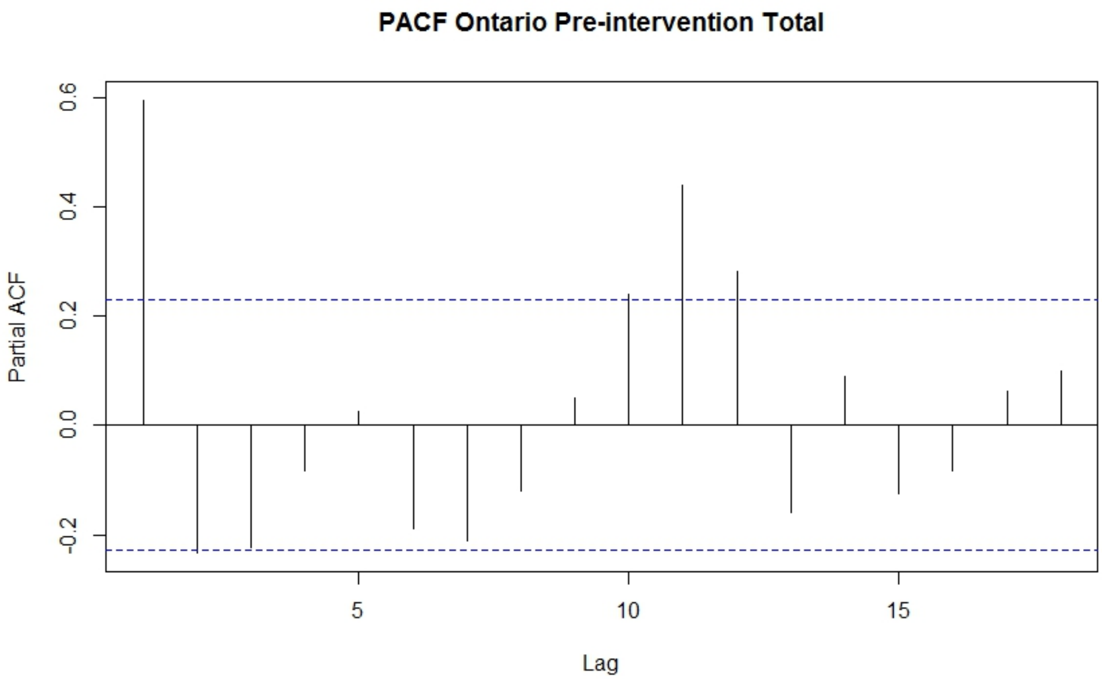

Figure 70: PACF ON Total

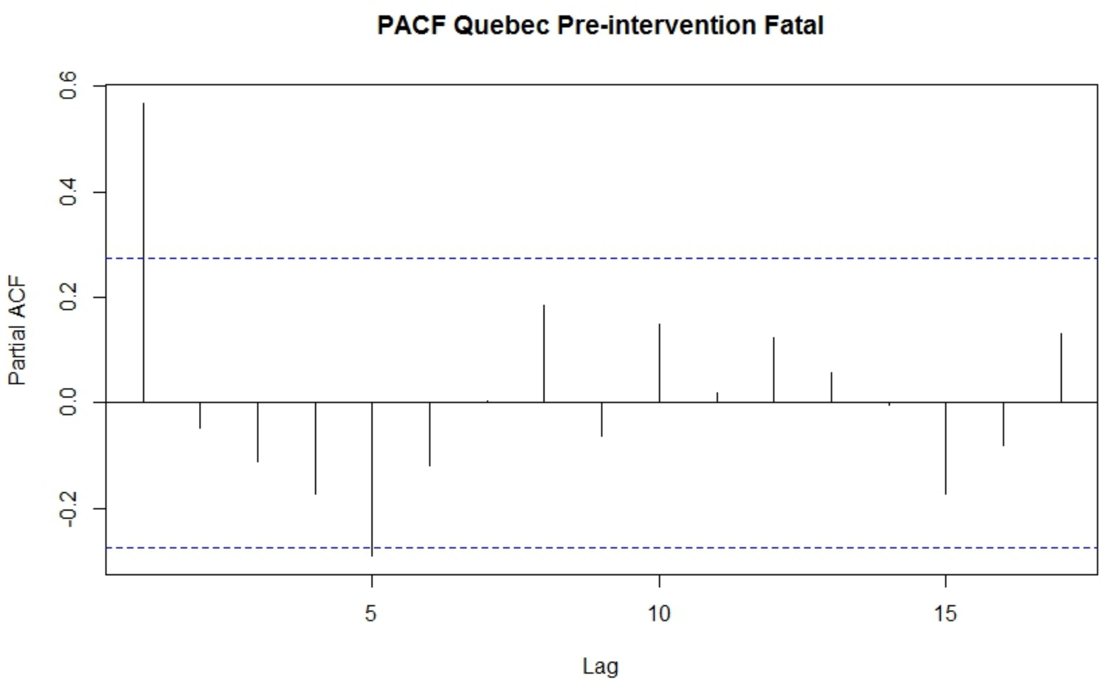

Figure 71: PACF QC Fatal

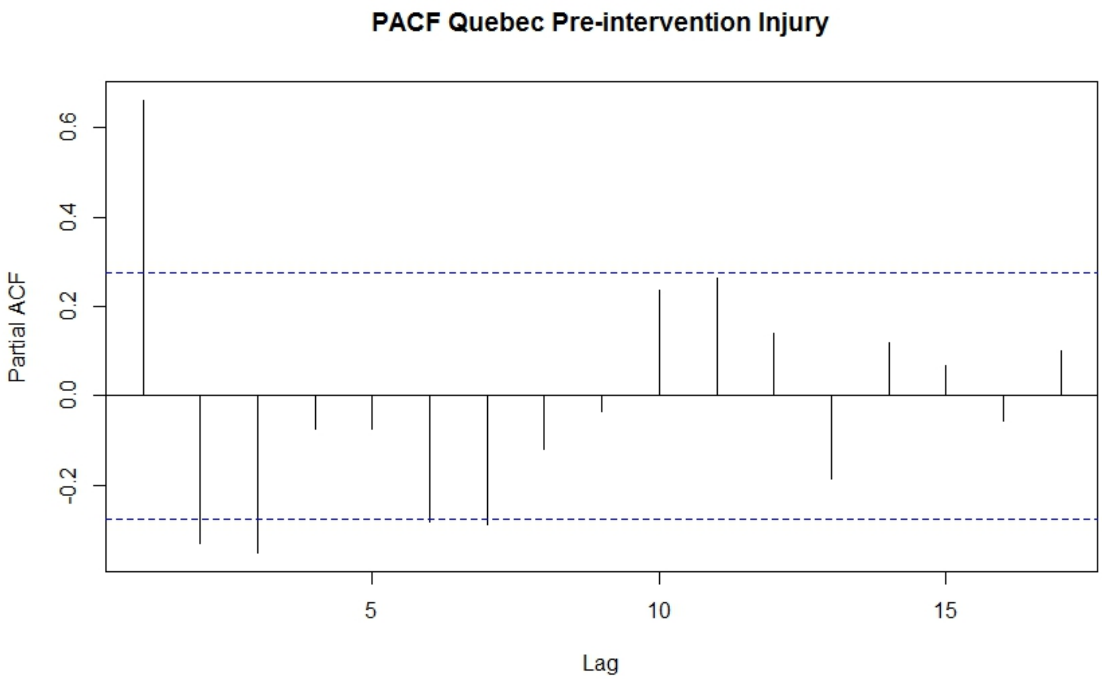

