

# Development of CMFs for Traffic Signal Installation at High-Speed Intersections

**Final Report**  
**September 2025**



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| <b>16. Abstract</b><br><p>Between 2016 and 2020, nearly 2,900 fatal, serious injury, and minor injury crashes occurred in Iowa at paved, all-way stop control and partial stop control intersections with at least one approach having a speed limit exceeding 45 mph, i.e., high-speed intersections. This increases to nearly 7,800 fatal, serious injury, and minor injury crashes when considering all paved, unsignalized intersections in the state. At the national level, 18% of all fatal crashes occurred at unsignalized intersections in 2018.</p> <p>Several factors can contribute to crashes at unsignalized intersections, including drivers failing to recognize the intersection, not complying with the traffic control, or selecting inappropriate gaps. Additionally, reaction times are reduced as speeds increase, and the severity of crashes is greater. In fact, the safe system speed for “car/car (side impact, intersections)” crashes is only approximately 30 mph. Traffic signal installation is a countermeasure that may be considered at high-speed intersections; however, national research presents mixed findings on its effectiveness.</p> <p>Since Iowa has a robust intersection database, high-quality crash data, and prior experience developing intersection safety performance functions (SPFs), this research focused on creating Iowa-specific crash modification factors (CMFs) for signalizing high-speed intersections. A five-step methodology was implemented.</p> <p>This research revealed that signal installations at non-ramp high-speed locations increase all but broadside crashes on most facility types. The findings showed that signal installation at high-speed intersections reduced broadside crashes by less than 64%, while rear-end crashes increased by more than 70%, depending on intersection geometric characteristics. Additional CMF values were derived for subsets of high-speed intersection types, including divided, undivided, three-leg, and four-leg intersections. This report showcases a comparative analysis of the impact of signalization on different classes of high-speed intersections. The study’s results were validated through hypothesis tests of proportions analysis and comparisons with existing literature.</p> |                                                                    |                                                                        |                        |
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# **DEVELOPMENT OF CMFs FOR TRAFFIC SIGNAL INSTALLATION AT HIGH-SPEED INTERSECTIONS**

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## EXECUTIVE SUMMARY

Between 2016 and 2020, nearly 2,900 crashes involving fatalities or injuries occurred at high-speed, unsignalized intersections in Iowa with at least one approach exceeding 45 mph. This number rises to almost 7,800 crashes when considering all paved, unsignalized intersections statewide. Traffic signal installation is a countermeasure that may be considered at high-speed intersections; however, national research presents mixed findings on its effectiveness. This study aimed to develop Iowa-specific crash modification factors (CMFs) for signaling high-speed intersections, leveraging the state's robust data systems and past work on intersection safety performance functions (SPFs).

A comprehensive literature review revealed that empirical Bayes (EB) and cross-sectional approaches are the most widely used methods to develop CMFs, each with strengths and limitations. Given limitations in before-and-after crash data for most Iowa intersections, this study used a cross-sectional analysis, comparing crash patterns at signalized and unsignalized intersections while controlling for traffic volumes and geometry.

Data were compiled from multiple sources, including the Iowa Department of Transportation's (DOT's) intersection inventory, crash database, and roadway asset management system (RAMS), along with supplemental tools like Google Street View and Pathways PathWeb. Seventy-three signalized non-ramp high-speed intersections were identified as treatment sites, and 813 non-ramp unsignalized intersections were retained as reference sites after rigorous screening for geometric and surface conditions.

A total of 252 SPFs were developed to model crashes by severity, manner of collision, vehicle action, and direction of travel. From these, 94 CMFs were found to be statistically significant at the 5% significance level. The results showed a consistent increase in total crashes following signal installation, driven largely by increases in rear-end, same-direction sideswipe, and stopped-vehicle crashes. However, broadside and perpendicular-direction crashes tended to decrease, consistent with expectations from signal installation. The CMFs for broadside crashes ranged from 0.383 to 0.639, indicating significant reductions. In contrast, rear-end crash CMFs exceeded 3.0.

Validation was conducted using comparisons with the CMFs in the Federal Highway Administration (FHWA) CMF Clearinghouse, hypothesis tests of crash type proportions, and local agency outreach regarding signal phasing. Results confirmed that permissive and protected-permissive left-turn phasing were associated with increased left-turn and angle crashes, suggesting that protected-only phasing may improve outcomes.

The study concluded that signal installation at high-speed intersections does not consistently reduce overall crashes or serious injuries and, in many cases, increases lower-severity crashes. Therefore, alternative intersection designs—such as roundabouts, reduced-conflict intersections, and median closures—should be considered prior to signal installation. Any signal installed should be accompanied by an access management strategy and include protected-only left-turn phasing where feasible.



## INTRODUCTION

Between 2016 and 2020, nearly 2,900 fatal, serious injury, and minor injury crashes occurred in Iowa at paved, all-way stop control and partial stop control intersections with at least one approach having a speed limit exceeding 45 mph, i.e., high-speed intersections. This increases to nearly 7,800 fatal, serious injury, and minor injury crashes when considering all paved, unsignalized intersections in the state. At the national level, 18% of all fatal crashes occurred at unsignalized intersections in 2018. Several factors can contribute to crashes at unsignalized intersections, including drivers failing to recognize the intersection, not complying with traffic control, or selecting inappropriate gaps. Additionally, reaction times are reduced as speeds increase, and the severity of crashes is greater.

Traffic signal installation is a countermeasure that may be considered at high-speed intersections. The Federal Highway Administration (FHWA) Crash Modification Factors Clearinghouse (<https://www.cmfclearinghouse.org>) has several crash modification factors (CMFs) pertaining to traffic signal installation. However, the CMF values can vary widely, originate from studies of various quality levels and analysis periods, and employ data from single geographic regions or states.

A CMF is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site. A CMF value below 1 indicates a reduction in crash count following countermeasure implementation. For example, if an intersection has 10 total crashes per year and a countermeasure with a CMF of 0.8 for all crashes is applied, it is expected that 8 crashes will occur annually following the implementation of the countermeasure.

The state of Iowa is well positioned to develop Iowa-specific CMFs for signaling high-speed intersections, given the state's comprehensive intersection database, high-quality crash data, and past/ongoing efforts to develop intersection safety performance functions (SPFs). Therefore, the objective of this project was to develop Iowa-specific CMFs with respect to the installation of traffic signals at high-speed intersections. This report summarizes the work conducted as part of this project and consists of six main chapters:

- Introduction, discussing the value of this project
- Literature Review, summarizing the state of the practice
- Data Sources, providing a comprehensive overview of the data sources utilized in this project
- Methodology, detailing the step-by-step analysis conducted to develop the CMFs
- Findings and Discussion, highlighting the results of the analysis and the effectiveness of signalization at high-speed intersections in reducing crashes
- Conclusions, summarizing the key takeaways and recommendations for future implementation or research

## LITERATURE REVIEW

A comprehensive review of the methodologies commonly used to develop CMFs was conducted, focusing on studies aimed at developing CMFs for signalizing intersections. This section summarizes the findings of the literature review.

### CMF Development Methods

CMF development methods are generally classified into two categories: observational before-and-after studies and cross-sectional studies.

#### *Observational Before-and-After Studies*

Observational before-and-after studies are applied when the exact installation date of the treatment is known and when there is enough before and after crash data. Observational before-and-after studies are prevalent in the literature. The literature has five types of these studies.

#### Naïve Before-and-After Studies

This approach calculates the CMF of a treatment based only on sites where the treatment has been applied. It is considered the simplest approach to calculate a CMF. It calculates the CMF as the ratio of the after-treatment crashes to the before-treatment crashes. This method does not consider how the specific treatment sites compare to other similar sites or overall safety trends. It usually overestimates the treatment's impact due to the regression-to-the mean problem, which happens when a specific location experiences an unusually high count of crashes in a given period followed by a low count of crashes in the following period due to natural fluctuations, meaning that the crash count tends to converge to a long-term mean.

#### Yoked Comparison and Comparison Group Approaches

These approaches account for the changes in external factors over time that the naïve approach does not. This is accomplished by pairing each treatment site with a comparison site (or group of sites) that did not receive the treatment and that has a similar crash history trend and comparable traffic, geometric, and geographic characteristics. Assuming that all factors have changed in the same manner at both the treatment and comparison sites, the ratio of the comparison sites' crashes in the after period to those in the before period is used to calculate the crashes in the after period at the treated sites if the countermeasure had not been implemented. The CMF is calculated as the ratio of the observed crashes at the treatment sites to the calculated crashes if no countermeasure had been implemented. The primary downside of this approach is that it does not account for the regression-to-the-mean problem.

## Empirical Bayes Approach

In the empirical Bayes (EB) approach, the after-treatment crash frequency if the countermeasure had not been implemented is calculated more precisely using a large set of untreated sites that have similar characteristics to the treated sites. SPFs and their overdispersion factors, which are a key component in the EB approach, are used to estimate the expected count of crashes at the treatment sites if no treatment had been applied. This approach addresses the common regression-to-the-mean issue in before-and-after studies. It incorporates traffic volume changes, makes better use of limited data, and accounts for external factors that might influence crash frequency.

## Full Bayes Approach

The full Bayes (FB) approach is similar to the EB approach in that both utilize a reference population. However, the FB approach substitutes the EB approach's point estimate with an expected crash frequency and its variance, generating a distribution of likely values. The FB approach allows for a multivariate analysis. It also treats each time period as an individual data point and integrates the estimation of the SPF and treatment effects within a single step, whereas these are two separate steps in the EB method. However, these advantages come at the expense of high complexity levels.

## *Cross-Sectional Studies*

Cross-sectional studies are often employed when it is challenging to isolate the impact of a single treatment due to the presence of multiple treatments or when the exact installation date of a treatment is unknown. Two primary cross-sectional CMF development approaches are documented in the literature: the naïve and regression-based methods. Both approaches begin by identifying a set of similar sites based on predefined features such as number of legs, control type, whether the roadway is divided/undivided, number of lanes, area type, and traffic level.

In the naïve method, sites are divided into two groups based on the presence of the treatment. The CMF is calculated as the ratio of the average crash frequency at treatment sites to that at no-treatment sites.

In the regression-based method, regression analysis is utilized to fit an SPF that includes treatment presence as an independent variable. The regression model derives the CMF as the exponent of the treatment variable's coefficient.

## **CMFs for Signalizing Intersections**

The FHWA CMF Clearinghouse was reviewed to identify research studies that developed CMFs for signalizing intersections. This research resulted in the following list:

1. *NCHRP Report 491: Crash Experience Warrant for Traffic Signals* (1)
2. *Accident Modification Factors for Traffic Engineering and ITS Improvements* (2)
3. *Validation and Application of Highway Safety Manual (Part D) in Florida* (3)
4. Comparison of safety evaluation approaches for intersection signalization in Florida (4)
5. *Safety Evaluation of Signal Installation with and without Left Turn Lanes on Two Lane Roads in Rural and Suburban Areas* (5)
6. A full Bayes before-after study accounting for temporal and spatial effects: Evaluating the safety impact of new signal installations (6)

These studies were reviewed with a focus on the analysis methods, factors considered for grouping intersections, types of crashes, number of treatment and reference sites, and resulting CMF values. The subsections below summarize the review findings.

### *Analysis Methods*

Table 1 shows that in all research studies except for study number 6, the EB approach was used to develop the CMFs. Study number 6, on the other hand, utilized the FB approach. Study number 3, however, investigated all methods except FB and yoked comparison across a wide spectrum of crash types. Consequently, CMF values resulting from various methods were selected based on statistical significance.

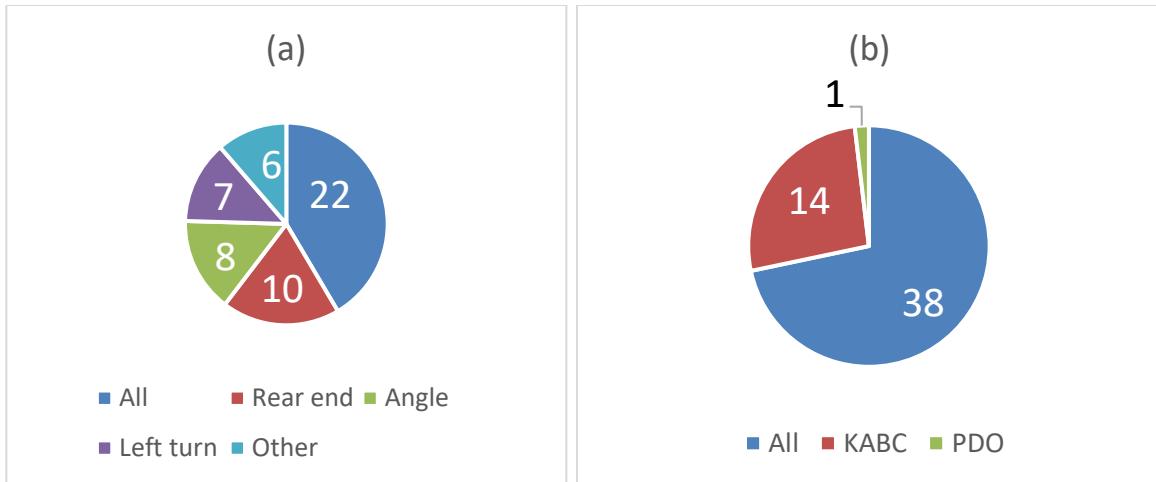
**Table 1. Summary of analysis methods**

| <b>Research Study</b> | <b>Naïve Before-and-After</b> | <b>Comparison Group</b> | <b>EB</b> | <b>FB</b> | <b>Cross-Sectional</b> |
|-----------------------|-------------------------------|-------------------------|-----------|-----------|------------------------|
| <b>1</b>              |                               |                         | Y         |           |                        |
| <b>2</b>              |                               |                         | Y         |           |                        |
| <b>3</b>              | Y                             | Y                       | Y         |           | Y                      |
| <b>4</b>              |                               |                         | Y         |           |                        |
| <b>5</b>              |                               |                         | Y         |           |                        |
| <b>6</b>              |                               |                         |           | Y         |                        |

### *Crash Types*

Figure 1(a) shows that the majority (nearly 60%) of the developed CMFs considered target crashes. Among these, rear-end collisions were the most frequently addressed, with 10 CMFs, followed by angle crashes and left-turn crashes with 6 CMFs. Other less common crash types, such as right turn same roadway, right turn different roadway, sideswipe, and head-on, each had fewer than 3 developed CMFs, totaling 6 CMFs. Notably, the relatively low frequency of target crashes led to the development of CMFs that do not consider crash severity. Figure 1(b) illustrates that 72% of the developed CMFs are applicable to all crashes.





**Figure 1. CMFs by (a) crash type and (b) crash severity**

### *Sample Sizes*

Table 2 demonstrates the extensive variation in sample sizes among the reviewed research studies. The sample sizes range from 2 to 100 treatment sites and from 19 to 1,405 reference sites. Notably, the sample size is significantly influenced by the factors used for selecting the treatment and reference sites, which are outlined in the subsequent section.

**Table 2. Summary of sample sizes**

| <b>Research Study</b> | <b>Sample Size</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>1</b>              | <p>Intersections converted from stop to signal:</p> <ul style="list-style-type: none"> <li>• 3-leg: 22</li> <li>• 4-leg: 100</li> </ul> <p>A reference group of signalized intersections:</p> <ul style="list-style-type: none"> <li>• 3-leg: 19</li> <li>• 4-leg: 96</li> </ul> <p>A reference group of stop-controlled intersections:</p> <ul style="list-style-type: none"> <li>• 3-leg: 99</li> <li>• 4-leg: 199</li> </ul>                                                                                                                                                                                                                     |
| <b>2</b>              | <p>Different sample sizes were obtained from both California and Minnesota. Below is the breakdown of the sample sizes:</p> <p>California:</p> <ul style="list-style-type: none"> <li>• 3-leg/2 lanes on major road: treatment sites: 4, and reference sites: 1,405</li> <li>• 4-leg/2 lanes on major road: treatment sites: 14, and reference sites: 742</li> <li>• 4-leg/4 lanes on major road: treatment sites: 10, and reference sites: 183</li> </ul> <p>Minnesota</p> <ul style="list-style-type: none"> <li>• 3-leg: treatment sites: 2, and reference sites: 522</li> <li>• 4-leg: treatment sites: 15, and reference sites: 763</li> </ul> |
| <b>3</b>              | <p>Treatment sites: 32 intersections</p> <ul style="list-style-type: none"> <li>• Rural areas: 8, and urban areas: 24</li> <li>• 3-leg: 15, and 4-leg: 9</li> </ul> <p>Comparison sites: 202 sites with similar roadway characteristics and annual average daily traffic (AADT) values</p>                                                                                                                                                                                                                                                                                                                                                          |
| <b>4</b>              | This publication could not be accessed. The only information available is that the sample size is greater than 50 intersections.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| <b>5</b>              | <p>Treatment sites (3-leg: 36, and 4-leg: 81)</p> <p>Reference sites (3-leg: 129, and 4-leg: 276)</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| <b>6</b>              | <p>Treatment sites: 19 intersections</p> <p>Reference sites: 107 intersections</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |

*Considered Factors*

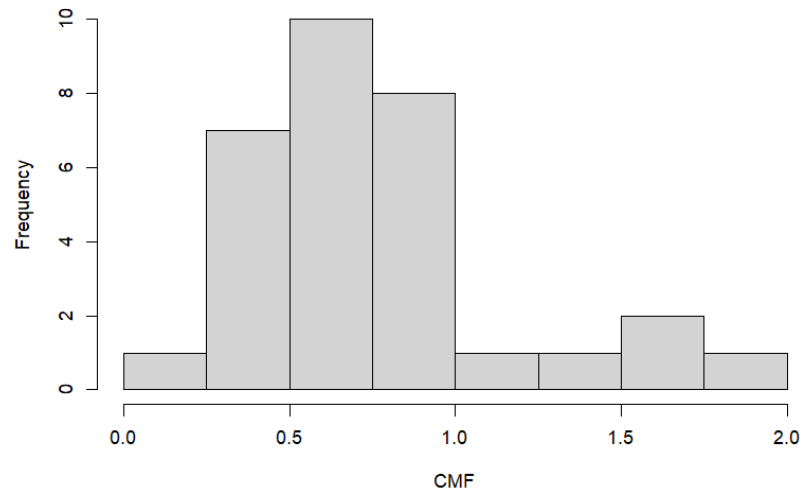
The factors utilized for grouping the treatment sites and selecting corresponding reference sites are summarized in Table 3. The number of legs is the most frequently used factor. Among the factors, AADT is noteworthy because it was used to conduct a disaggregate analysis to assess how the statistical significance of a CMF changes when grouping intersections based on AADT.

**Table 3. Summary of considered factors**

| <b>Research Study</b> | <b>Factors</b>                                                                                                                                                                                                                                                                                                                                                 |
|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>1</b>              | AADT<br>Speed<br>Geometry: <ul style="list-style-type: none"> <li>• Number of legs</li> <li>• Sight distance adequacy</li> </ul>                                                                                                                                                                                                                               |
| <b>2</b>              | AADT<br>Geometry: <ul style="list-style-type: none"> <li>• Number of legs</li> <li>• Number of lanes</li> </ul>                                                                                                                                                                                                                                                |
| <b>3</b>              | Area type<br>Number of legs                                                                                                                                                                                                                                                                                                                                    |
| <b>4</b>              | This publication could not be accessed. The only factor listed in the abstract is AADT.                                                                                                                                                                                                                                                                        |
| <b>5</b>              | Geometry: <ul style="list-style-type: none"> <li>• Number of legs</li> <li>• Number of lanes</li> <li>• No left-turn lanes on the major road</li> <li>• Stop-controlled on the minor road</li> </ul> Location: <ul style="list-style-type: none"> <li>• No public street intersection within 100 ft</li> <li>• No rail grade crossing within 500 ft</li> </ul> |
| <b>6</b>              | Geometric design<br>Traffic control characteristics                                                                                                                                                                                                                                                                                                            |

*Resulting CMF Values*

Figure 2 indicates that the majority of the developed CMFs are below 1 (86%), suggesting a reduction in crash frequencies following signal installation. Notably, all CMFs greater than one pertain to rear-end collisions occurring in both urban and rural areas, with the original intersection control type being all-way and partial stop control. Signals are well known for the dilemma zone, in which drivers must decide whether to stop or proceed before the signal turns red. The various decisions made by drivers result in a higher probability of rear-end crashes at signalized intersections (7).