Figure 72: PACF QC Injury

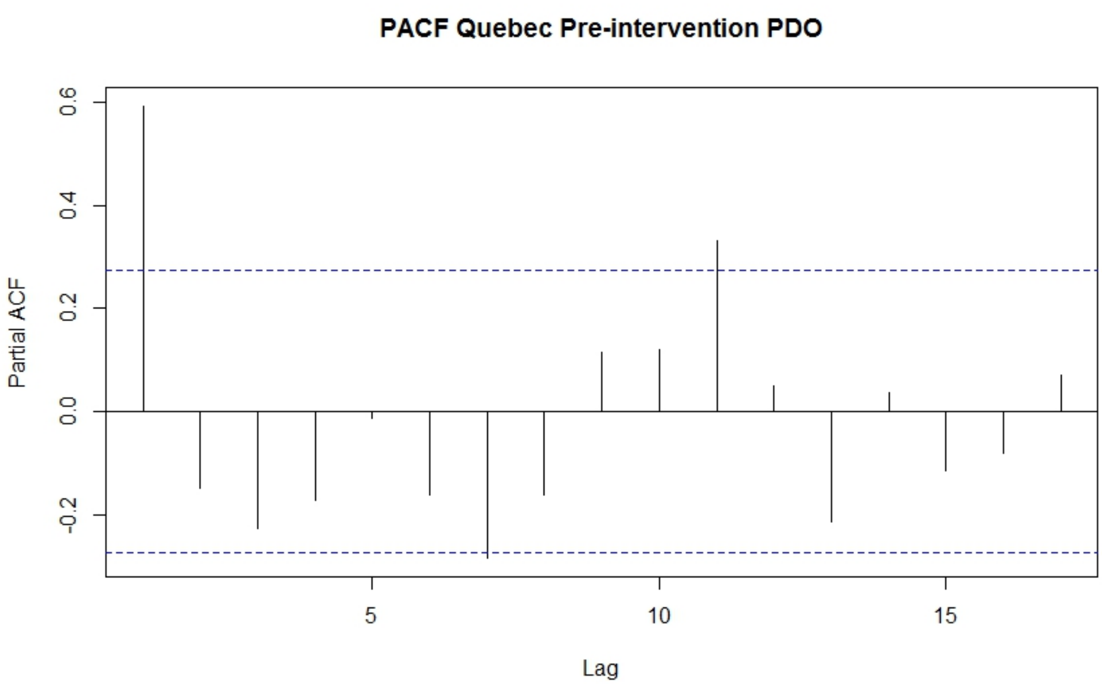

Figure 73: PACF QC PDO

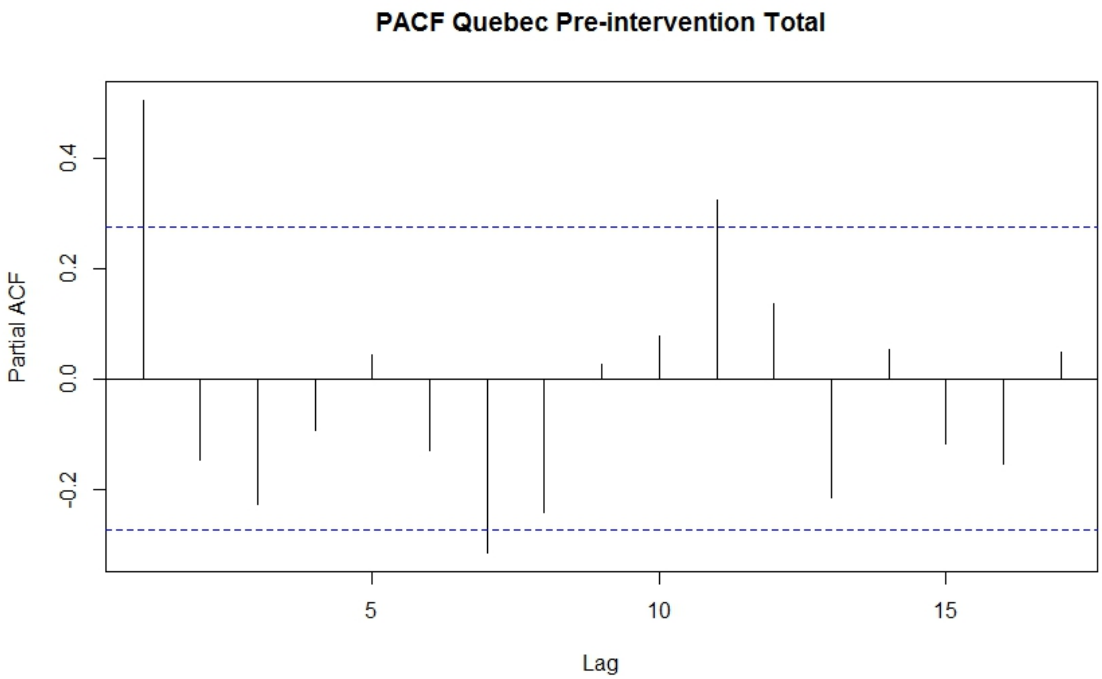

Figure 74: PACF QC Total

B.6 Pre-intervention Time Plots