**Figure 2. Distribution of CMF values**

## DATA SOURCES

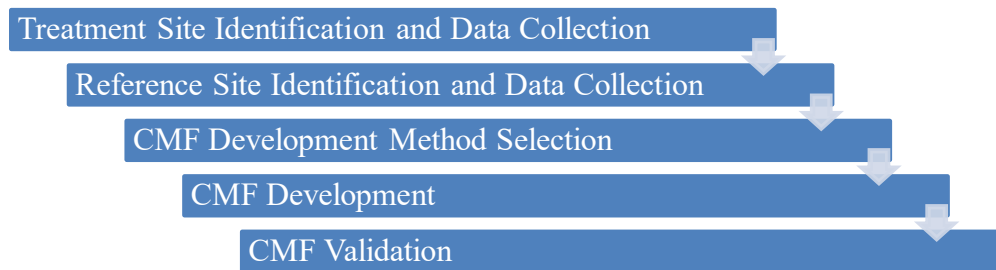
For this study, a variety of data sources were utilized to collect information about the treatment sites (i.e., signalized intersections) and the reference sites (i.e., unsignalized intersections). The data sources used and their usage are shown in Table 4.

**Table 4. Data sources and usage**

| <b>Data Source</b>                              | <b>Usage</b>                                                                                                                                                                                                                                                                       |
|-------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Intersection Inventory Database                 | Iowa DOT intersection database, developed in 2017 with targeted updates made in 2023. Used to identify the treatment and reference sites.                                                                                                                                          |
| Crash Database                                  | Iowa DOT reportable crash database. Used to obtain the count of crashes at each treatment and reference site.                                                                                                                                                                      |
| Iowa DOT Roadway Asset Management System (RAMS) | Three RAMS layers—Iowa linear reference system (LRS) Network, Traffic Information, and Surface Type—were used to identify where ramps are located, obtain AADT values at each leg of the treatment sites, and exclude reference sites with at least one unpaved leg, respectively. |
| Google Street View                              | 360-degree roadway images collected by Google. Used to assess road characteristics at treatment sites, including speed limits, control types, signal installation dates, lane configurations, and the presence of medians.                                                         |
| Pathways PathWeb                                | Panoramic, rear-facing, and roadway surface images, collected for the Iowa DOT by Pathways. Used as an alternative to Google Street View when more recent images were available.                                                                                                   |
| Iowa Geographic Map Server                      | Statewide, multiyear aerial image dataset. Used to collect the geometric characteristics of signalized intersections when PathWeb and Google Street View were unable to provide the necessary information.                                                                         |

## METHODOLOGY

A five-step methodology, presented in Figure 3, was followed to develop CMFs for signalizing high-speed intersections. The following subsections provide details about each step in the methodology.

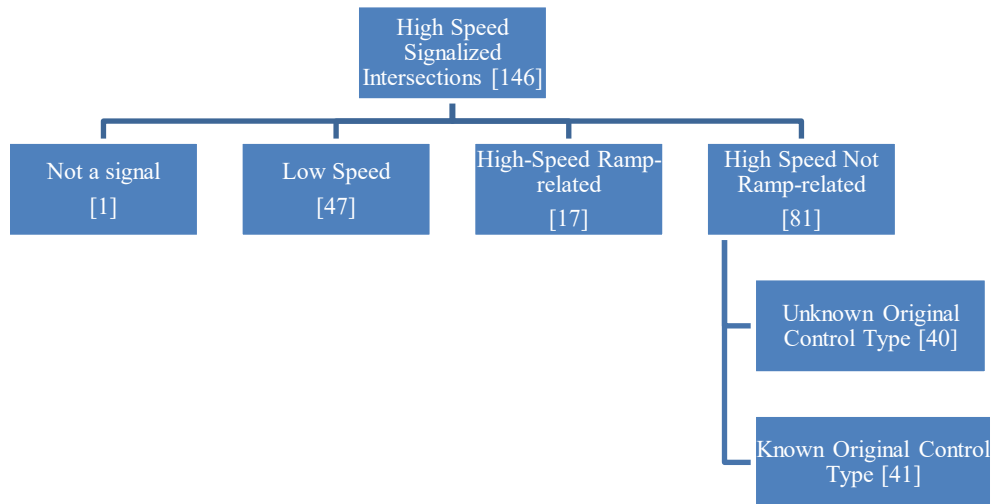


**Figure 3. High-level project methodology**

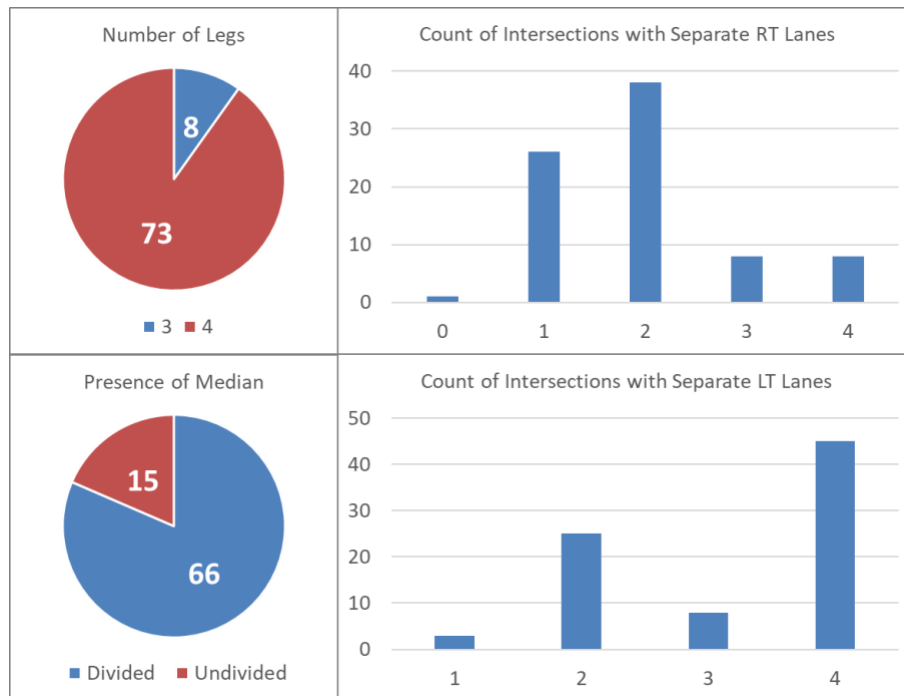
### **Treatment Site Identification and Data Collection**

In this step, the intersection database was used to identify all treatment sites, with a focus on signalized intersections where at least one leg has a speed limit greater than 45 mph. Additional characteristics were manually collected using resources such as Google Street View, PathWeb, and the Iowa Geographic Map Server to establish a homogeneous set of treatment sites. Key intersection characteristics included the presence of medians, the number of legs with separate right- and left-turn lanes, the presence of ramps as intersection legs, the traffic control type prior to signal installation, and the dates of the first and last images showing the presence/absence of signalization.

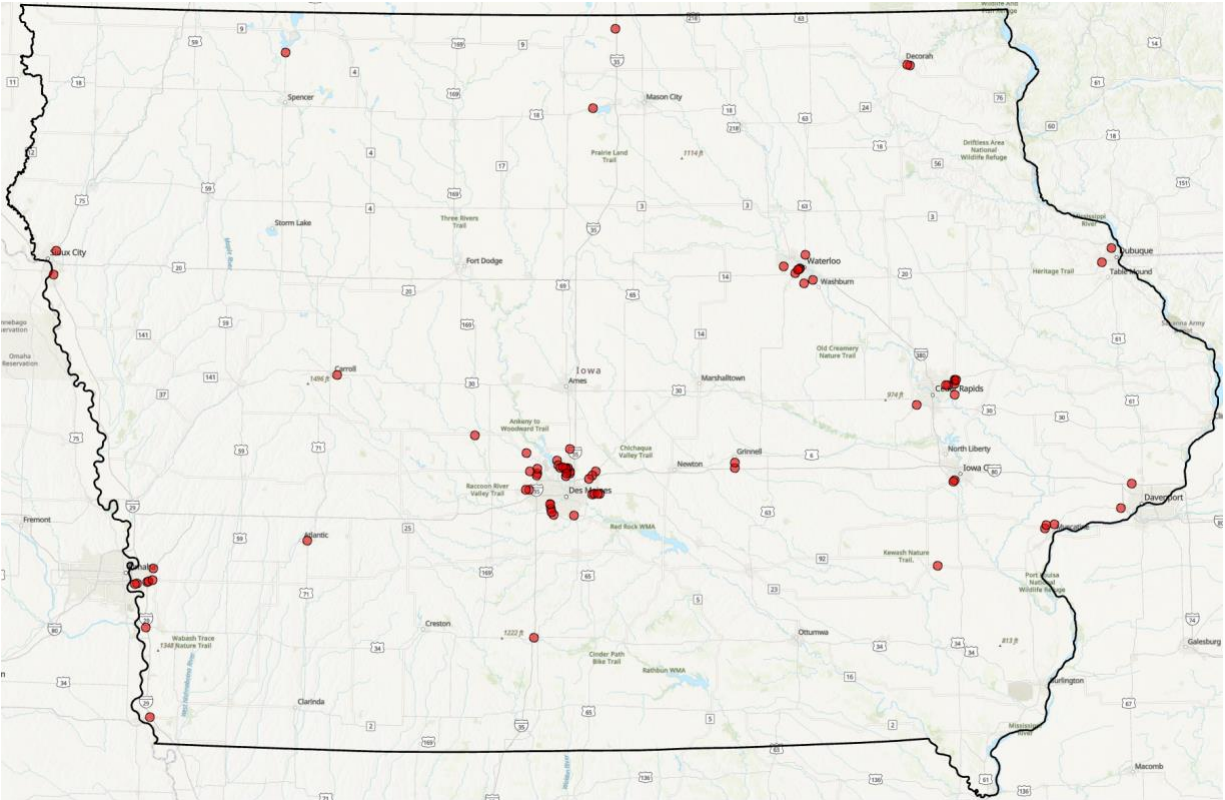
The dates of the first and last images showing the presence/absence of signalization were critical in assessing the feasibility of conducting an EB before-and-after analysis for CMF development, depending on the availability of pre- and post-installation crash data. These image dates were also used to verify the accuracy of the control type reported in the intersection database. Additionally, the speed limit was validated for all legs of each intersection. As a result of this manual data collection, the high-speed signalized intersection database was refined, as shown in Figure 4. Figure 5 and Figure 6 highlight the major characteristics of the non-ramp-related high-speed signalized intersections and show their spatial distribution.



**Figure 4. Breakdown of high-speed signalized intersections in the intersection database**



**Figure 5. Geometric characteristics of non-ramp-related high-speed signalized intersections**



**Figure 6. Map of non-ramp-related high-speed signalized intersections**

In addition to manual data collection, the RAMS Traffic Information layer was used to obtain both major and minor AADT values for each intersection, with a focus on the middle year of the five-year period following signal installation. Furthermore, the five-year crash count was calculated for each intersection, covering the five years after signal installation at the intersections. To expand the list of treatment sites with sufficient after-installation crash data, a second set of CMFs was also developed using three years of crash data.

### **Reference Site Identification and Data Collection**

Regardless of the CMF development methodology, reference sites must be identified to develop SPFs for an EB before-and-after analysis, establish a comparison group for estimating no-treatment crashes at treatment sites, or represent the population of intersections needed to develop cross-sectional models.

The first step in reference site selection was to identify all unsignalized intersections in the intersection database, which resulted in 28,190 potential reference sites. Because the intersection database had not been comprehensively updated since its initial development, the traffic control at each intersection was validated using the following three-step process, which reduced the number of potential reference sites to 28,049 intersections:



1. Spatially join crashes to reference sites. The same methodology used to identify intersection crashes during SPF development, which had been approved by the Iowa Department of Transportation (DOT), was utilized.
2. Create a summary of traffic control at the vehicle level by reference site.
3. Manually review reference sites where at least one crash was reported as having a traffic signal control type, which could suggest that the traffic control changed during the five-year period.

Since ramp-related intersections are inherently different from traditional intersections—in that ramps feature one-way entry and departure—the potential reference sites were separated into ramp-related and non-ramp-related intersections using the following methodology:

1. Spatially join ramps to reference sites using a 250 ft buffer.
2. Identify potential ramp-related reference sites.
3. Manually review the reference sites identified in the previous step.

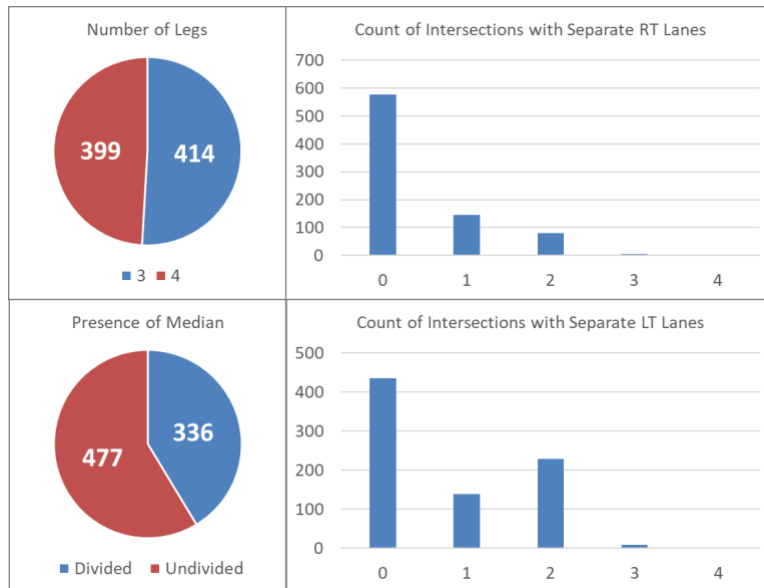
As expected, the majority of the unsignalized intersections were found to be non-ramp related (27,506). Ramp-related intersections were excluded from the analysis because of the complexity of traffic movements and the challenges in accurately assigning crashes to intersections, especially at the reference sites. To ensure that both the treatment and reference sites have similar traffic conditions, the retained non-ramp-related reference sites were limited to intersections with major and minor AADT values within 10% of those of the non-ramp-related treatment sites. This step reduced the number of non-ramp-related reference sites to 1,019.

The last intersection refinement step involved excluding intersections with at least one unpaved leg. The following methodology was used:

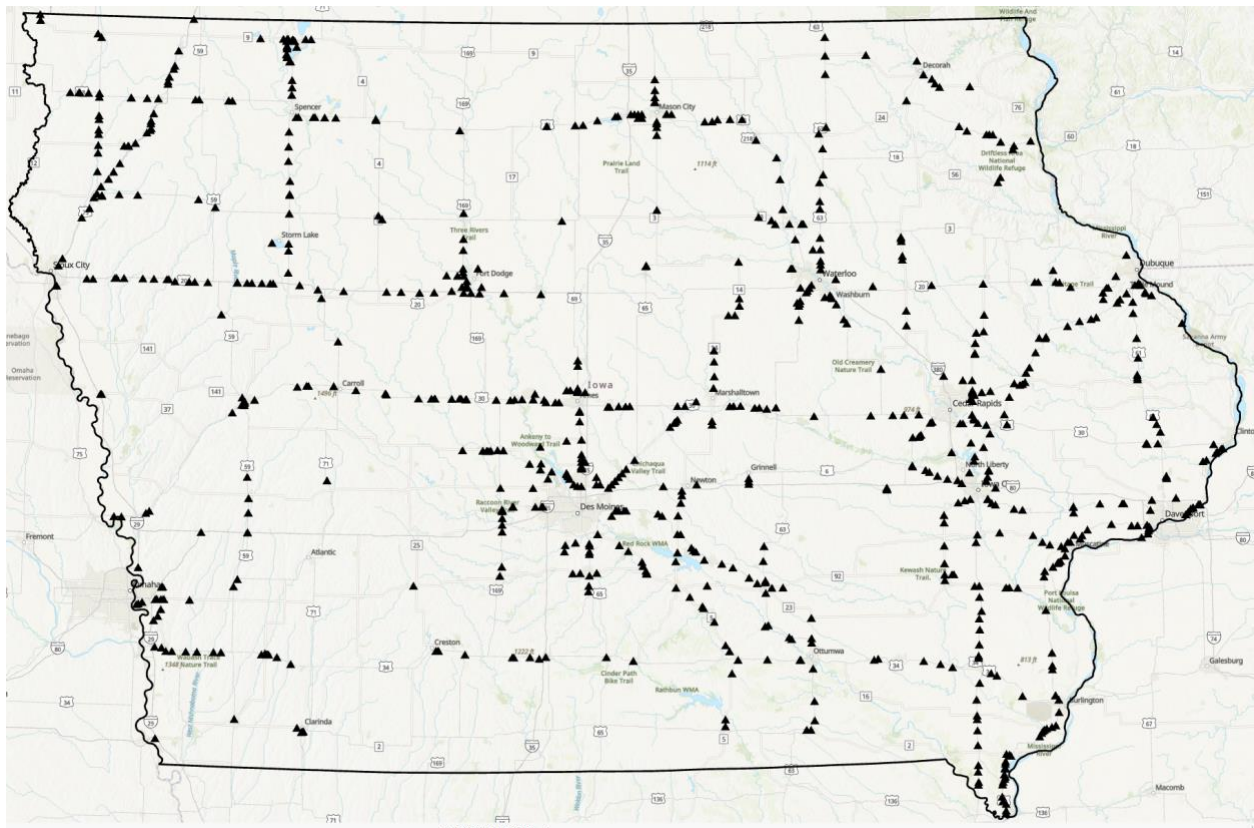
1. Identify unpaved roads using the surface type from the RAMS Surface Type layer.
2. Spatially join unpaved roads to reference sites using a 250 ft buffer.
3. Exclude intersections with at least one unpaved segment within 250 ft.

This reduced the reference sites to 813.

After identifying the reference sites, the number of legs, the presence of a median, and major and minor AADT values were obtained from the intersection database. The team also obtained the number of legs with separate right-turn (RT) and left-turn (LT) lanes from the approach layer of the intersection database. The team was unable to identify 37 reference sites from the approach layer of the intersection database. Therefore, corresponding data were collected manually using Google Street View for these sites. Crashes between 2019 and 2023 were joined to the reference sites and summarized by type and severity. Figure 7 highlights the major characteristics of the non-ramp-related unsignalized intersections. Figure 8 shows the locations of the reference sites.



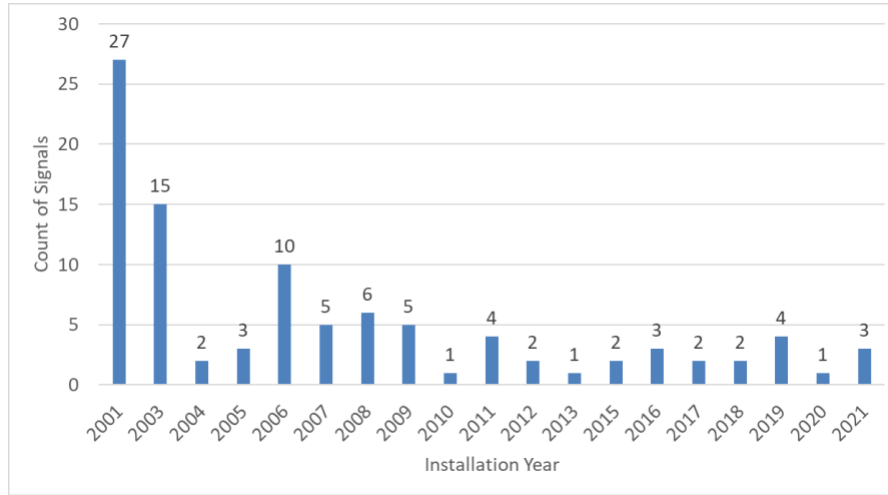
**Figure 7. Geometric characteristics of non-ramp-related high-speed unsignalized intersections**



**Figure 8. Map of non-ramp-related high-speed unsignalized intersections**

## Selection of CMF Development Method

After collecting the characteristics of the treatment and reference sites, the most appropriate method for developing CMFs was selected. Two key factors influenced the selection: the availability of signal installation dates and the availability of crash data from before and after the installations. As shown in Figure 9, most signals were installed before 2014, which limits access to before-installation crash data due to the Iowa DOT's 10-year crash data retention policies. Additionally, only a few signals (eight) were installed after 2019, limiting the availability of sufficient after-installation crash data. Therefore, cross-sectional analysis was selected as the method for developing CMFs in this project.