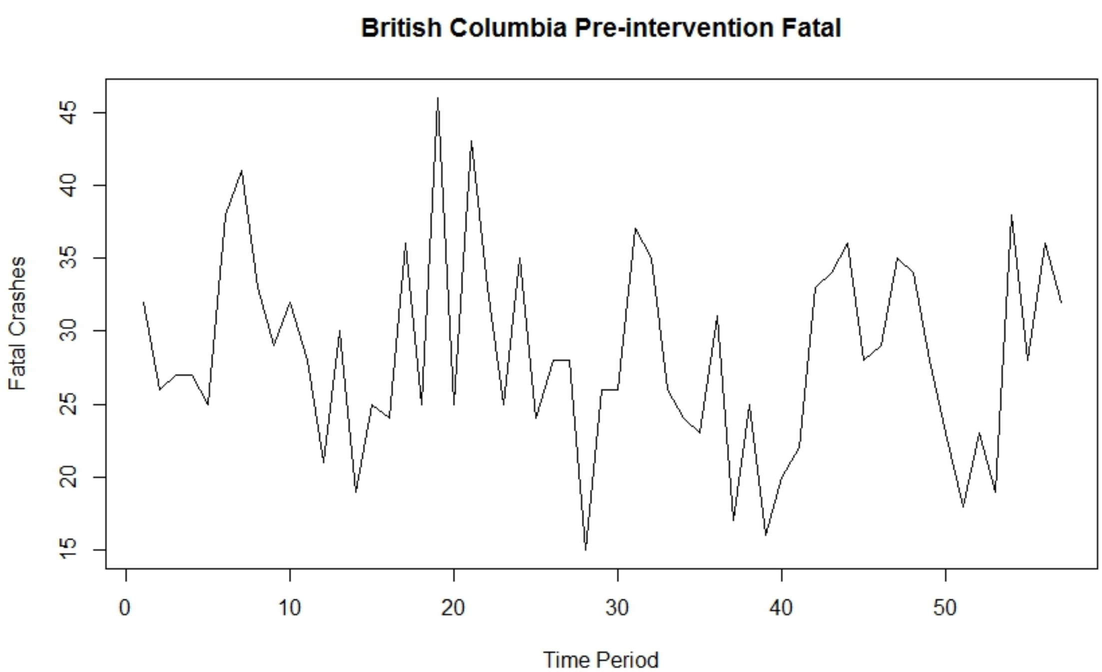

Figure 75: BC Pre-intervention Trend (Fatal)

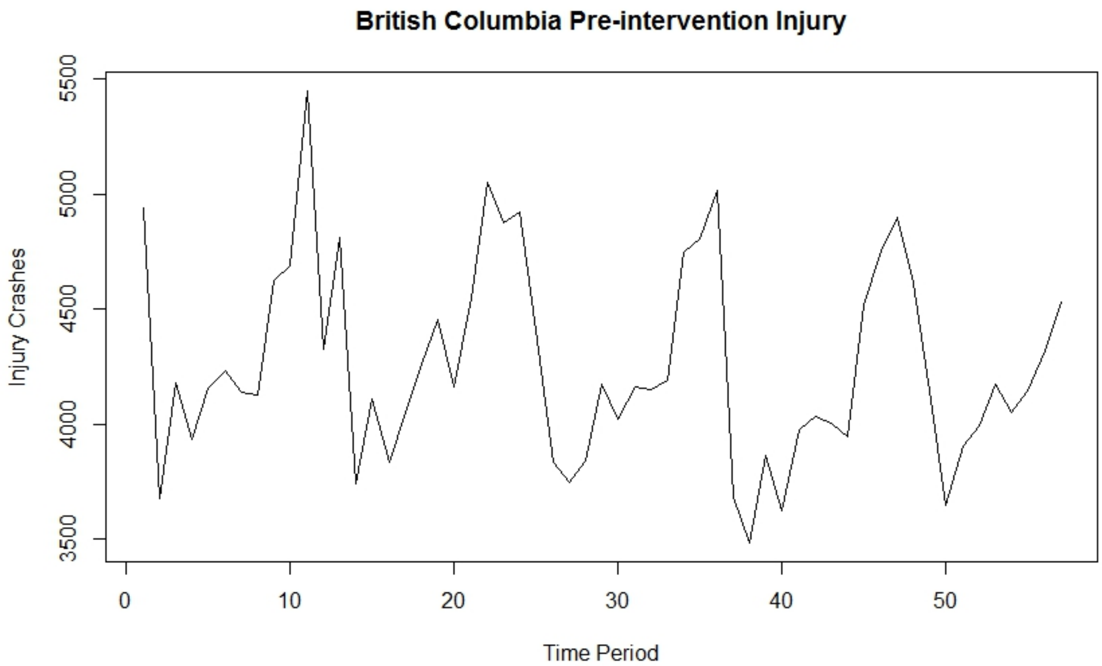

Figure 76: BC Pre-intervention Trend (Injury)