**Figure 9. Count of signals by installation year**

## CMF Development

To develop CMFs using cross-sectional analysis, SPFs must be fitted with a binary independent variable indicating the presence or absence of a signal at the intersection. The format of the SPFs is shown below:

$$\text{Predicted Crashes} = \exp(\alpha + \beta_1 \ln(\text{MINORAADT}) + \beta_2 \ln(\text{MAJORAADT}) + \beta_3 \text{SIGNAL})$$

The CMF value can be obtained as the exponent of  $\beta_3$ . The statistical significance of the CMF can be assessed by conducting hypothesis testing on the value of  $\beta_3$ , specifically, by testing the presence of strong evidence to prove that the value of  $\beta_3$  is not zero, which thus indicates that the value of the CMF is different than one. The hypothesis testing formulation is shown in the following:

- $H_0: \beta_3 = 0 \rightarrow CMF = 1$
- $H_a: \beta_3 \neq 0 \rightarrow CMF \neq 1$

- If the p-value of this hypothesis testing is less than a predefined significance level (e.g.,  $\alpha = 0.05$ ), there is enough evidence to prove that the CMF value is not 1.

A total of 252 SPFs were developed covering the following: two model types (Poisson and negative binomial), the six homogeneous intersection groups shown in Table 5, in addition to the group of all intersections, and the 18 crash severities and types shown in Table 6.

**Table 5. Homogeneous grouping logic for intersections**

| Factor                                | Groups                               |
|---------------------------------------|--------------------------------------|
| Median presence                       | Divided – Undivided                  |
| Number of legs                        | 3-Leg – 4-Leg                        |
| Number of legs with separate LT lanes | Min. one leg with a separate LT lane |
| Number of legs with separate RT lanes | Min. one leg with a separate RT lane |

**Table 6. Crash severities and types for CMF development**

| Crash Severities                              | Crash Types<br>(Manner of Collision) | Crash Types<br>(Vehicle Action)          | Crash Types<br>(Vehicle Direction of Travel)                |
|-----------------------------------------------|--------------------------------------|------------------------------------------|-------------------------------------------------------------|
| Total (KABCO)                                 | Angle                                | Crash involving a right-turning vehicle  | Crash involving vehicles moving in opposite directions      |
| Fatal through possible injury (KABC)          | Broadside                            | Crash involving a left-turning vehicle   | Crash involving vehicles moving in perpendicular directions |
| Fatal, serious, and minor injury (KAB)        | Rear end                             | Crash involving a vehicle changing lanes | Crash involving vehicles moving in the same direction       |
| Possible injury and property damage only (CO) | Sideswipe same direction             | Crash involving a stopped vehicle        |                                                             |
| Property damage-only (PDO)                    | Sideswipe opposite direction         |                                          |                                                             |
|                                               | Head-on                              |                                          |                                                             |

After identifying the CMFs that were statistically significant at the 5% significance level, additional refinement was performed based on sample size and the goodness of fit of the SPFs. The sample size criteria included crash counts greater than 300 and a reference-to-treatment site ratio exceeding 4:1, which were identified from the literature review. The goodness of fit was evaluated using the cumulative residuals (CURE) deviation percentage (CDP), with a threshold of less than 5%. Some of these assumptions were also relaxed, and the impact on the resulting CMFs was analyzed, as detailed in the Findings and Discussion chapter.

## CMF Validation

To ensure the robustness and reliability of the developed CMFs, three primary validation methods were employed: literature validation, hypothesis tests of proportions, and local agency

outreach. Each method provided a unique perspective on the credibility and applicability of the obtained CMFs.

### *1. Literature Validation*

A comparative analysis was conducted between the obtained CMFs and those available in the literature. This validation step ensured that the estimated CMFs fell within a reasonable range based on previous studies.

### *2. Hypothesis Tests of Proportions*

Two hypothesis tests of proportions were conducted to evaluate differences in crash proportions between signalized and unsignalized intersections and assess whether the proportions of different crash types follow a similar trend to the developed CMFs. The null hypothesis for both tests stated that the proportion of a specific crash type at signalized intersections is equal to that at unsignalized intersections. Two alternative hypotheses were tested:

- The proportion of a specific crash type at signalized intersections is lower than that at unsignalized intersections.
- The proportion of a specific crash type at signalized intersections is higher than that at unsignalized intersections.

### *3. Local Agency Outreach*

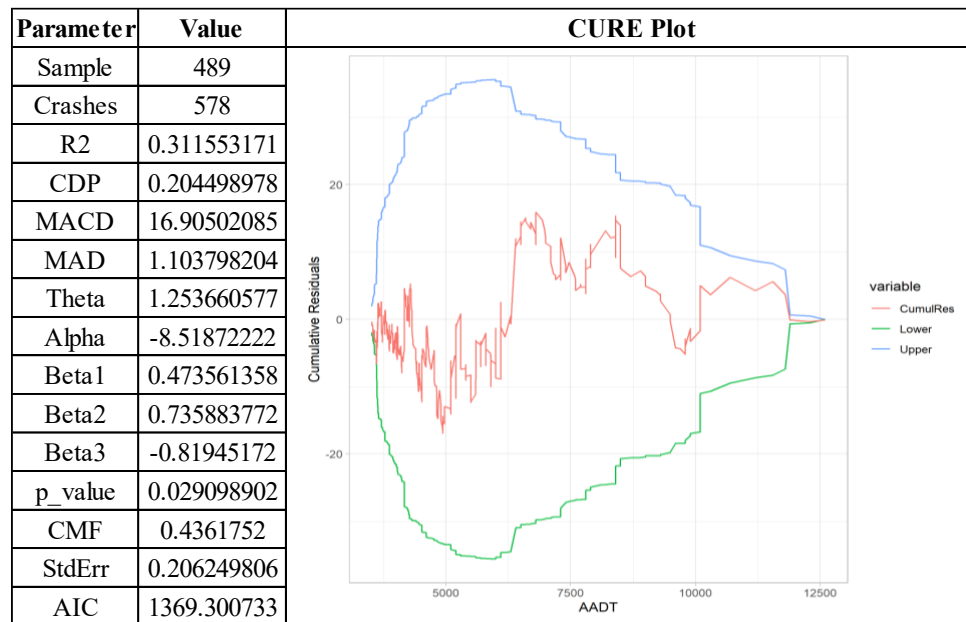
To enhance the contextual understanding of the obtained CMFs, 34 local agencies (counties and cities) were contacted to gather information on signal phasing. This outreach was particularly valuable in explaining unexpected CMF values, especially for angle crashes, by considering the impact of traffic signal operations.

## FINDINGS AND DISCUSSION

This research study resulted in 252 SPFs, from which 252 CMFs were derived for various high-speed intersection characteristics and crash types. Ninety-four CMFs were statistically significant at the 5% significance level. The following subsections provide a detailed discussion of these SPFs and CMFs and the findings of the validation efforts.

### Sample SPF

A sample SPF model summary and CURE plot are shown in Figure 10. This model represents broadside crashes at undivided intersections. The CURE plot shows that cumulative residuals fluctuate around zero without exhibiting specific trends, indicating a good model fit. The model parameters ( $\beta_1$ ,  $\beta_2$ , and  $\beta_3$ ) demonstrate reasonable relationships between predicted crashes, traffic volume, and traffic control. Specifically,  $\beta_1$  and  $\beta_2$  indicate that broadside crash frequency increases with higher major and minor AADT values. Conversely,  $\beta_3$  shows that intersections with traffic signals experience lower broadside crash frequencies compared to those with other traffic control types. The resulting CMF for this model is 0.436, with a p-value of 0.029, indicating high statistical significance. The model's CDP is 0.2%, which is well below the recommended 5% threshold. Appendix A provides a complete table of the 94 SPFs that yielded statistically significant CMFs at the 5% significance level.



**Figure 10. Sample SPF model parameters and CURE plot**

### Discussion of CMF Values

The crash types for which CMF values were calculated can be grouped into four categories: severity, manner of collision, vehicle action, and colliding vehicles' directions of travel. Table 7

presents all of the statistically significant CMF values. The bolded CMFs are those meeting three literature-based criteria listed in the methodology section. Furthermore, the underlined CMFs are those obtained using three years of crash data instead of five years. The following subsections provide detailed observations for each crash type group and the results of consistency and reasonableness checks for the CMF values.

**Table 7. Summary of CMF values**

| Crash Type                                                                                                                                 |                                                             | Intersection Category |              |              |              |              |              |              |
|--------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|-----------------------|--------------|--------------|--------------|--------------|--------------|--------------|
|                                                                                                                                            |                                                             | All                   | 3-Leg        | 4-Leg        | Divided      | Undivided    | Separate RT  | Separate LT  |
| Severity                                                                                                                                   | KABCO                                                       | <b>1.795</b>          | <b>1.504</b> | <b>1.730</b> | <b>2.023</b> | <b>0.798</b> | 1.453        | <b>1.722</b> |
|                                                                                                                                            | KABC                                                        | <b>1.440</b>          |              | <b>1.398</b> | <b>1.614</b> | <b>0.590</b> | 1.202        | <b>1.323</b> |
|                                                                                                                                            | KAB                                                         |                       |              |              |              | <b>0.282</b> |              |              |
|                                                                                                                                            | CO                                                          | <b>2.004</b>          | <b>1.664</b> | <b>1.930</b> | <b>2.278</b> |              | 1.586        | <b>1.961</b> |
|                                                                                                                                            | PDO                                                         | <b>2.033</b>          | <b>1.652</b> | <b>1.958</b> | <b>2.328</b> |              | 1.629        | <b>2.024</b> |
| Manner of Collision                                                                                                                        | Rear end                                                    | 3.690                 | <b>3.408</b> | 3.520        | <b>4.405</b> | <b>1.761</b> | 3.311        | <b>3.865</b> |
|                                                                                                                                            | Sideswipe same-direction                                    | 2.969                 | 2.224        | 3.141        | 2.936        | 2.812        | 2.815        | 2.814        |
|                                                                                                                                            | Angle                                                       | <b>2.436</b>          |              | <b>2.631</b> | 3.229        |              | 1.820        | <b>2.390</b> |
|                                                                                                                                            | Broadside                                                   | <b>0.561</b>          | <b>0.383</b> | <b>0.565</b> | <b>0.639</b> | <b>0.436</b> | <b>0.452</b> | <b>0.563</b> |
|                                                                                                                                            | Head on                                                     | <b>2.276</b>          |              | <b>2.084</b> | <b>4.221</b> |              |              |              |
| Vehicle Action                                                                                                                             | Crash involving a stopped vehicle                           | 3.764                 | 2.835        | 3.733        | <b>4.752</b> | <b>1.788</b> | 3.142        | 4.112        |
|                                                                                                                                            | Crash involving a left-turning vehicle                      | <b>1.730</b>          |              | <b>1.773</b> | <b>1.987</b> | <b>0.624</b> | 1.311        | <b>1.620</b> |
|                                                                                                                                            | Crash involving a right-turning vehicle                     | <b>1.680</b>          |              | <b>1.632</b> | <b>1.925</b> |              | 1.536        | 1.515        |
| Direction of Travel                                                                                                                        | Crash involving vehicles moving in opposite directions      | <b>2.545</b>          |              | <b>2.296</b> | <b>3.089</b> |              | 1.627        | <b>2.289</b> |
|                                                                                                                                            | Crash involving vehicles moving in perpendicular directions | <b>0.577</b>          | <b>0.361</b> | <b>0.590</b> | <b>0.660</b> | <b>0.449</b> | <b>0.476</b> | <b>0.573</b> |
|                                                                                                                                            | Crash involving vehicles moving in the same direction       | <b>3.595</b>          | <b>2.959</b> | 3.515        | <b>4.142</b> | <b>1.763</b> | 3.129        | 3.651        |
| Count of Signalized Intersections                                                                                                          |                                                             | 73                    | 6            | 67           | 61           | 12           | 72           | 73           |
| Count of Unsignalized Intersections                                                                                                        |                                                             | 813                   | 414          | 399          | 336          | 477          | 246          | 389          |
| Green cells represent CMFs less than one (improvement in safety condition).                                                                |                                                             |                       |              |              |              |              |              |              |
| Red cells represent CMFs greater than one (worsening safety condition).                                                                    |                                                             |                       |              |              |              |              |              |              |
| Blank cells correspond to statistically insignificant CMFs.                                                                                |                                                             |                       |              |              |              |              |              |              |
| Bolded CMFs are those meeting three literature-based criteria (crash frequency > 300, reference-to-treatment sites ratio > 4:1, CDP < 5%). |                                                             |                       |              |              |              |              |              |              |
| Underlined CMFs are obtained using three years of crash data instead of five years.                                                        |                                                             |                       |              |              |              |              |              |              |

### *Severity Analysis*

The CMFs for KABCO (total) crashes range from approximately 1.5 to 2.5, generally increasing for more complex intersection types like divided intersections (CMF = 2.02). These values that exceed 2 may suggest potential overestimation or unique local conditions. For KAB (fatal, serious, and minor injury) crashes, only one CMF was statistically significant. The value of that CMF is 0.282. However, the sample size for signalized intersections is only 12, which is low. Furthermore, the 71.8% reduction in injury crashes may be an overestimate. The CMFs for CO (possible injury and property damage) crashes and PDO (property damage-only) crashes show a similar pattern, with higher values for more complex intersection types. These values are consistent with an increase in low-severity crashes.

### *Manner of Collision Analysis*

Rear-end crashes have the highest CMFs, exceeding 3.5 across all intersection types except undivided intersections and intersections with a maximum of one leg with a separate right turn. The large CMFs for rear-end crashes are consistent with the literature, where studies have found that signalization tends to increase rear-end collisions due to abrupt stopping behavior. On the other hand, broadside crashes have CMFs less than 1, indicating a reduction in crashes involving vehicles entering the intersection from approaches at a perpendicular angle, which aligns with the expected results from a reduction in crossing conflicts.

Same-direction sideswipe crashes have higher CMFs, generally between 2 and 3. This crash increase may be associated with the stop-and-go traffic pattern at signalized intersections, which leads to lane-changing behavior to avoid stopping. It may also be associated with lanes merging or dropping near signalized intersections. Furthermore, angle crashes have CMFs greater than 1, indicating increased crashes at signalized intersections. Although a reduction in crossing conflicts is expected, this increase in angle crashes may be associated with permissive turn phasing, which will be discussed later.

### *Vehicle Action Analysis*

The CMFs for crashes involving stopped vehicles are consistently high (e.g., 2.835 for three-leg intersections), which aligns with the increase in sudden stops and rear-end collisions due to signalization. However, these values are somewhat larger than expected, especially for undivided intersections and intersections with separate left-turn lanes. Regarding turn-related crashes, left-turn crashes have moderate CMFs, mostly ranging from 1.5 to 2, suggesting partial mitigation of conflicts but an increase in crashes due to the potential presence of permissive turning phases. Right-turn crashes show similar CMFs to left-turn crashes.

### *Direction of Travel Analysis*

The CMFs for crashes involving perpendicular directions of travel are consistently below 1, reflecting the effectiveness of signalization. This is consistent with expectations and with the



CMF values for broadside crashes, as signalization eliminates many crossing conflicts. For crashes involving vehicles moving in opposite directions, the CMFs range from 1.6 to 3. The higher CMFs for opposite-direction crashes (e.g., 3.1 for divided intersections) may indicate unique issues like insufficient signal timing or poor visibility, which merit further investigation. The CMFs for same-direction crashes are the highest in this category, with values exceeding 4 at divided intersections. This aligns with the increase in rear-end and sideswipe same-direction collisions noted above.

## Validation

The following subsections highlight the findings of the three validation methodologies conducted in this research project.

### *Literature-Based Validation*

The calculated CMFs were validated by comparing them with values from the literature, specifically from studies summarized in the FHWA CMF Clearinghouse. The maximum and minimum CMF values for each crash type from these studies are presented in Table 8. A calculated CMF was considered to be validated if it fell within the range of CMFs reported in the literature. The CMFs for both rear-end and KABCO (fatal through possible injury) crashes for undivided high-speed intersections fall within the range of values from the literature, confirming their validity.

**Table 8. CMF ranges in the signal installation literature**

| Crash Type | Minimum CMF | Maximum CMF |
|------------|-------------|-------------|
| Angle      | 0.230       | 0.700       |
| Left turn  | 0.400       | 0.500       |
| Rear End   | 1.427       | 1.950       |
| KABCO      | 0.560       | 0.840       |
| KABC       | 0.465       | 0.860       |
| PDO        | 0.898       | 0.898       |

Supplemental CMFs were developed using three years of crash data. This analysis resulted in two additional CMFs that did not exist in the five-year analysis. These two CMFs are for undivided intersections and for KABCO (total) crashes and crashes involving a vehicle turning left. The CMF for KABCO crashes is 0.798, which falls within the range of minimum and maximum values reported in the literature, validating its reliability. Similarly, the CMF for crashes involving left-turning vehicles is 0.624. While this value does not fall strictly within the range of values reported in the literature, it can be considered reasonable and effectively validated, providing additional insights into crash mitigation at these types of intersections.

## Hypothesis Tests of Proportions

Table 9 functions as a validation tool for comparing and checking the alignment of the obtained CMF values with the results of hypothesis tests of proportions. The colors shown in the table mean the following:

- **Green:** Both the proportions test and the CMF indicate a reduction in the analyzed crash type after signal installation.
- **Red:** Both the proportions test and the CMF indicate an increase in the analyzed crash type after signal installation.
- **Black:** The proportions test and the CMF do not align, showing a mismatch.
- **Blue:** Insufficient evidence exists to reject the null hypothesis in the proportions test.
- **White:** No statistically significant CMF was identified.

**Table 9. Alignment check between CMFs and hypothesis tests of proportions**

| Crash Type          |                                                             | Intersection Category |       |       |         |           |             |             |
|---------------------|-------------------------------------------------------------|-----------------------|-------|-------|---------|-----------|-------------|-------------|
|                     |                                                             | All                   | 3-Leg | 4-Leg | Divided | Undivided | Separate RT | Separate LT |
| Severity            | KABC                                                        |                       |       |       |         |           |             |             |
|                     | KAB                                                         |                       |       |       |         |           |             |             |
|                     | CO                                                          |                       |       |       |         |           |             |             |
|                     | O                                                           |                       |       |       |         |           |             |             |
| Manner of Collision | Rear end                                                    |                       |       |       |         |           |             |             |
|                     | Sideswipe same-direction                                    |                       |       |       |         |           |             |             |
|                     | Angle                                                       |                       |       |       |         |           |             |             |
|                     | Broadside                                                   |                       |       |       |         |           |             |             |
|                     | Head On                                                     |                       |       |       |         |           |             |             |
| Vehicle Action      | Crash involving a stopped vehicle                           |                       |       |       |         |           |             |             |
|                     | Crash involving a left-turning vehicle                      |                       |       |       |         |           |             |             |
|                     | Crash involving a right-turning vehicle                     |                       |       |       |         |           |             |             |
| Direction of Travel | Crash involving vehicles moving in opposite directions      |                       |       |       |         |           |             |             |
|                     | Crash involving vehicles moving in perpendicular directions |                       |       |       |         |           |             |             |
|                     | Crash involving vehicles moving in the same direction       |                       |       |       |         |           |             |             |

The analysis revealed several key findings regarding the relationship between the hypothesis test of proportions results and the CMF values for various crash types. Both methods consistently indicate a reduction in broadside crashes and crashes involving vehicles moving in perpendicular directions following signal installation. Conversely, both approaches show an increase in six crash types: CO crashes, PDO crashes, rear-end crashes, angle crashes, crashes involving stopped vehicles, and crashes involving vehicles heading in the same direction.