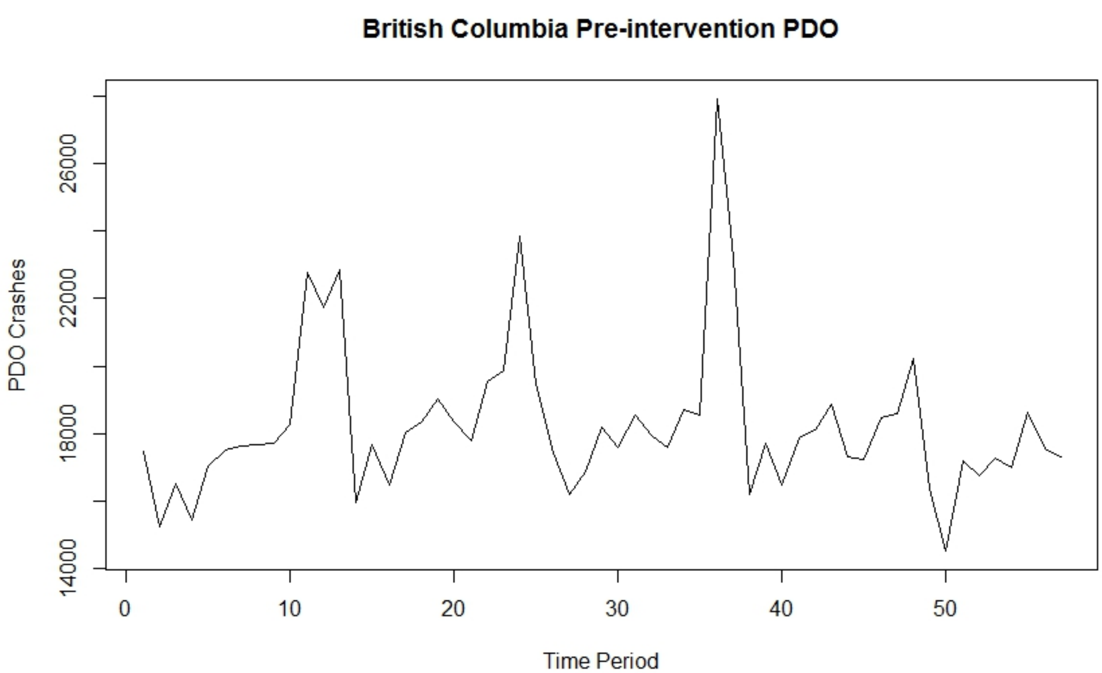

Figure 77: BC Pre-intervention Trend (PDO)

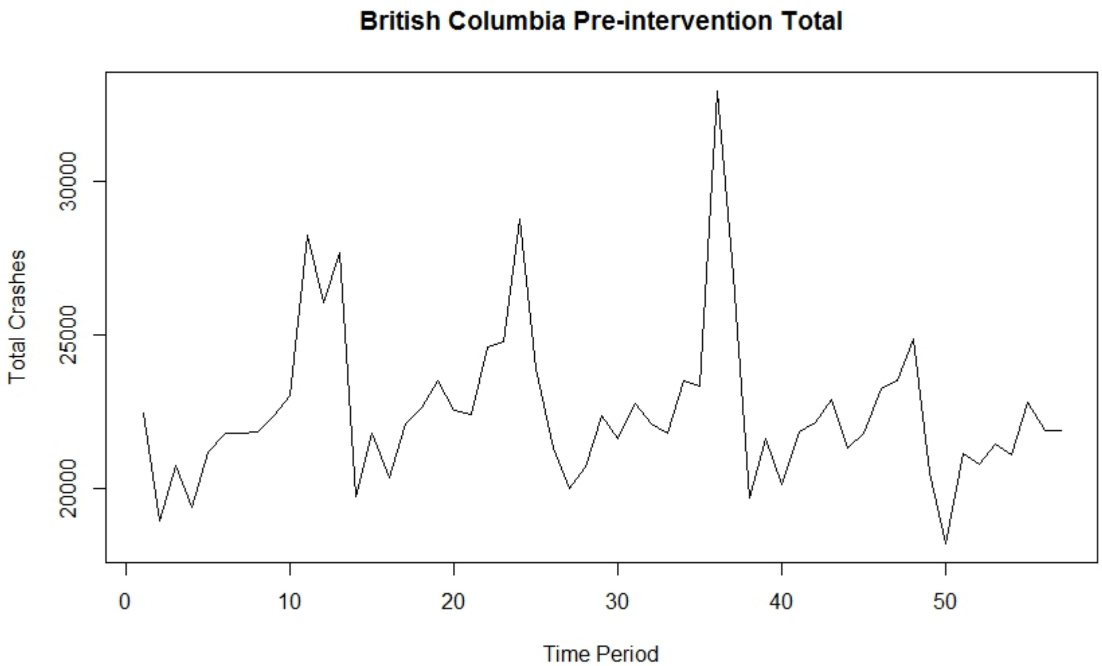

Figure 78: BC Pre-intervention Trend (Total)

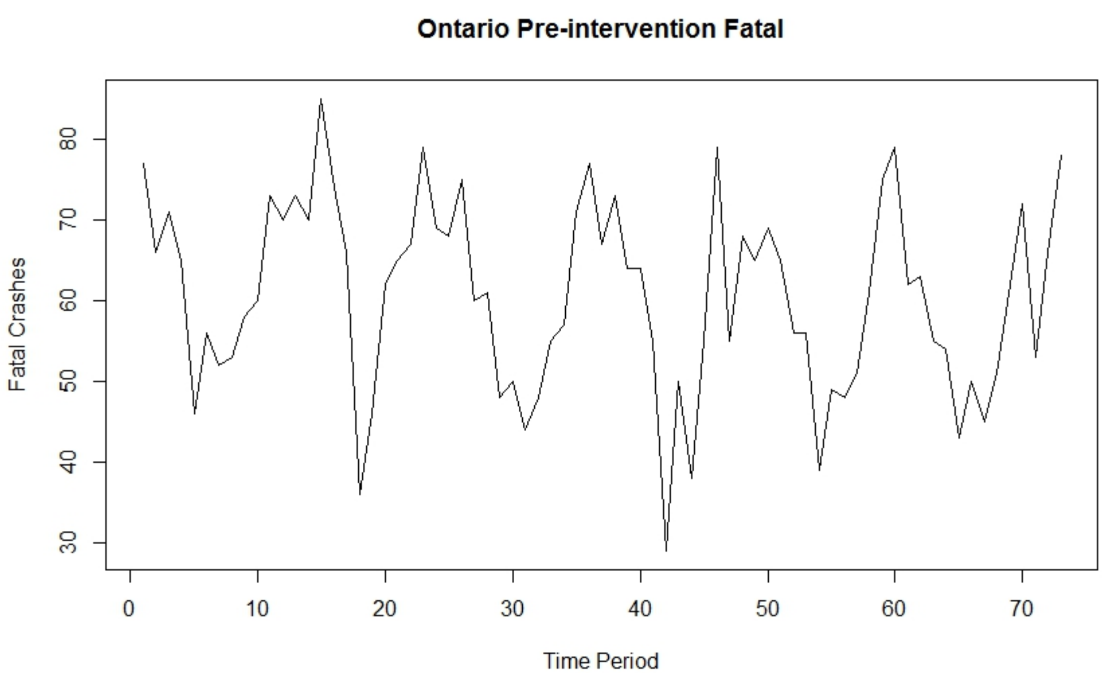

Figure 79: ON Pre-intervention Trend (Fatal)

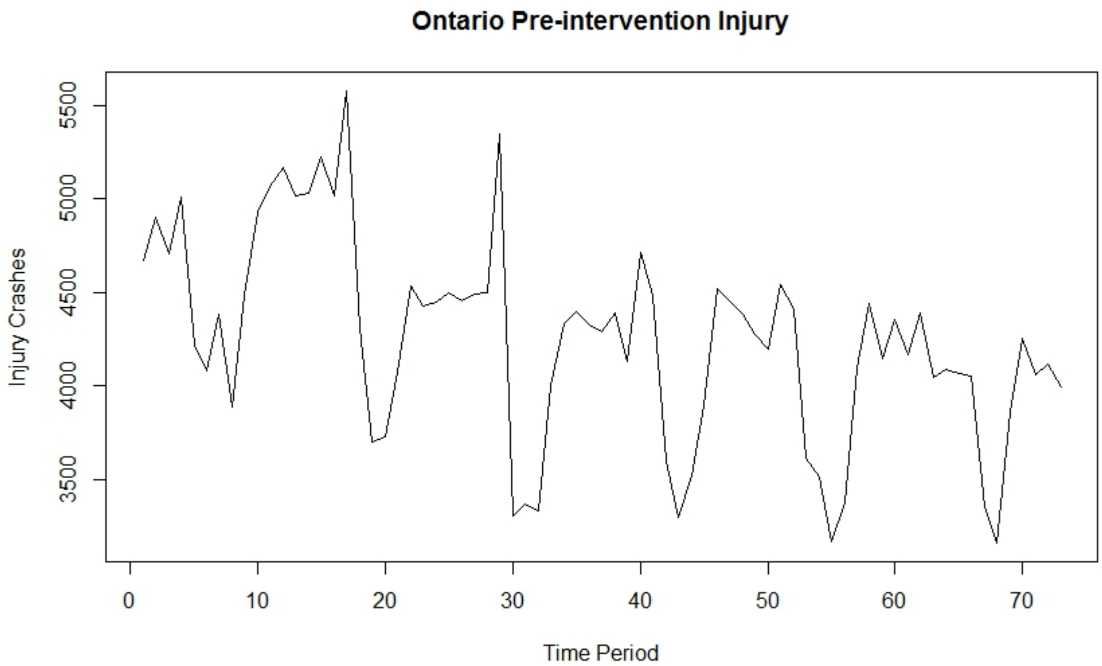

Figure 80: ON Pre-intervention Trend (Injury)

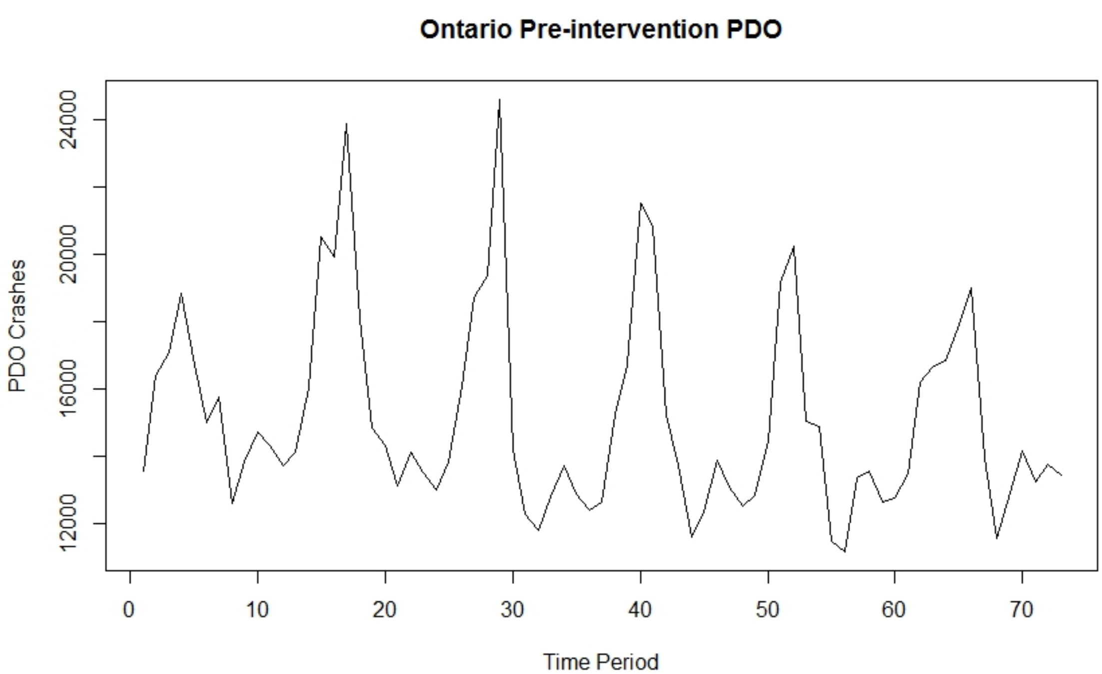

Figure 81: ON Pre-intervention Trend (PDO)