For several crash types, the hypothesis test of proportions results show no significant difference in proportions between signalized and unsignalized intersections for the majority of the high-speed intersection subsets. These crash types include sideswipe same-direction crashes, head-on crashes, crashes involving right-turning vehicles, and crashes involving vehicles moving in opposite directions. As a result, the CMFs associated with these crash types were excluded from the final recommendations due to a lack of statistical significance.

Additionally, a discrepancy was observed for two crash types: KABC crashes and crashes involving left-turning vehicles. While the CMFs suggest an increase in these crash types after signal installation, the hypothesis test of proportions results indicate the opposite.

### *Local Agency Outreach*

Useful phasing information was obtained from 18 out of the 34 local agencies contacted, covering 53 signalized intersections. The collected data included details on left-turn and right-turn phasing for each intersection leg, with classifications of protected, permitted, or protected-permitted.

Since the primary focus of this validation effort was on angle and left-turn crashes, the reported phasing information was aggregated into broader categories, as presented in Table 10. The analysis revealed that 64% of the signalized intersections include a permitted phase or a combination of permitted and protected phasing. Permitted phasing requires drivers to make gap acceptance decisions, which can introduce variability in driver behavior and lead to an increased likelihood of conflict, particularly for left-turning vehicles interacting with opposing through traffic. This characteristic of permitted phasing helps explain the high CMF values obtained for angle and left-turn crashes. This conclusion was supported by comparing the average angle and left-turn crash rates at all-protected signals and signals with a permitted phase. Table 11 shows that signals that have only protected left-turn phasing have lower average angles and left-turn crash rates.

**Table 10. Signal phasing summary**

| <b>Left-Turn Phasing Type</b>                    | <b>Count of Intersections</b> |
|--------------------------------------------------|-------------------------------|
| All Protected                                    | 19                            |
| All Protected-Permitted                          | 7                             |
| 50/50 Protected/Permitted                        | 12                            |
| 50/50 Protected-Permitted/Permitted              | 5                             |
| 50/50 Protected-Permitted/Protected              | 3                             |
| 75/25 Protected-Permitted/Protected              | 1                             |
| 25/50/25 Protected-Permitted/Protected/Permitted | 3                             |
| 25/75 Protected-Permitted/Protected              | 2                             |
| 50/25/25 Protected-Permitted/Protected/Permitted | 1                             |

**Table 11. Average crash rate comparison by signal phasing**

| <b>Signal Phasing Type</b>     | <b>Average Angle Crash Rate</b> | <b>Average LT Crash Rate</b> |
|--------------------------------|---------------------------------|------------------------------|
| Signals with a Permitted Phase | 0.408                           | 0.983                        |
| All-Protected Signals          | 0.293                           | 0.828                        |

This conclusion was also supported by comparing the major cause distribution of angle crashes at all-protected signals and signals with a permitted phase, as shown in Table 12. The top major cause of angle crashes at intersections with a permitted phase is failure to yield the right of way (FTYROW) while making a left turn, which may be associated with permitted phasing. On the other hand, angle crashes at all-protected signals are mainly associated with running a traffic signal.

**Table 12. Major cause comparison of angle crashes by signal phasing**

| <b>Major Cause</b>                               | <b>Signals with a Permitted Phase</b> | <b>All-Protected Signals</b> |
|--------------------------------------------------|---------------------------------------|------------------------------|
| <b>FTYROW: Making a Left Turn</b>                | 62%                                   | 31%                          |
| <b>Ran Traffic Signal</b>                        | 14%                                   | 40%                          |
| <b>Made Improper Turn</b>                        | 9%                                    | 7%                           |
| <b>Unknown</b>                                   | 3%                                    | 8%                           |
| <b>Other (Explain in Narrative): Other</b>       | 4%                                    | 4%                           |
| <b>FTYROW: Making A Right Turn On Red Signal</b> | 1%                                    | 4%                           |

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

This research project used cross-sectional analysis to develop a comprehensive list of Iowa-specific CMFs for signalizing high-speed intersections. Multiple validation steps were performed to ensure the robustness of these CMFs, including examining various aspects of the data and comparing the results with values reported in the literature. The finalized list of CMFs is presented in Table 13, representing the culmination of rigorous analysis and verification efforts. The key takeaways from this research are as follows:

1. Traffic signal installation is a countermeasure that may be considered at high-speed intersections. This research reveals that such installations increase all but broadside crashes on most facility types.
  - a. Overall intersection crashes are predicted to increase.
  - b. The intersection will not experience a significant reduction in overall serious injury crashes.
  - c. The intersection may experience a reduction in broadside/right-angle (“T-bone”) collisions, although the intersection will still experience some broadside crashes from red light running and permissive left-turn collisions.
  - d. The intersection will also experience an increase in mainline rear-end collisions. Due to higher speeds, these rear-end crashes will be more severe.
2. KABCO crash reductions were only observed on undivided intersections. This may be because these intersections generally occur in more suburban/urban transition zones, where driver expectancy of encountering traffic signals is increased.

### Recommendations and Considerations

When selecting the right countermeasure at high-speed intersections, the research recommends taking into consideration the following points:

1. Alternatives to high-speed traffic signals should be evaluated before high-speed traffic signals are proposed. Alternative intersections should be considered, such as the following:
  - a. Roundabout
  - b. Reduced-conflict intersection
  - c. Right-in/right-out
  - d. Median closure
2. The trade-offs of high-speed traffic signals should be communicated to the traveling public and local officials during intersection evaluation.
3. Any potential traffic signal at a high-speed location should be part of a corridor access management agreement.
  - a. This agreement should consider other existing intersections that may already be signalized or other intersections that may also be signalized in the near term.
  - b. The impact of the first signal can set a precedent for future intersections.

- c. This agreement should note “major intersections” instead of “pre-determined signal locations.”
4. Protected-only left-turn phasing is strongly recommended over permissive or protected-permissive phasing. This could mean all-day protected left-turn movements or left-turn phasing that varies based on time-of-day peak traffic and/or left-turn queue detection.

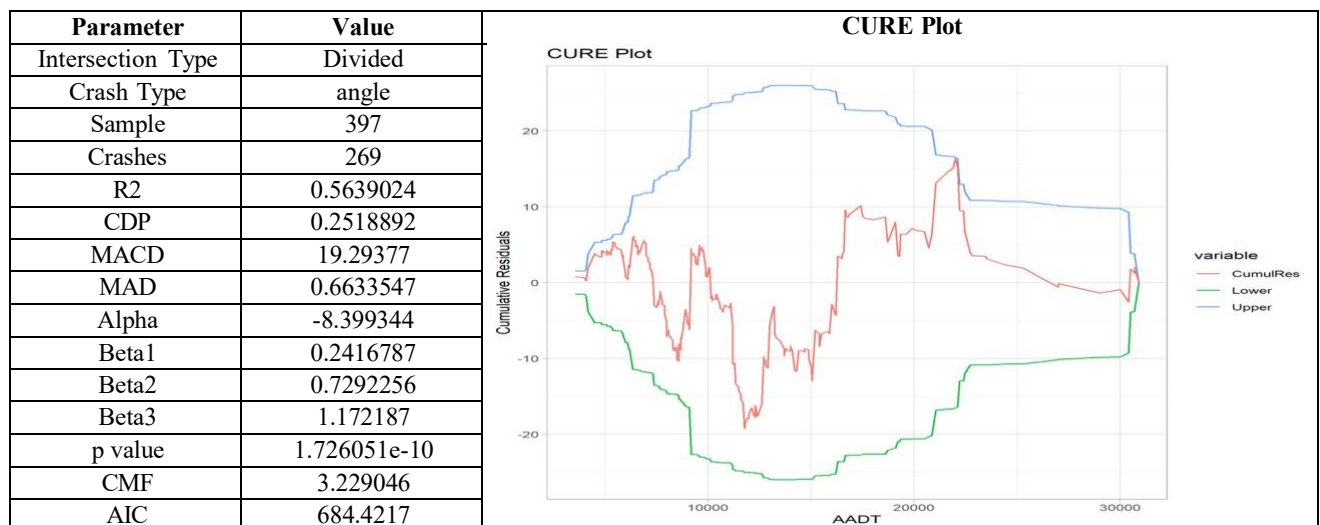
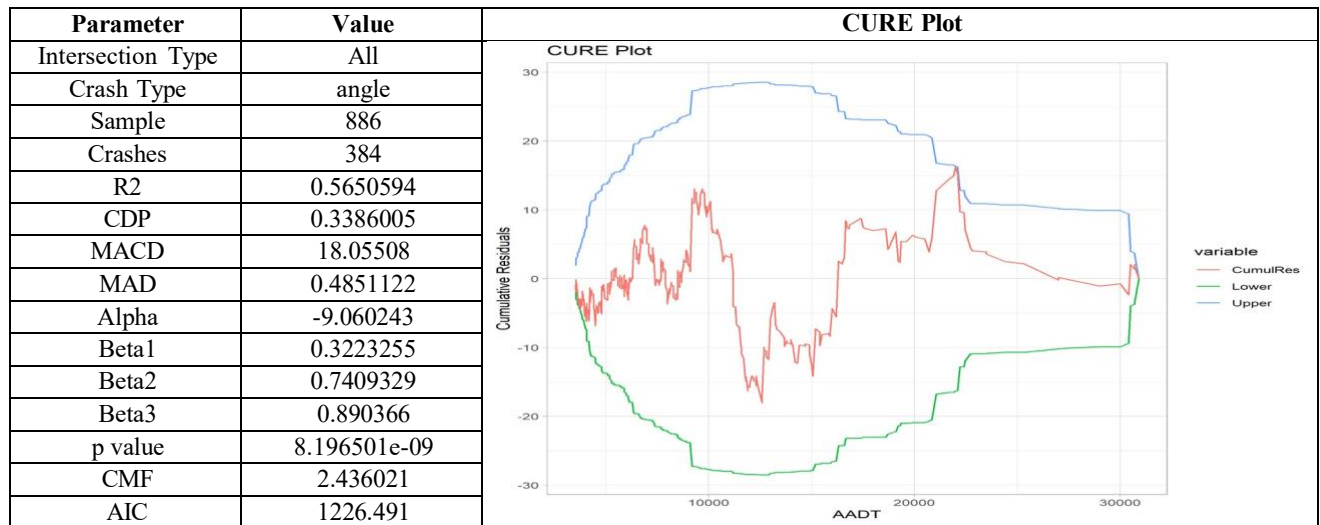
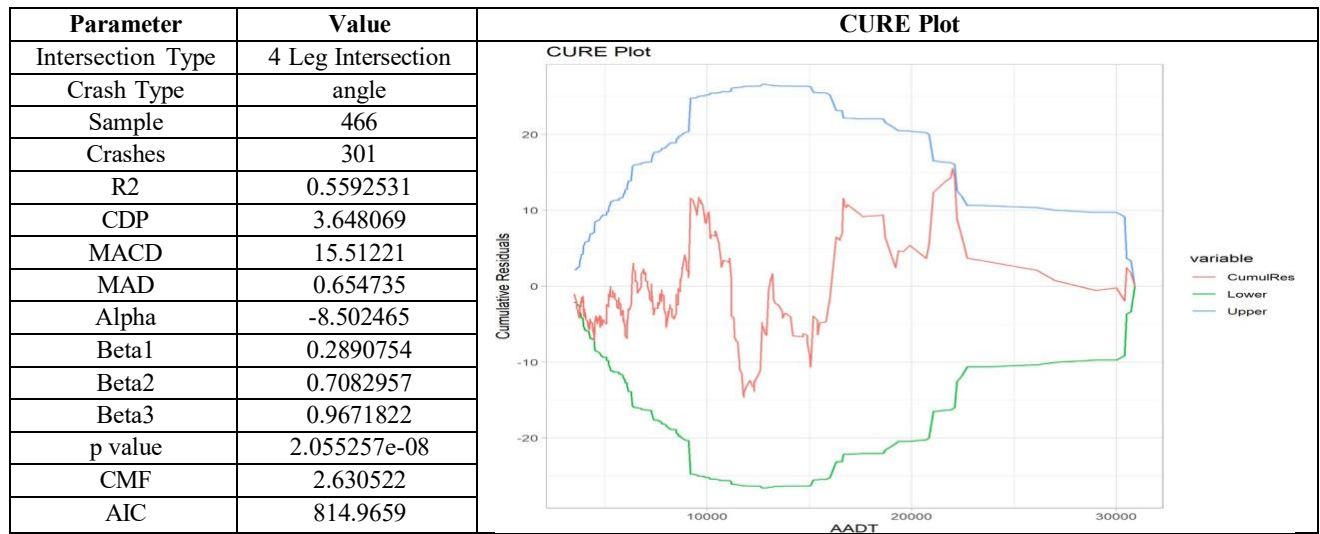
**Table 13. Final CMF recommendations**

| Crash Type                                                                                                                                                 |                                                             | Intersection Category |       |       |         |           |             |             |
|------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|-----------------------|-------|-------|---------|-----------|-------------|-------------|
|                                                                                                                                                            |                                                             | All                   | 3-Leg | 4-Leg | Divided | Undivided | Separate RT | Separate LT |
| Severity                                                                                                                                                   | KABCO                                                       | 1.795                 | 1.504 | 1.730 | 2.023   | 0.798     | 1.453       | 1.722       |
|                                                                                                                                                            | KABC                                                        | 1.440                 |       | 1.398 | 1.614   | 0.590     | 1.202       | 1.323       |
|                                                                                                                                                            | KAB                                                         |                       |       |       |         | 0.282     |             |             |
|                                                                                                                                                            | CO                                                          | 2.004                 | 1.664 | 1.93  | 2.278   |           | 1.586       | 1.961       |
|                                                                                                                                                            | O                                                           | 2.033                 | 1.652 | 1.958 | 2.328   |           | 1.629       | 2.024       |
| Manner of Collision                                                                                                                                        | Rear end                                                    | 3.690                 | 3.408 | 3.520 | 4.405   | 1.761     | 3.311       | 3.865       |
|                                                                                                                                                            | Sideswipe same-direction                                    | 2.969                 | 2.224 | 3.141 | 2.936   | 2.812     | 2.815       | 2.814       |
|                                                                                                                                                            | Angle                                                       | 2.436                 |       | 2.631 | 3.229   |           | 1.820       | 2.390       |
|                                                                                                                                                            | Broadside                                                   | 0.561                 | 0.383 | 0.565 | 0.639   | 0.436     | 0.452       | 0.563       |
|                                                                                                                                                            | Head on                                                     | 2.276                 |       | 2.084 | 4.221   |           |             |             |
| Vehicle Action                                                                                                                                             | Crash involving a stopped vehicle                           | 3.764                 | 2.835 | 3.733 | 4.752   | 1.788     | 3.142       | 4.112       |
|                                                                                                                                                            | Crash involving a left-turning vehicle                      | 1.730                 |       | 1.773 | 1.987   | 0.624     | 1.311       | 1.620       |
|                                                                                                                                                            | Crash involving a right-turning vehicle                     | 1.680                 |       | 1.632 | 1.925   |           | 1.536       | 1.515       |
| Direction of Travel                                                                                                                                        | Crash involving vehicles moving in opposite directions      | 2.545                 |       | 2.296 | 3.089   |           | 1.627       | 2.289       |
|                                                                                                                                                            | Crash involving vehicles moving in perpendicular directions | 0.577                 | 0.361 | 0.590 | 0.660   | 0.449     | 0.476       | 0.573       |
|                                                                                                                                                            | Crash involving vehicles moving in the same direction       | 3.595                 | 2.959 | 3.515 | 4.142   | 1.763     | 3.129       | 3.651       |
| Literature validation only                                                                                                                                 |                                                             |                       |       |       |         |           |             |             |
| Proportions test validation only                                                                                                                           |                                                             |                       |       |       |         |           |             |             |
| Both validation tests                                                                                                                                      |                                                             |                       |       |       |         |           |             |             |
| Not statistically significant – Value not reported                                                                                                         |                                                             |                       |       |       |         |           |             |             |
| <b>Bolded CMFs are those meeting three literature-based criteria (crash frequency &gt; 300, reference-to-treatment sites ratio &gt; 4:1, CDP &lt; 5%).</b> |                                                             |                       |       |       |         |           |             |             |

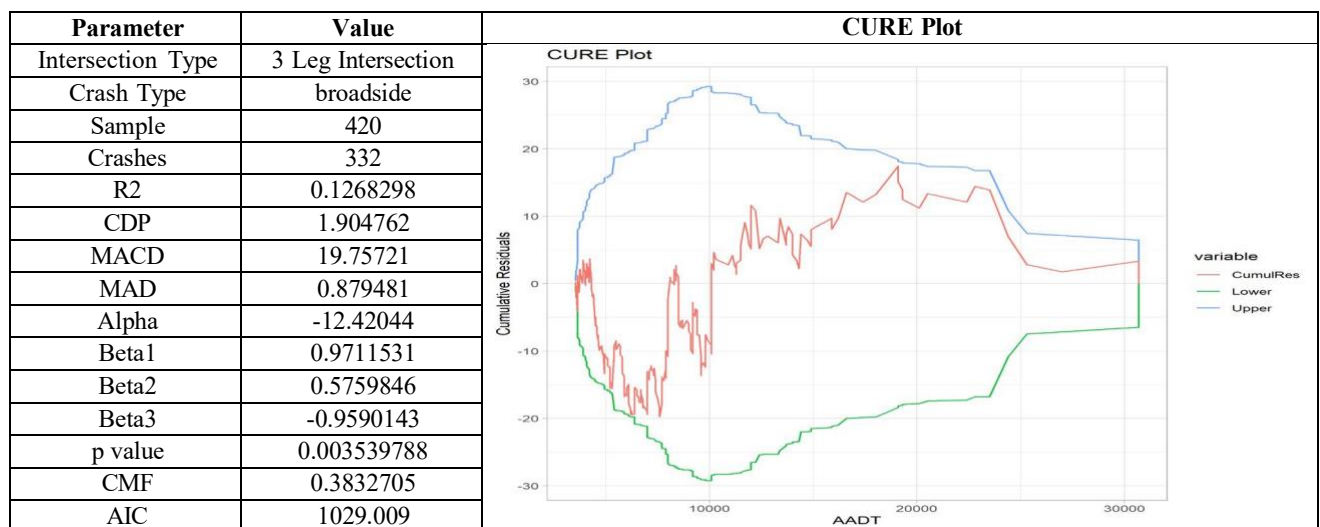
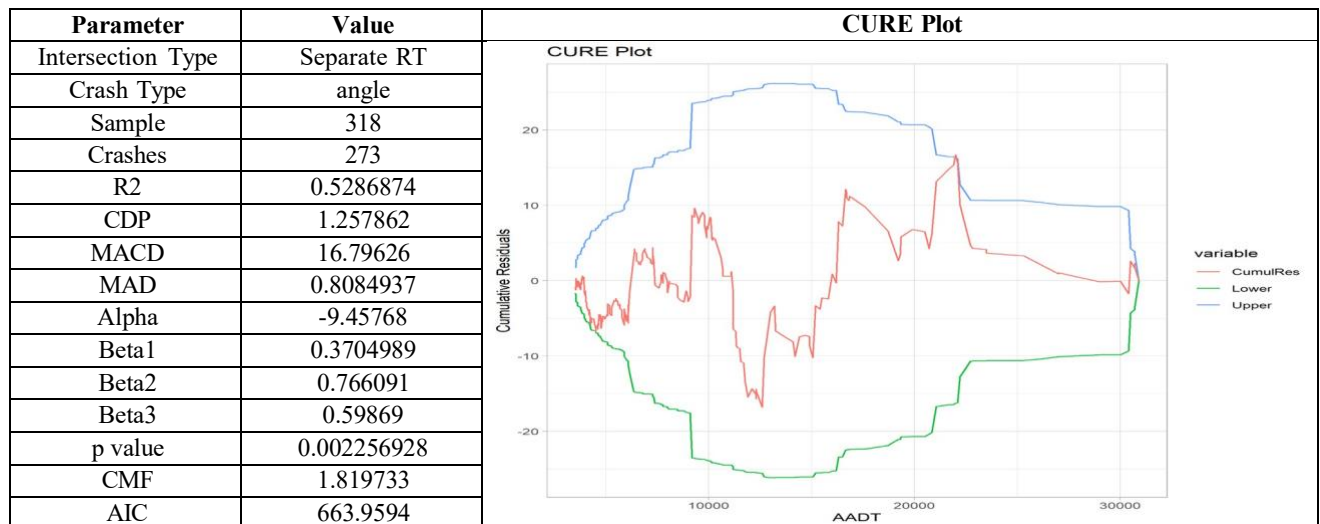
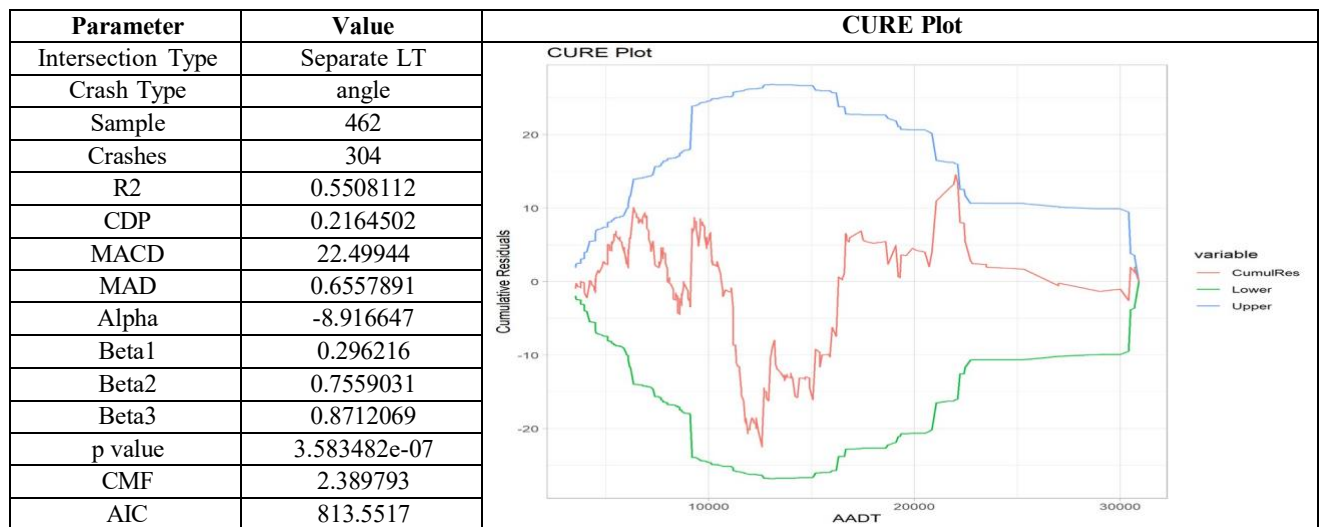
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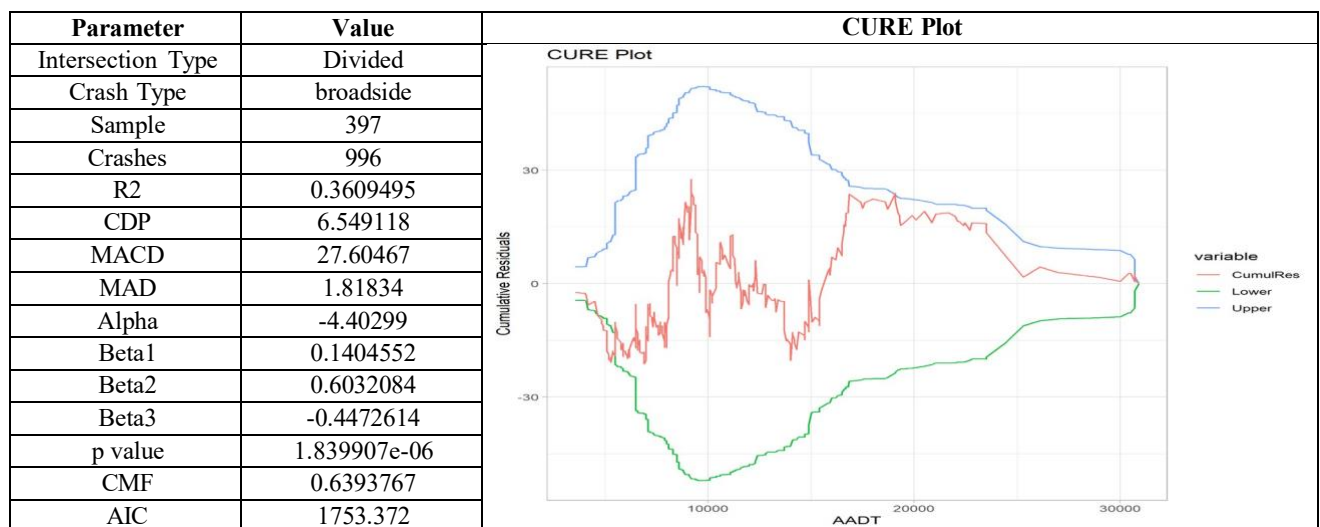
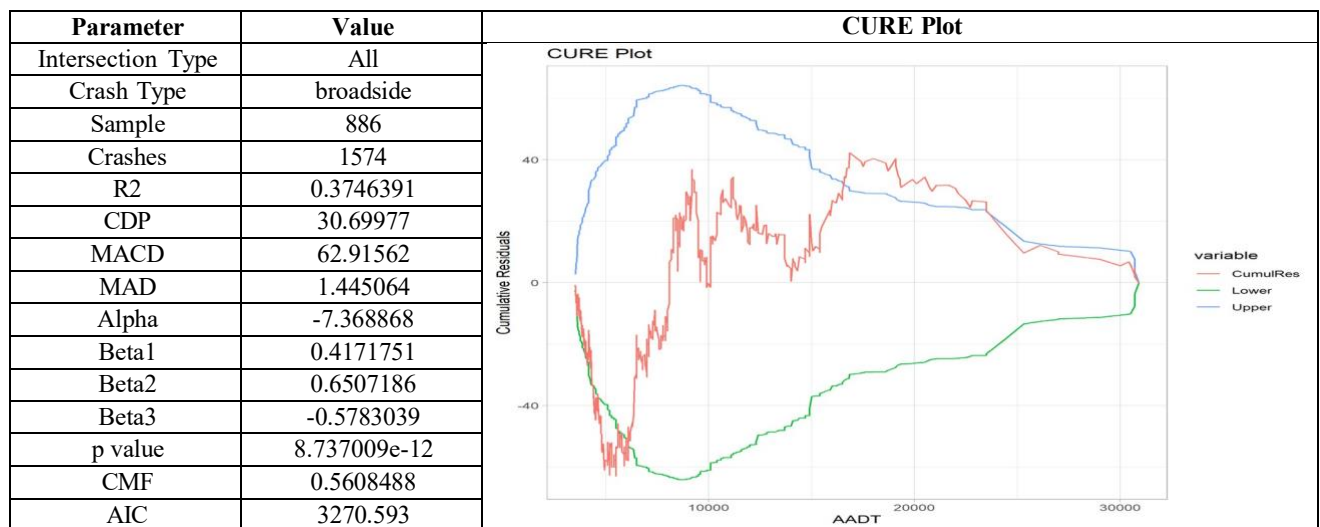
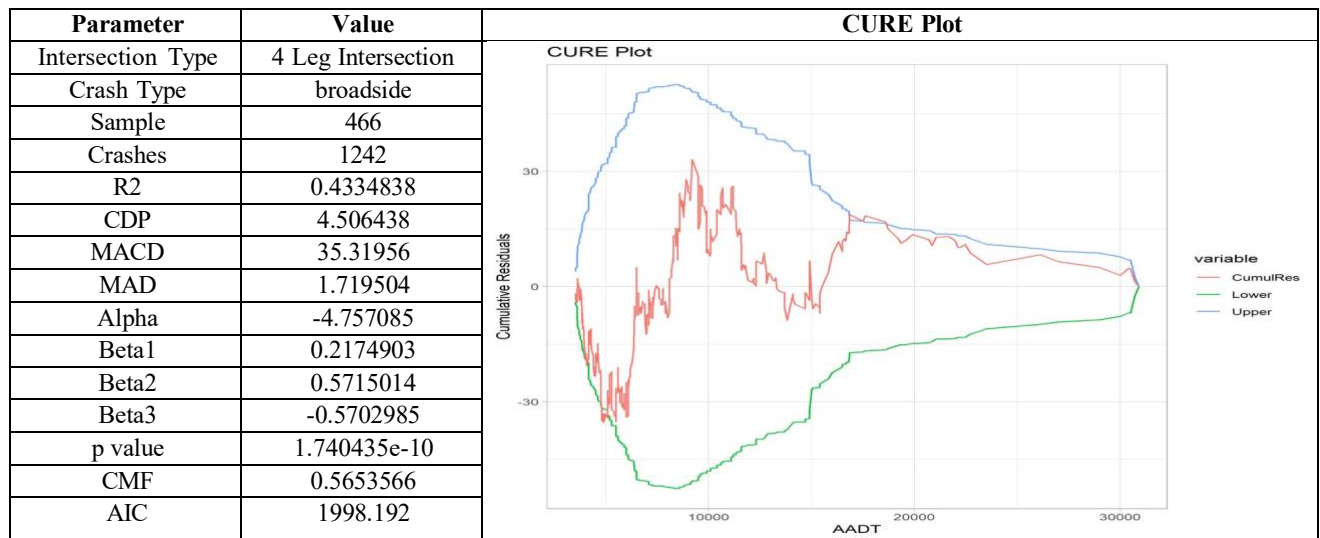
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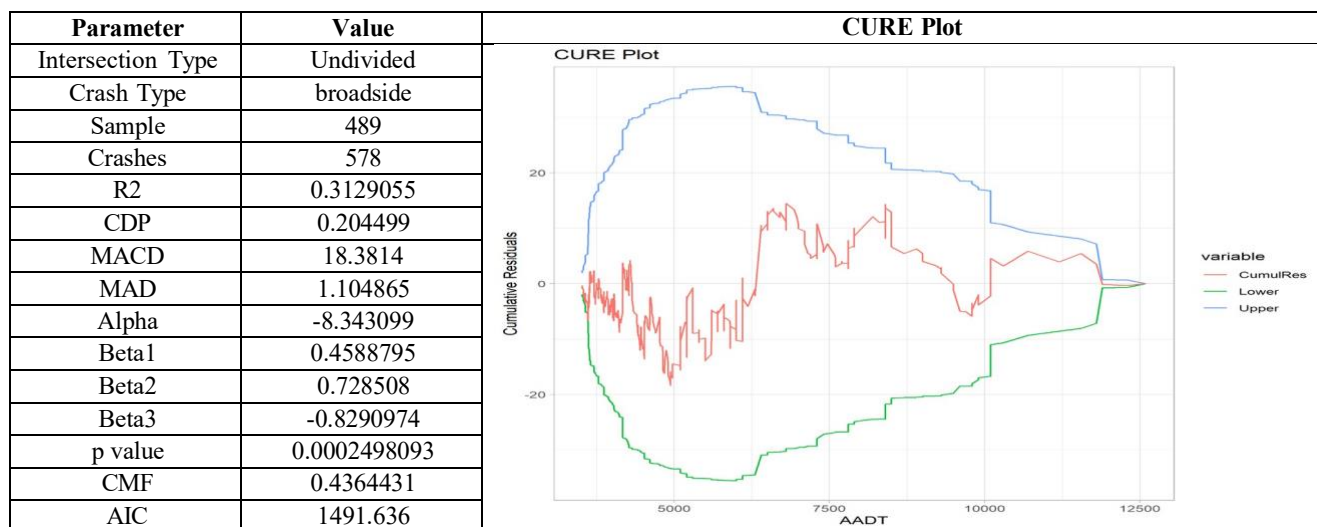
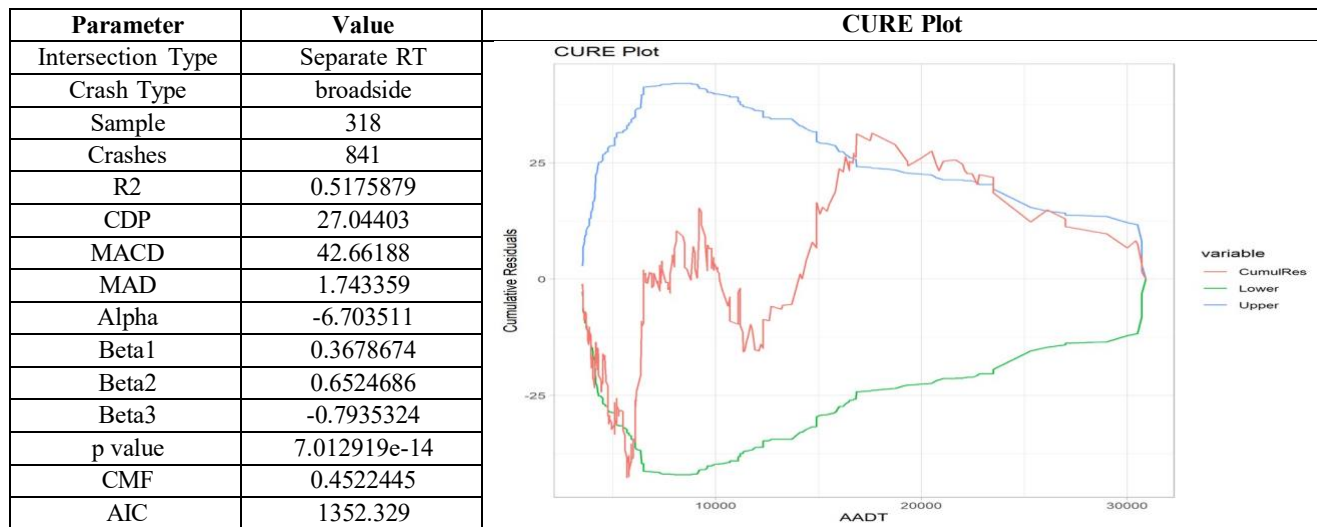
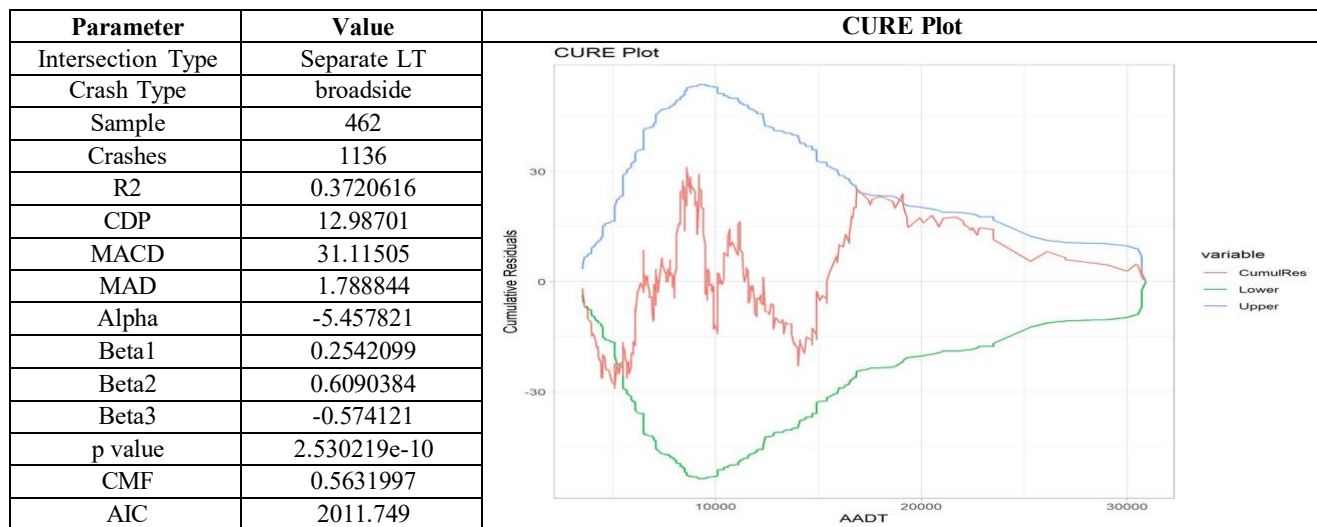
## APPENDIX A. SPFS DETAILED MODELS AND CURE PLOTS