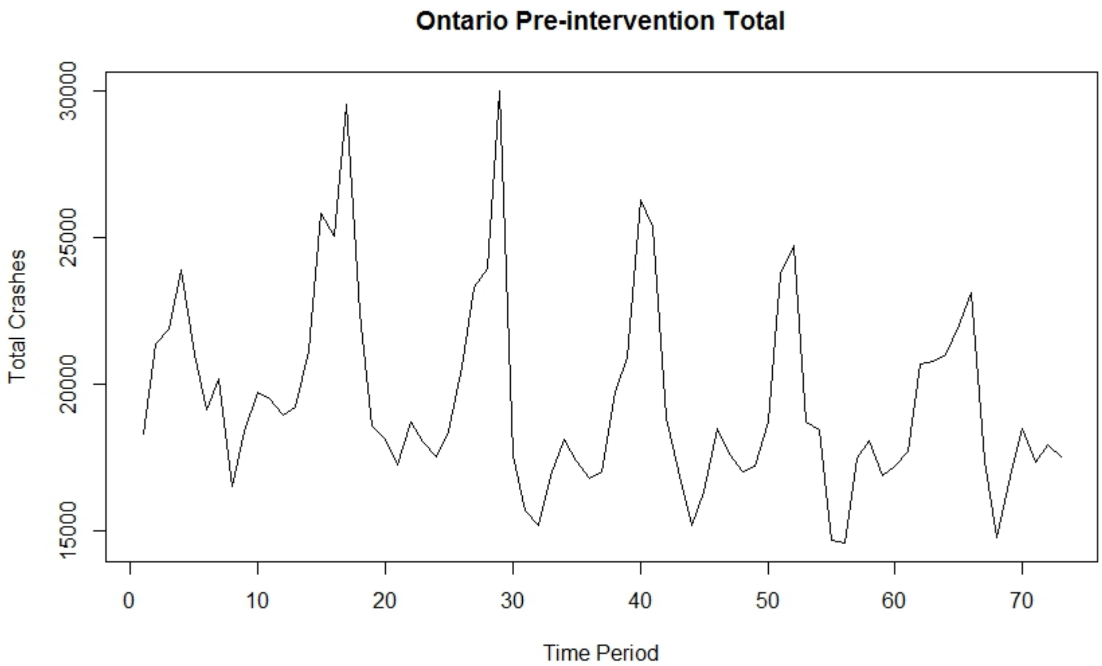

Figure 82: ON Pre-intervention Trend (Total)

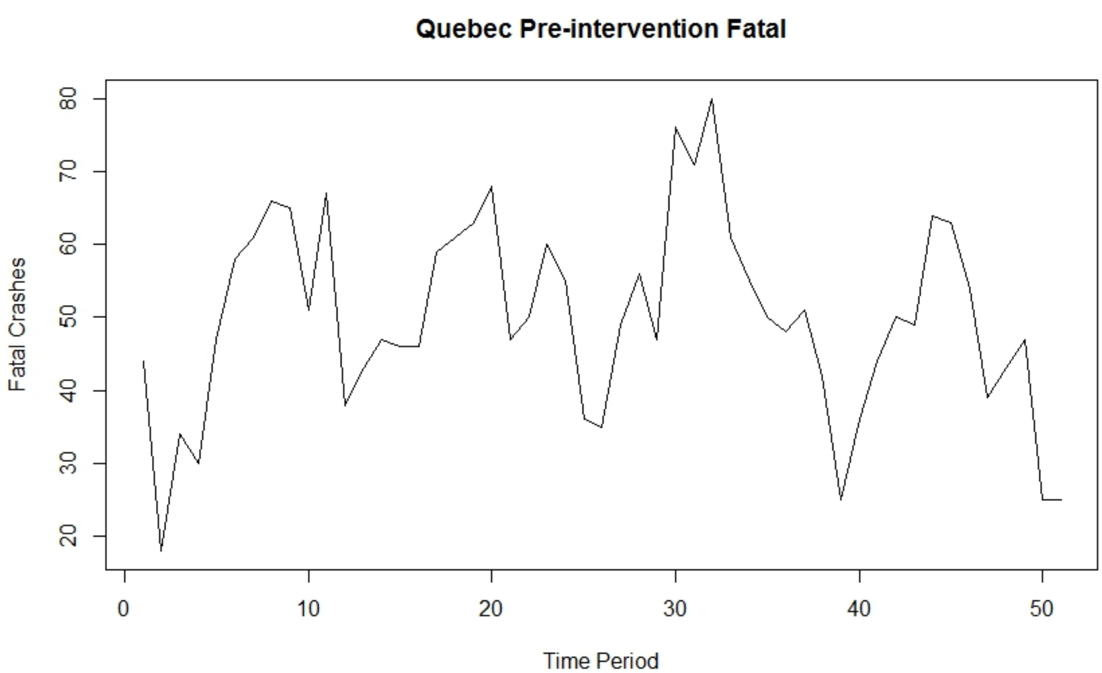

Figure 83: QC Pre-intervention Trend (Fatal)