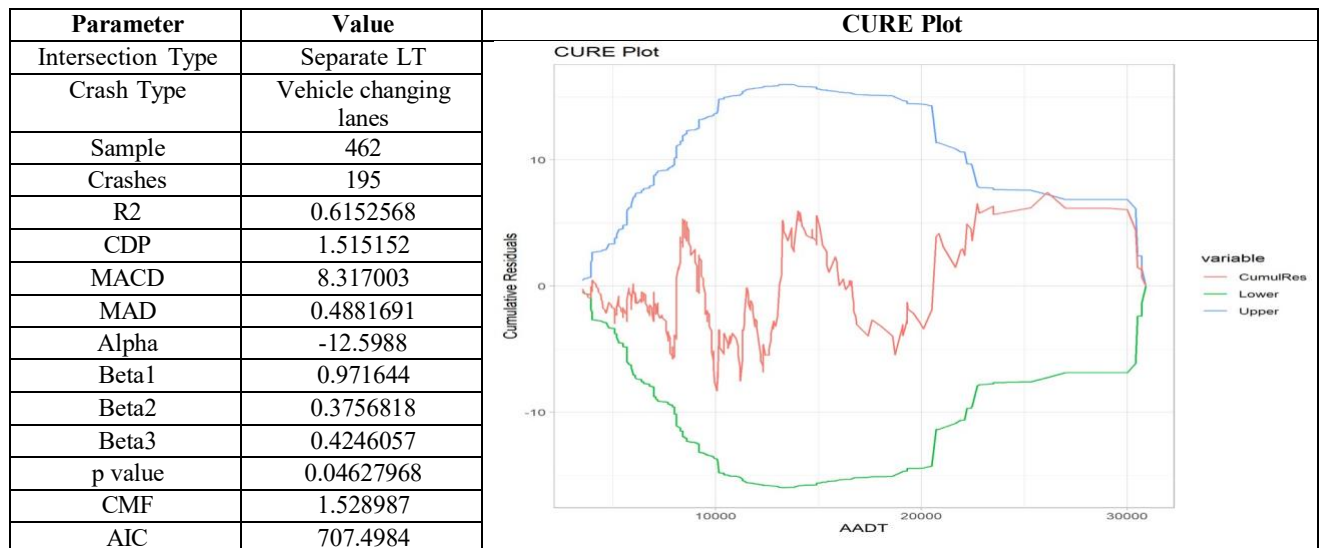
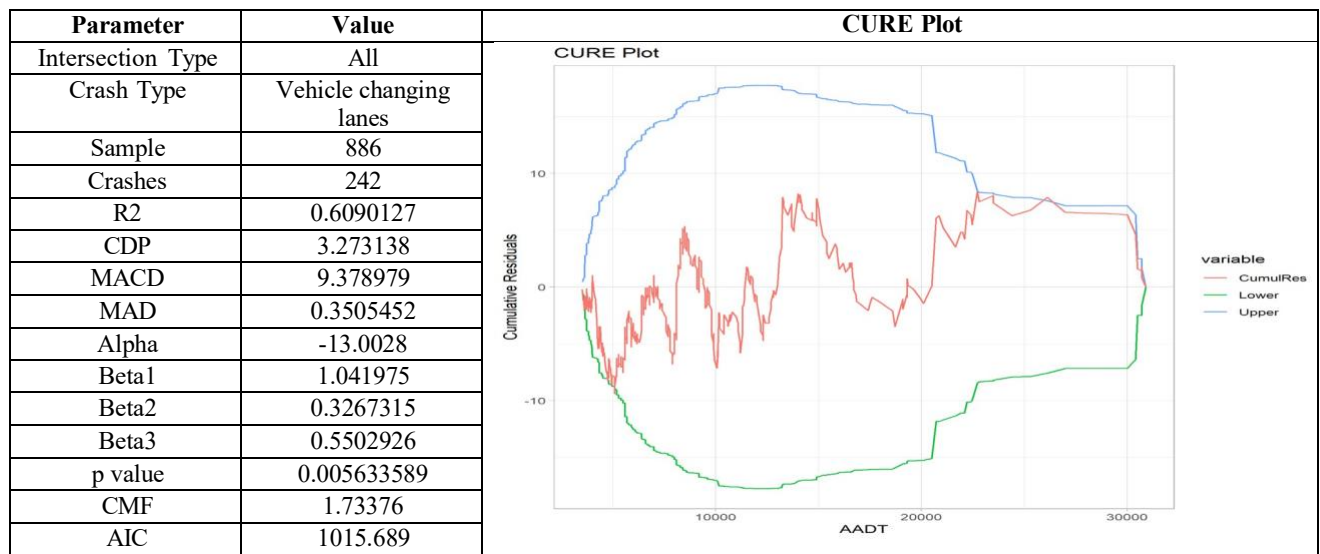
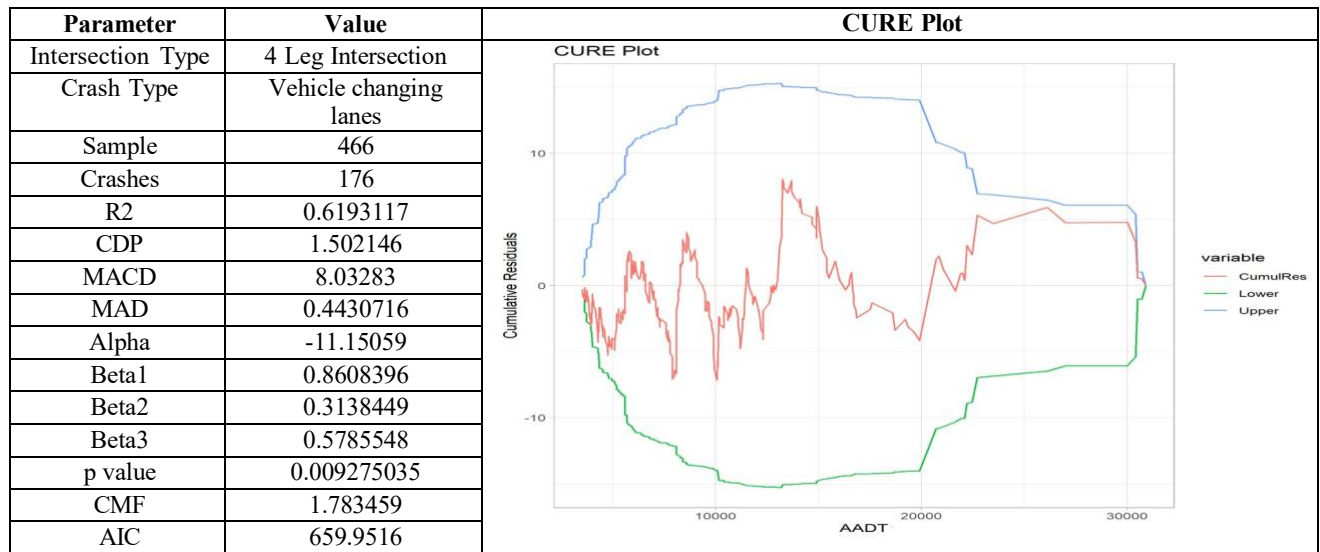


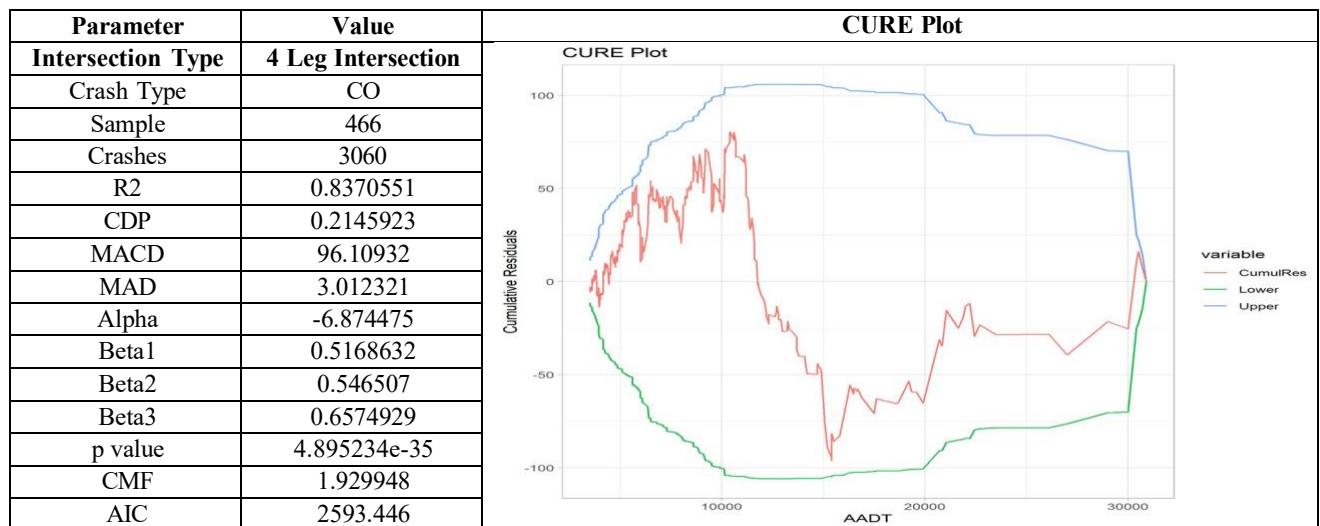
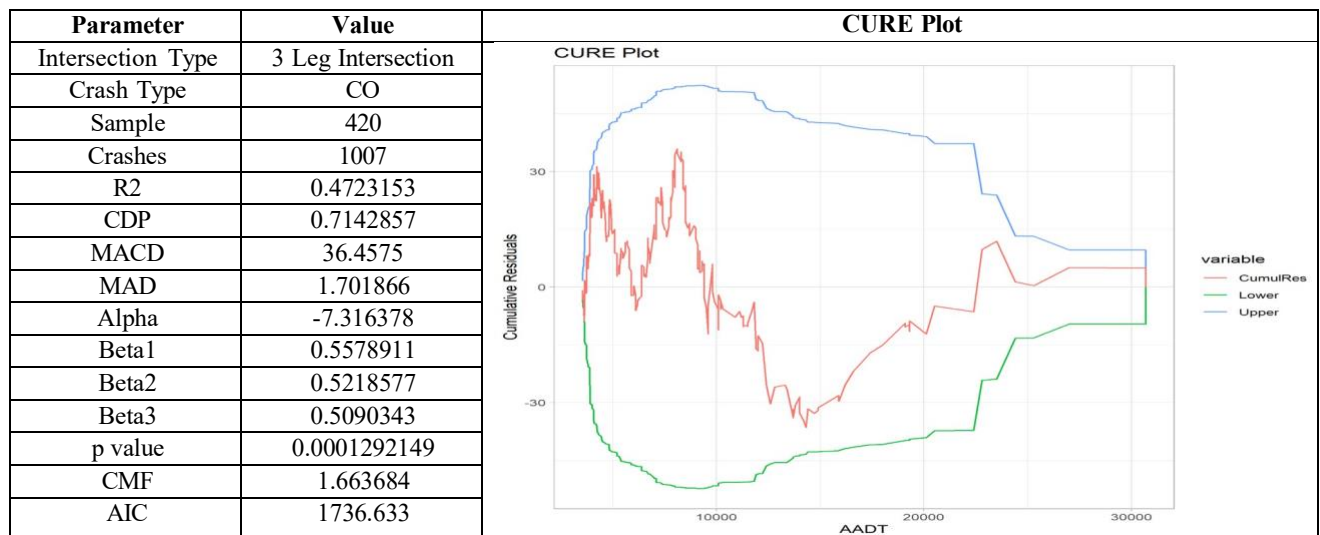
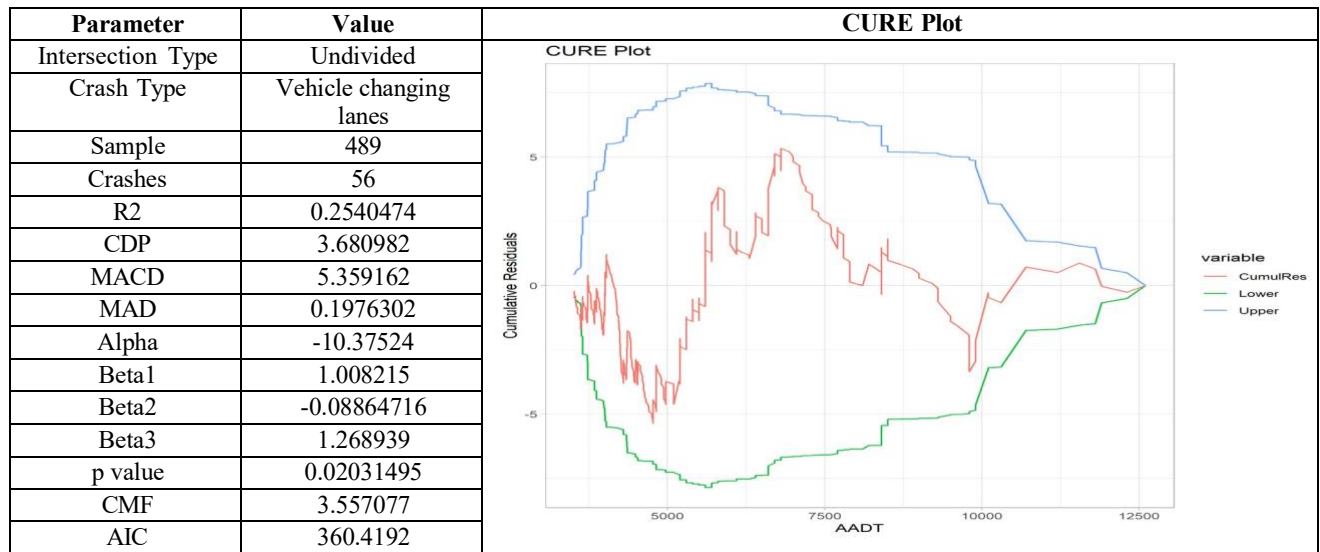


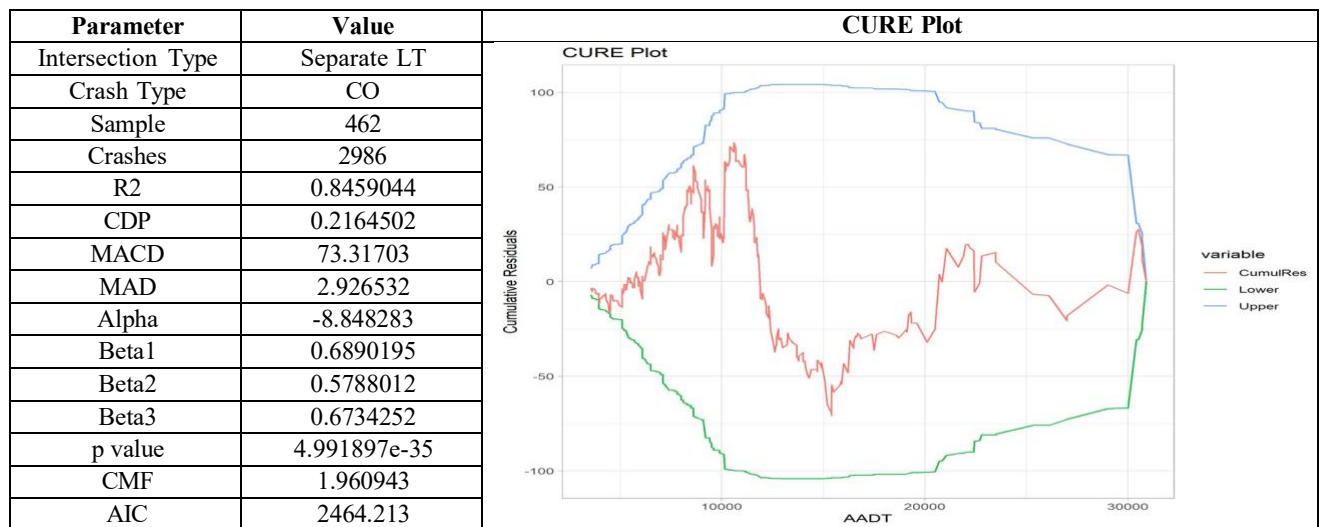
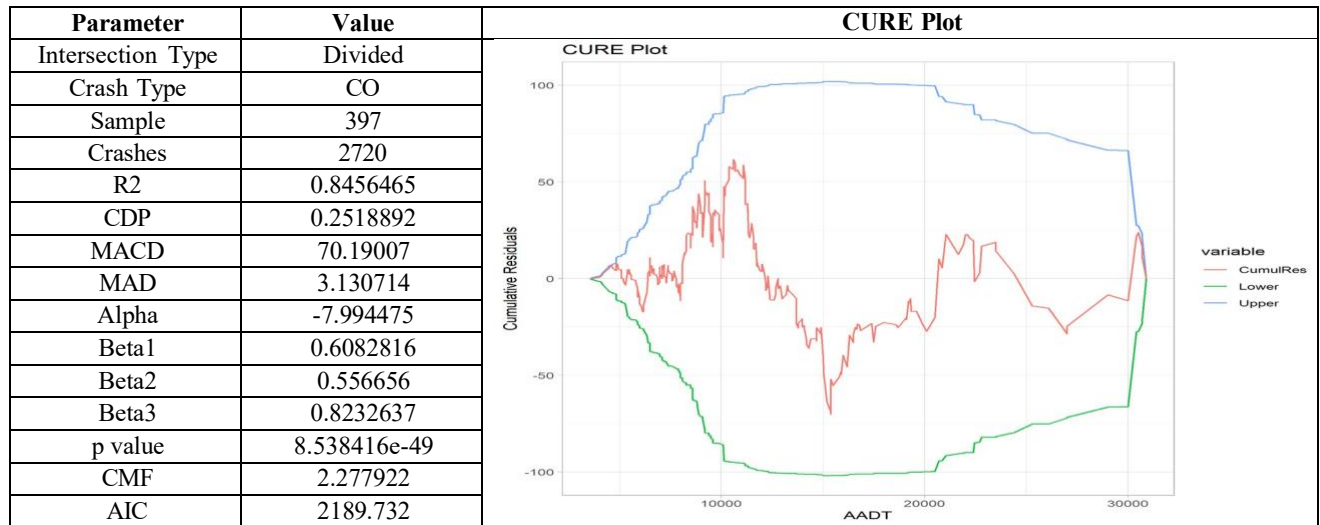
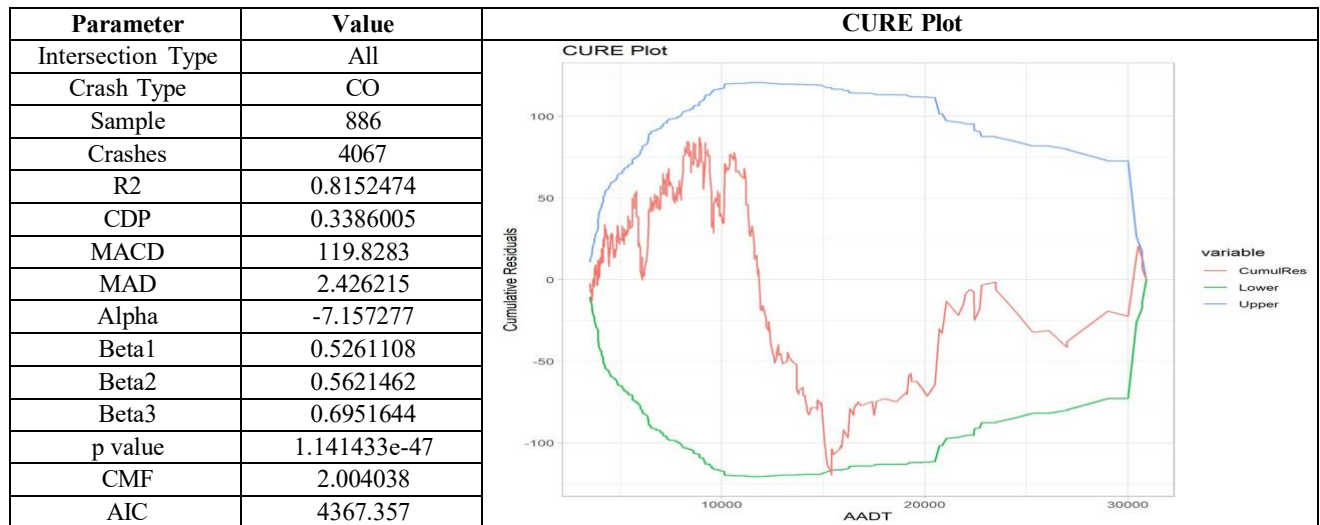




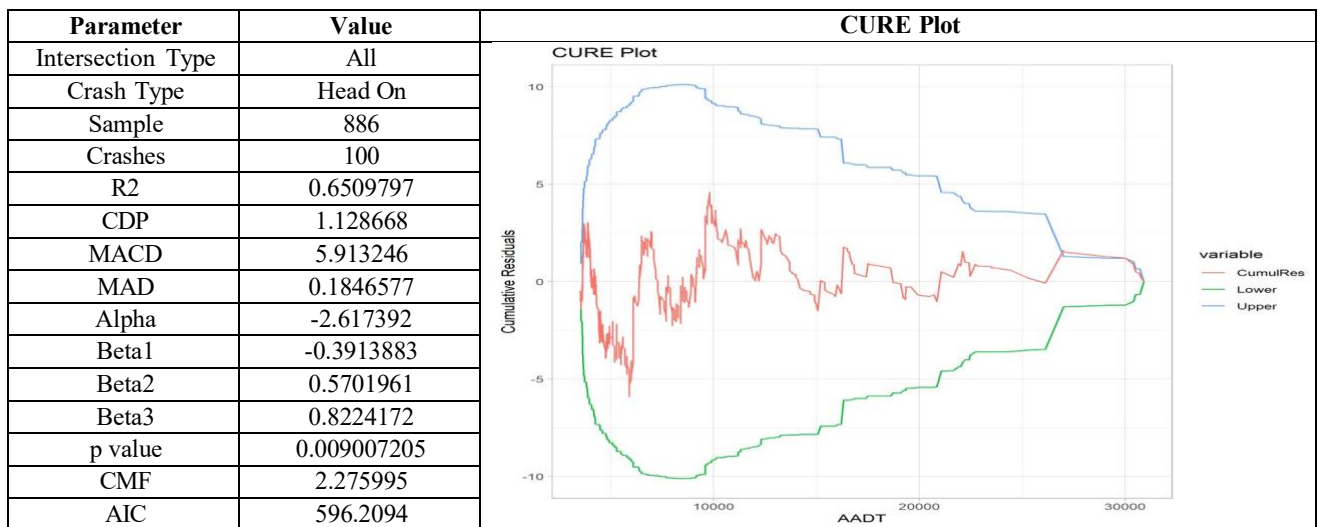
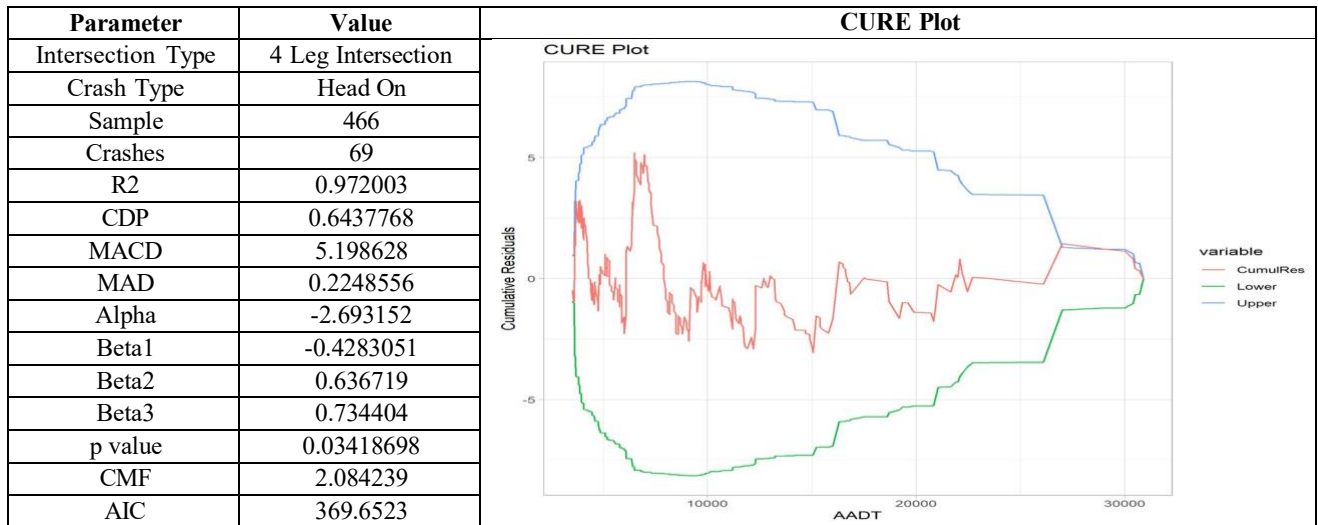
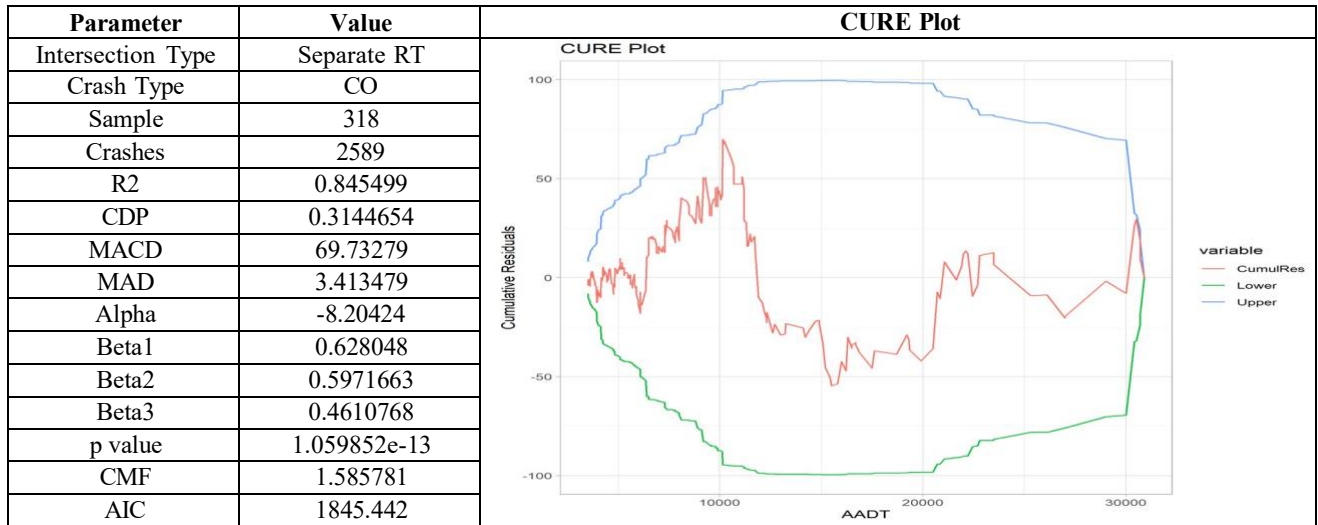


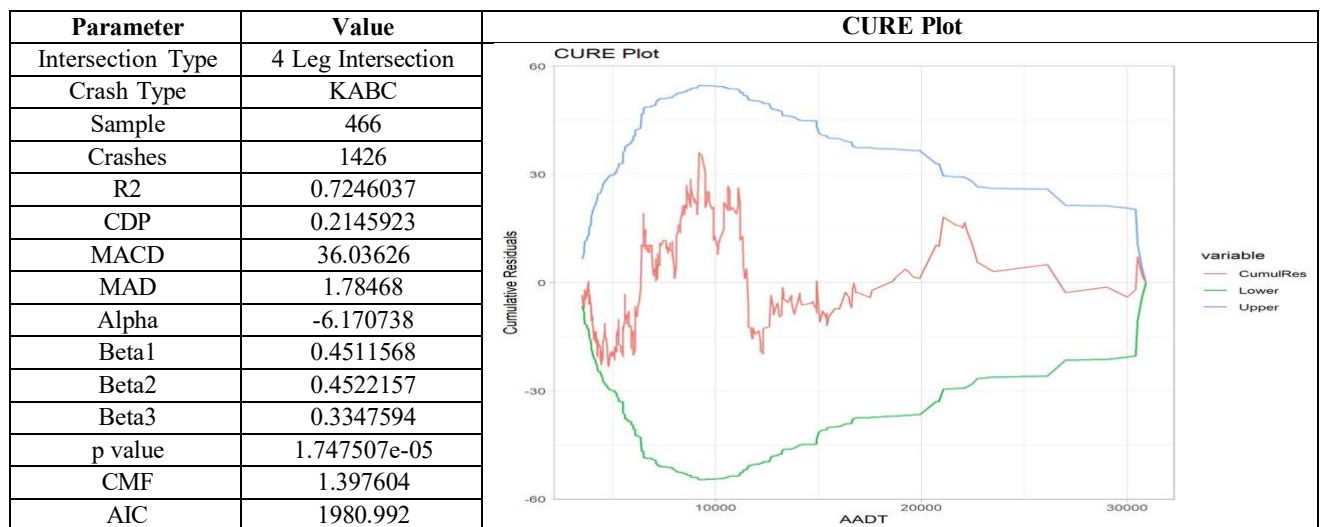
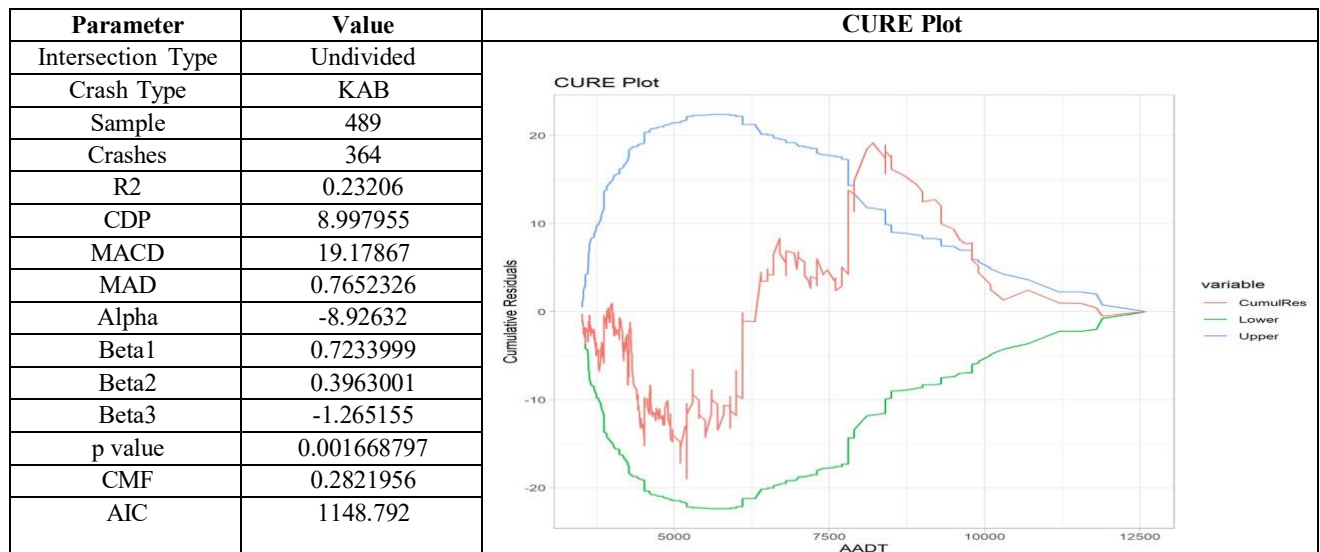
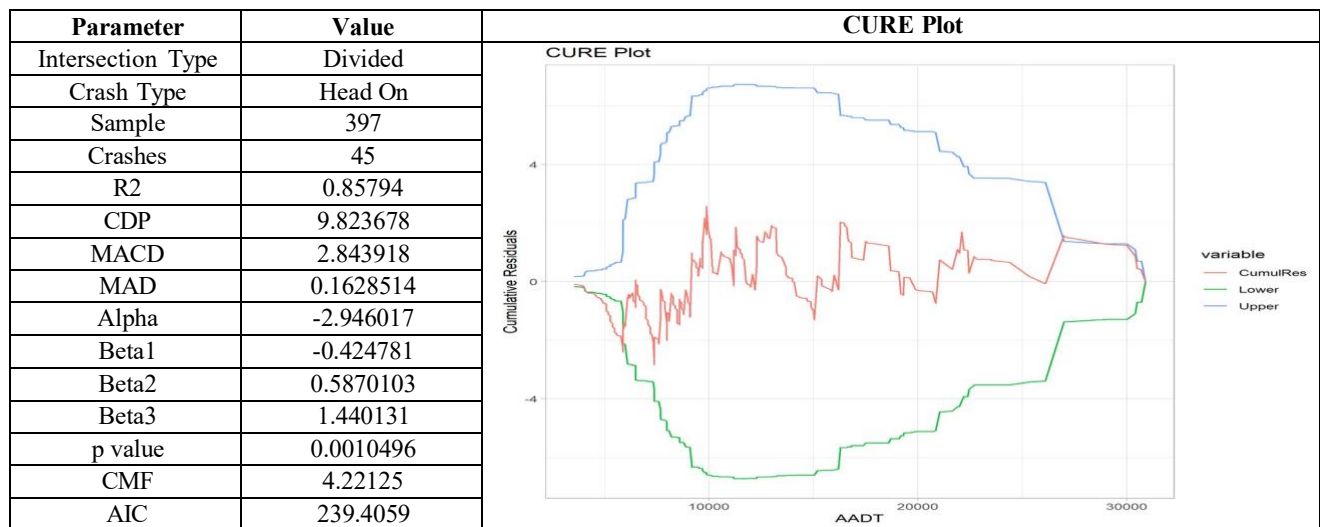




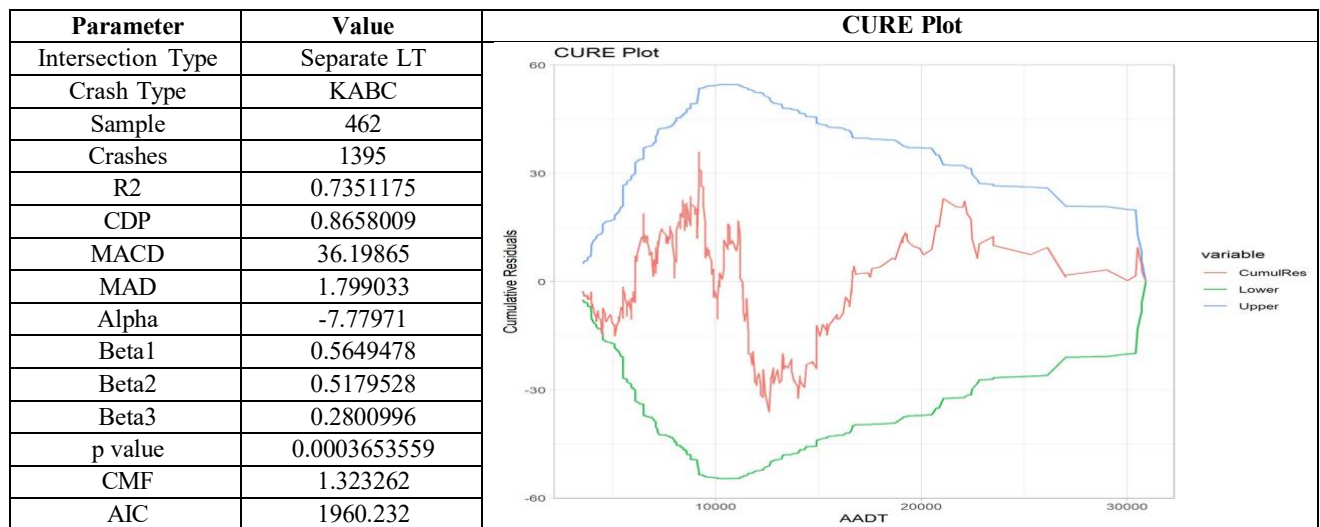
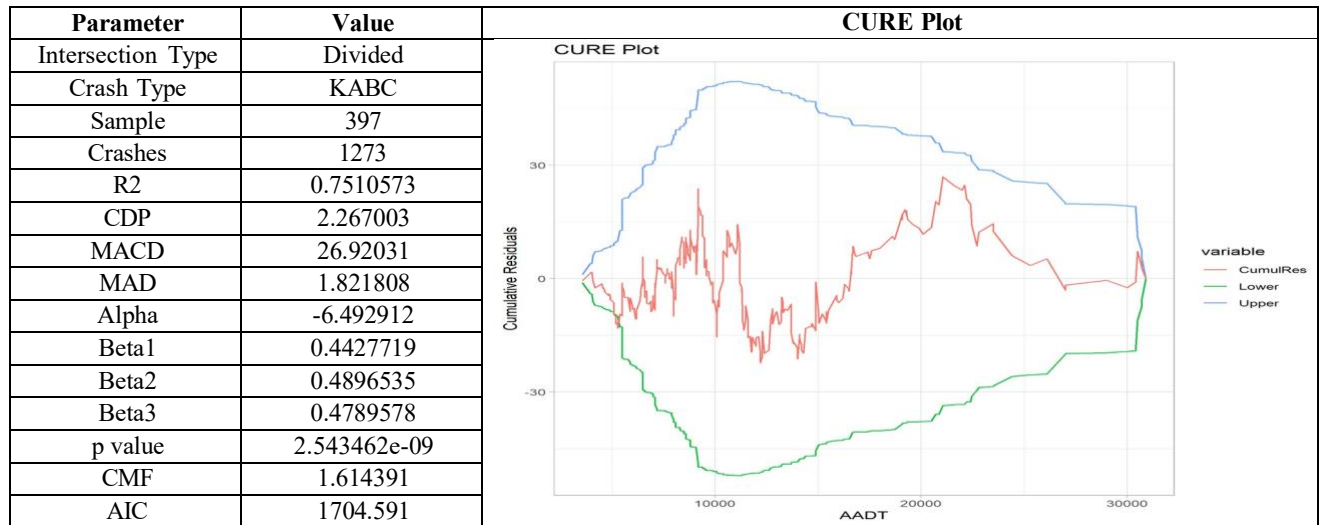
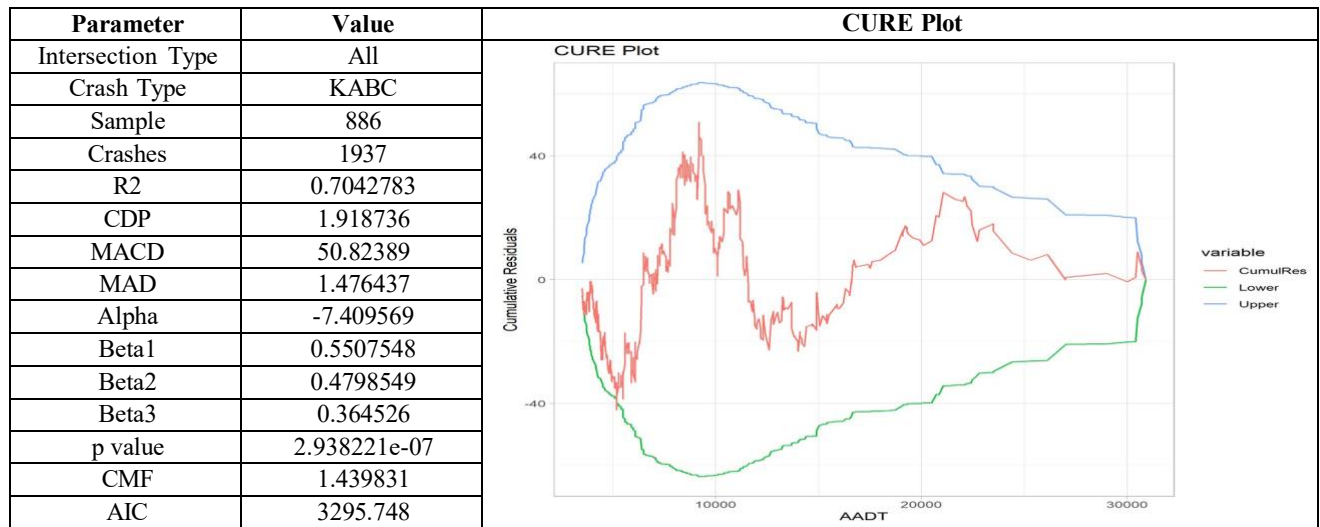