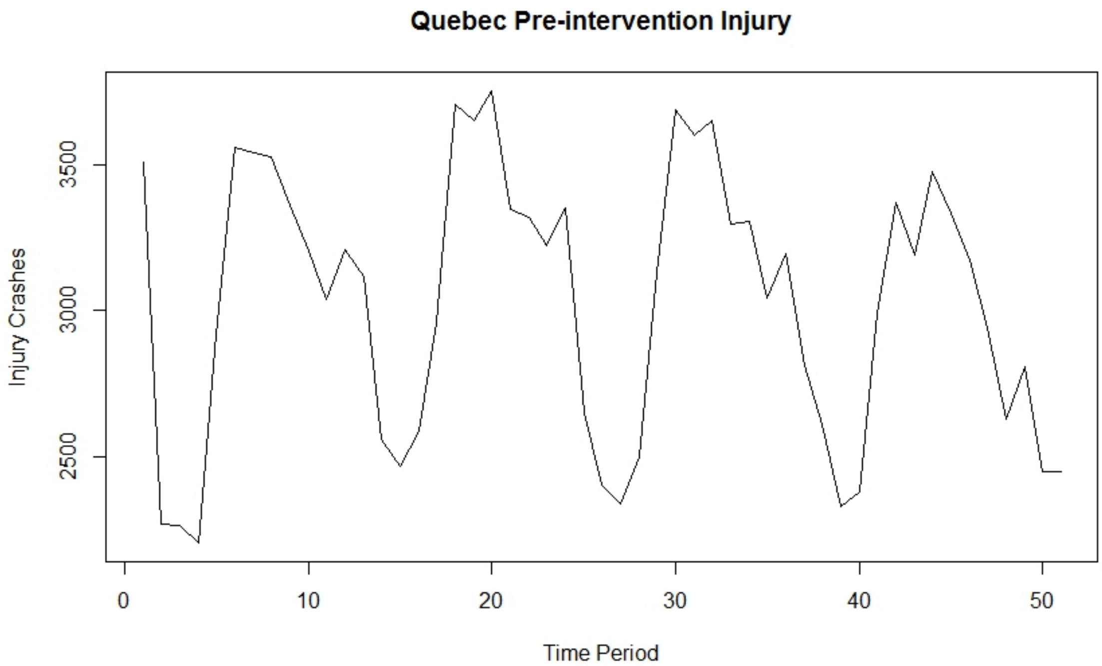

Figure 84: QC Pre-intervention Trend (Injury)

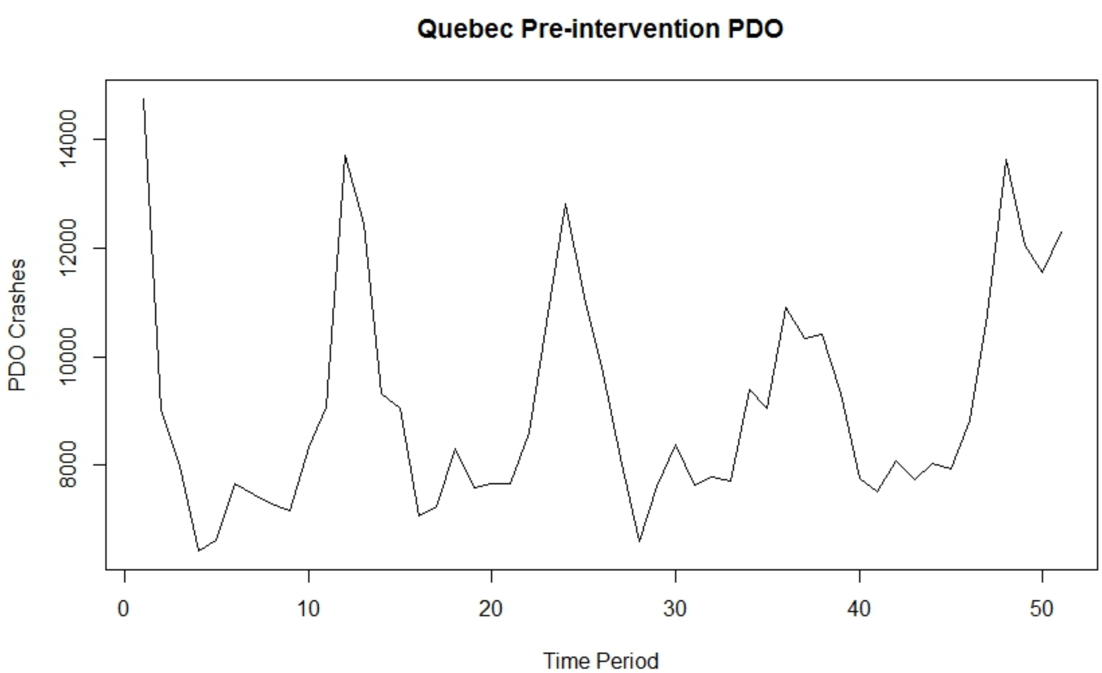

Figure 85: QC Pre-intervention Trend (PDO)

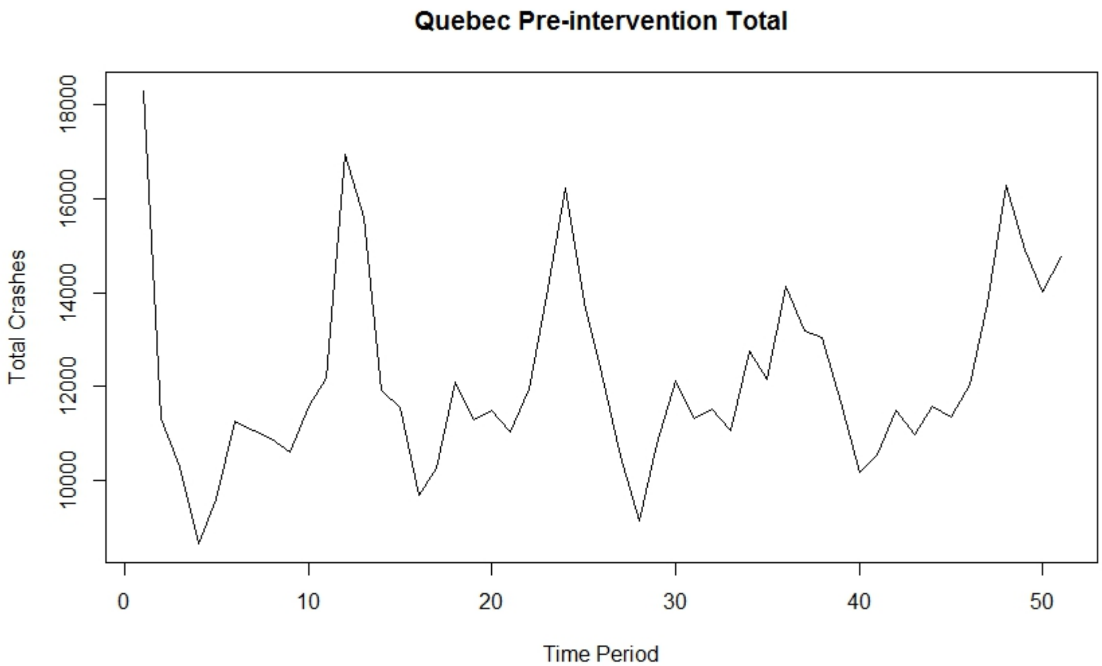

Figure 86: QC Pre-intervention Trend (Total)

B.7 Change in Collisions Post-Law:

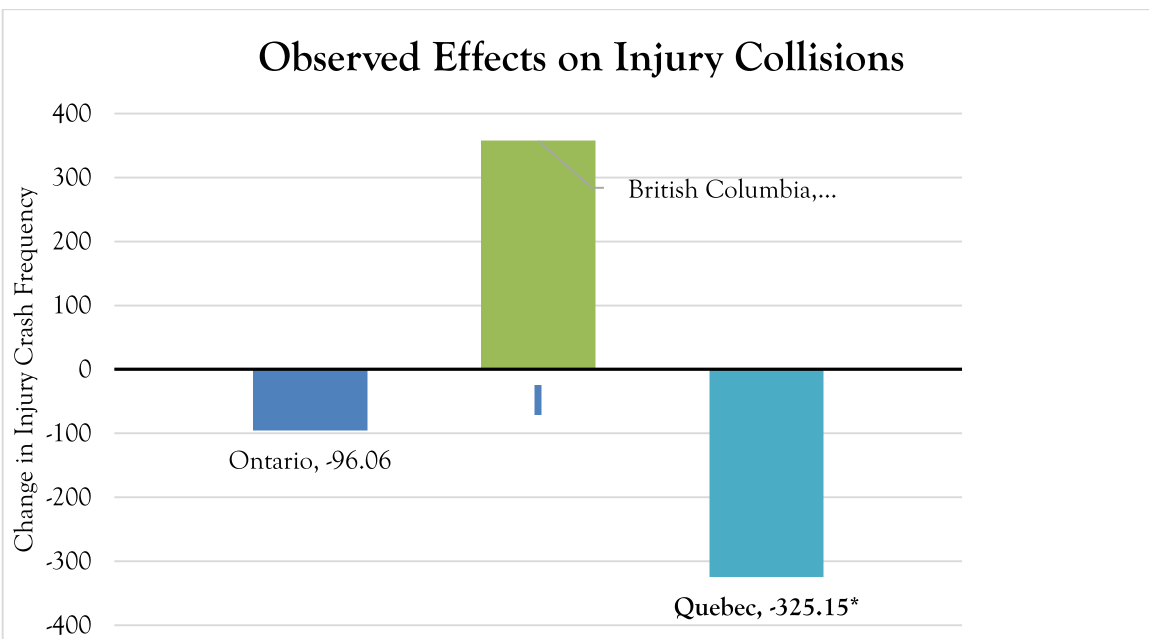

Figure 87: Change in Injury Collisions in Post-Intervention Period

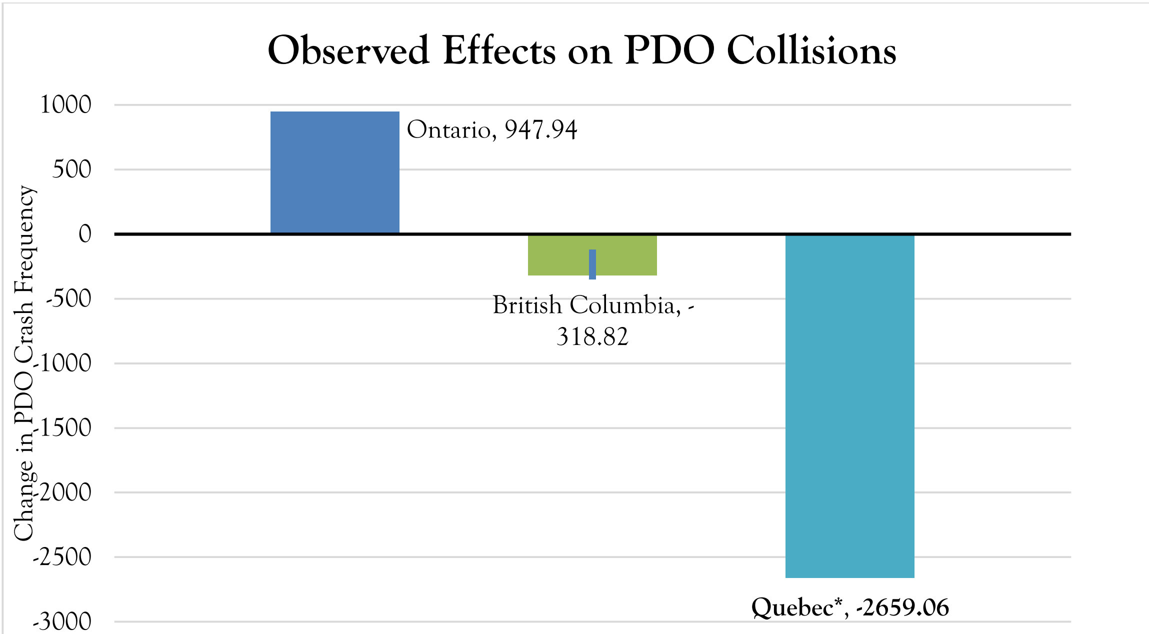

Figure 88: Change in PDO Collisions in Post-Intervention Period