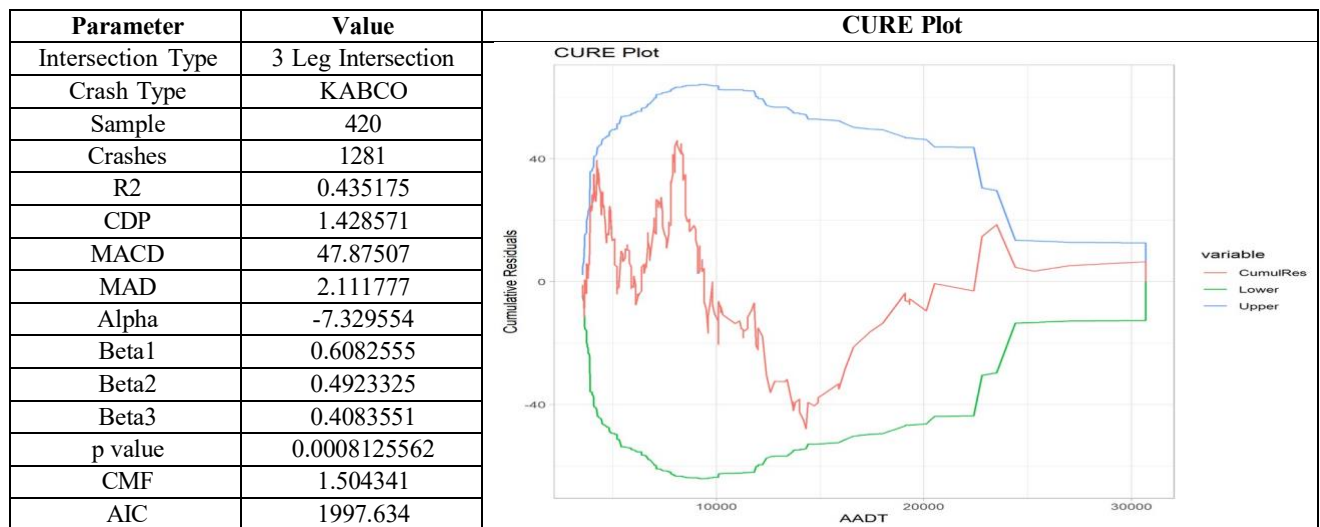
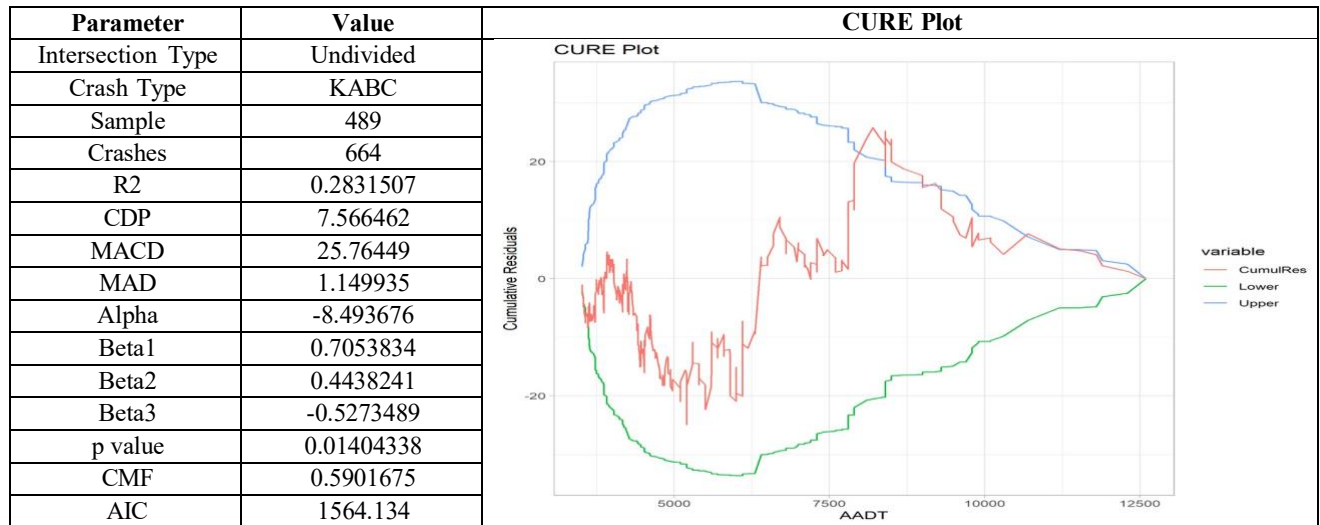
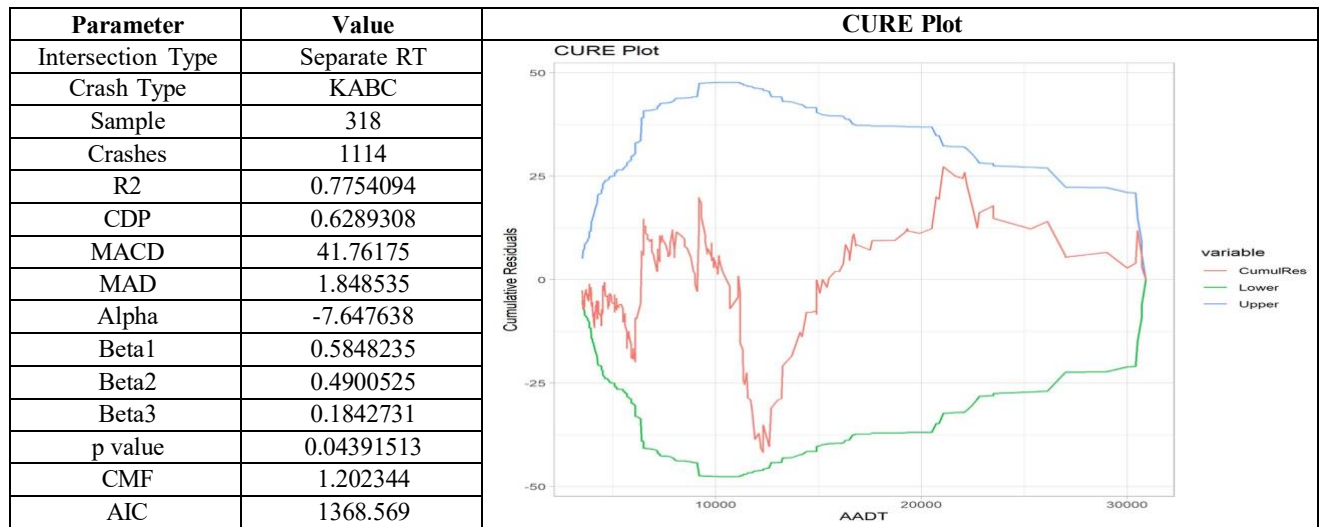


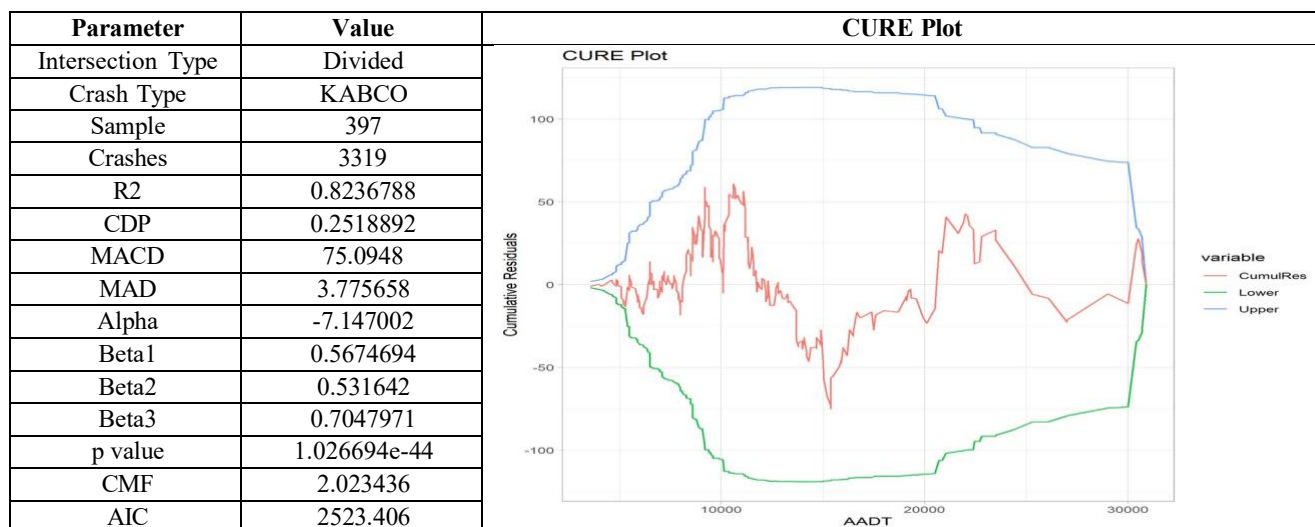
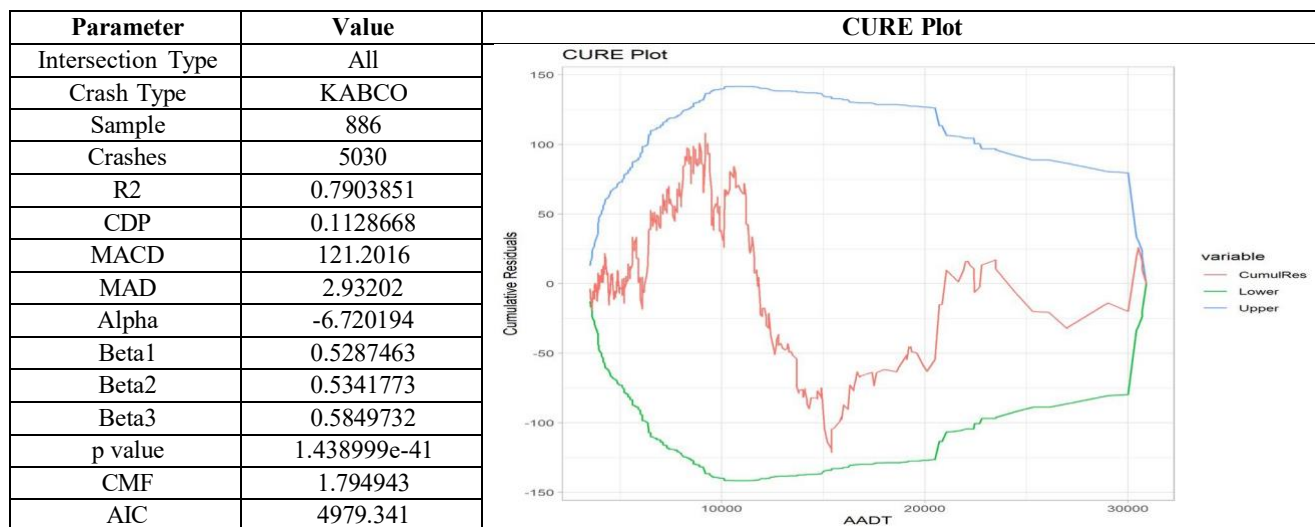
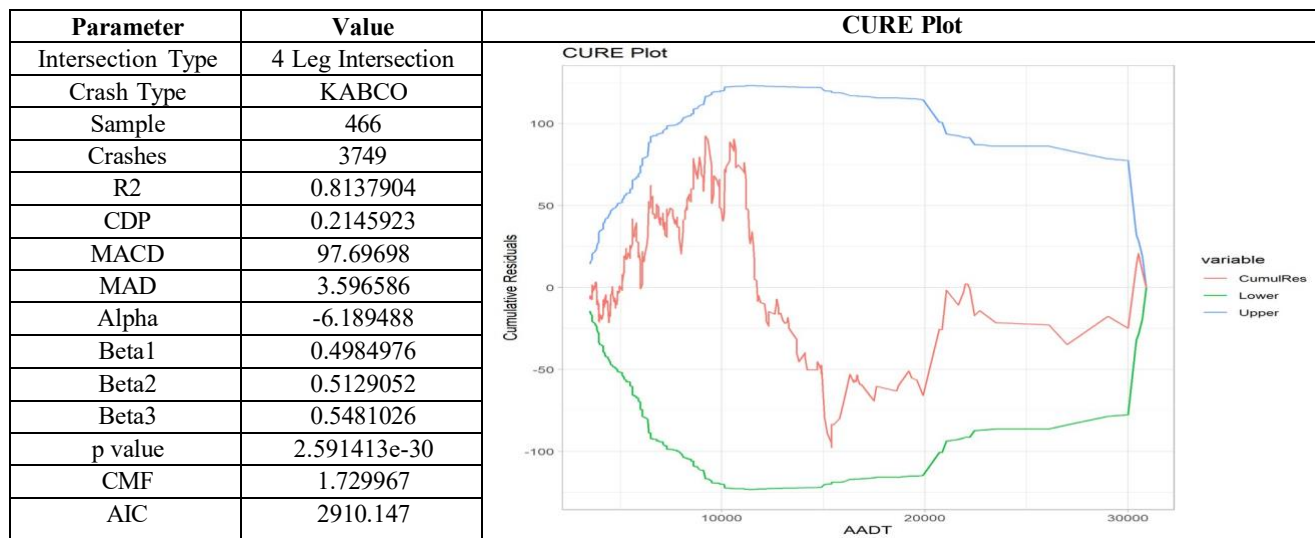


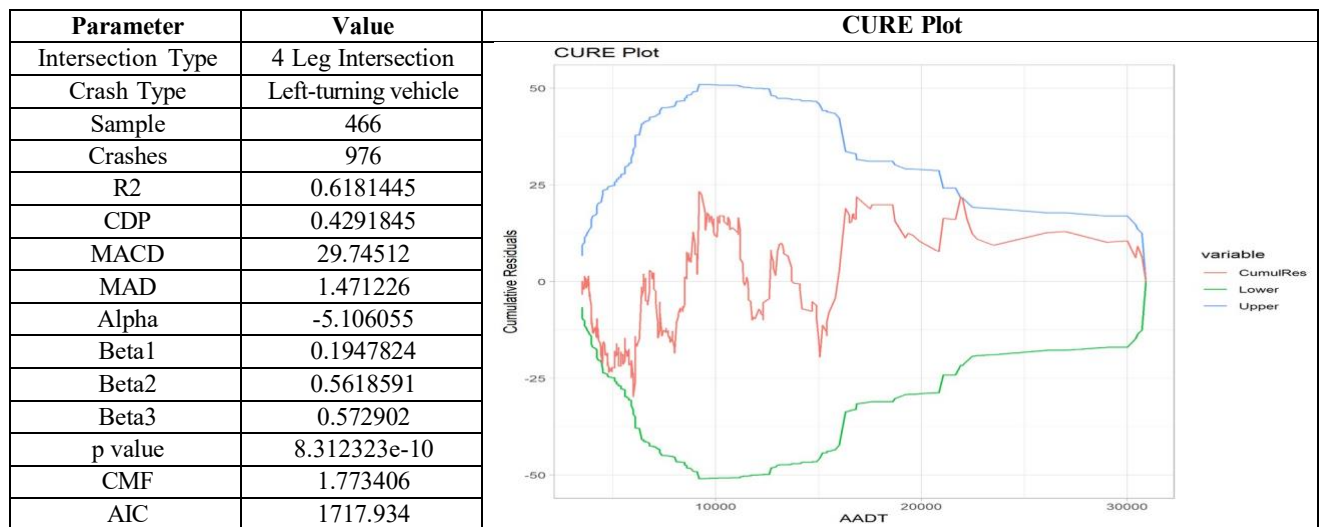
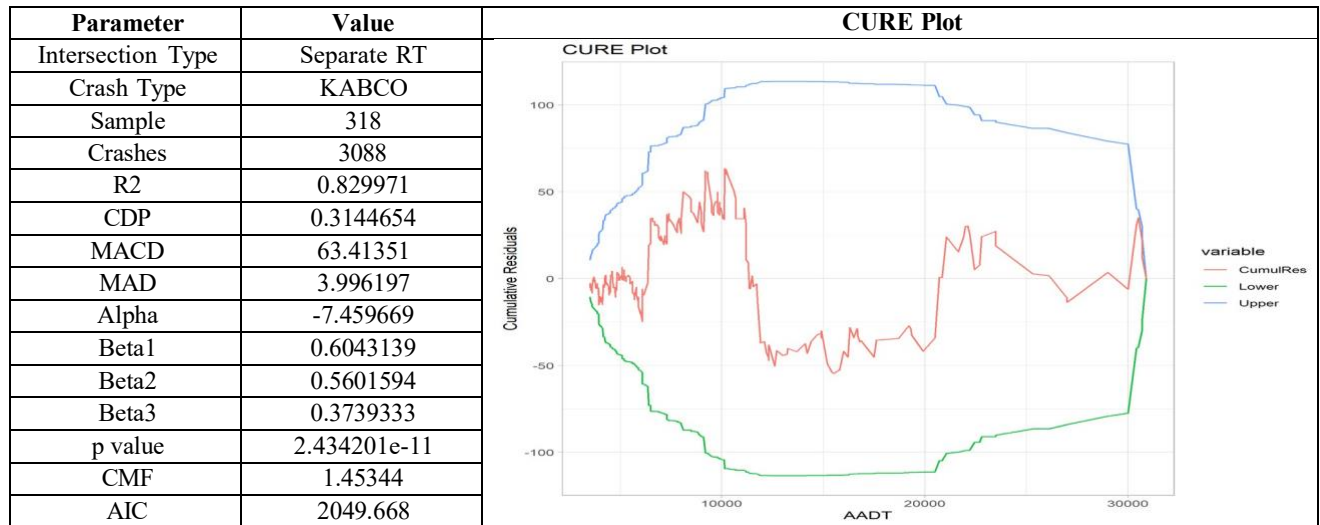
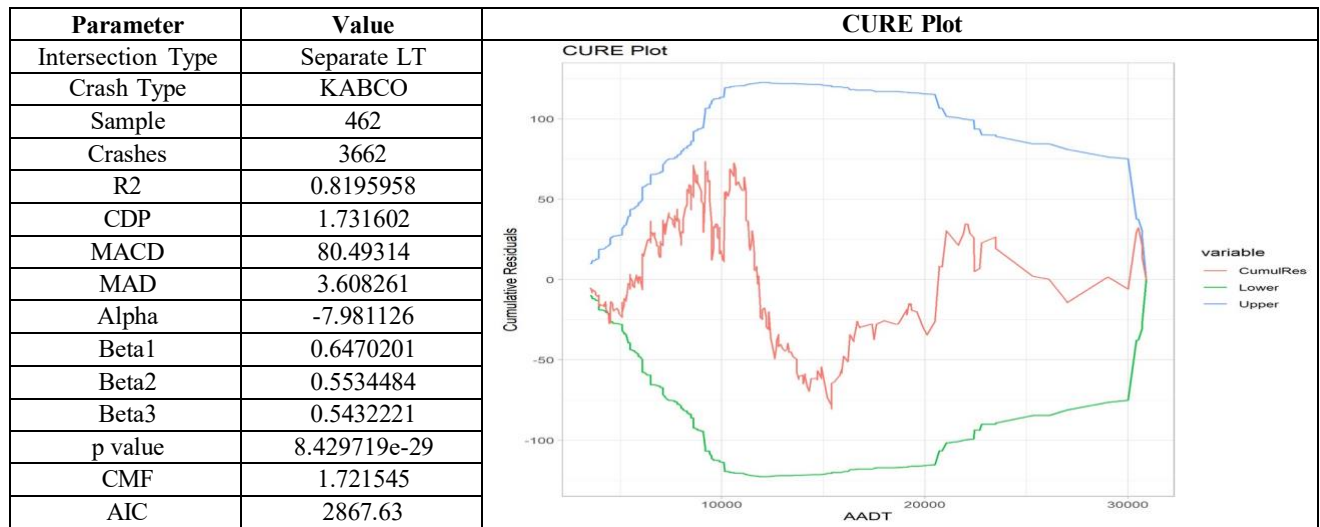


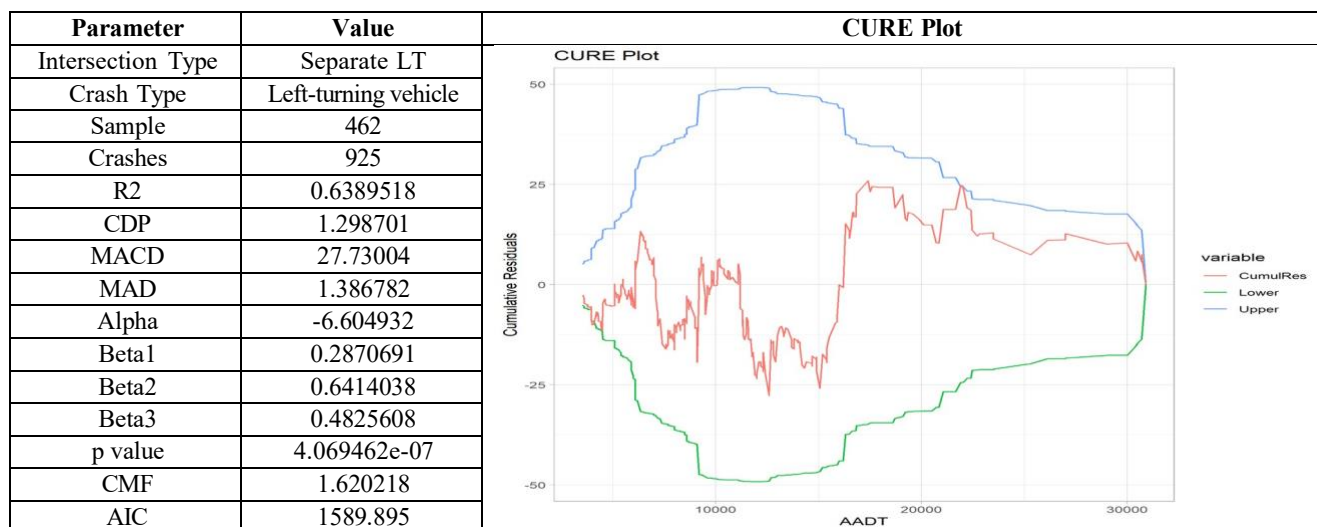
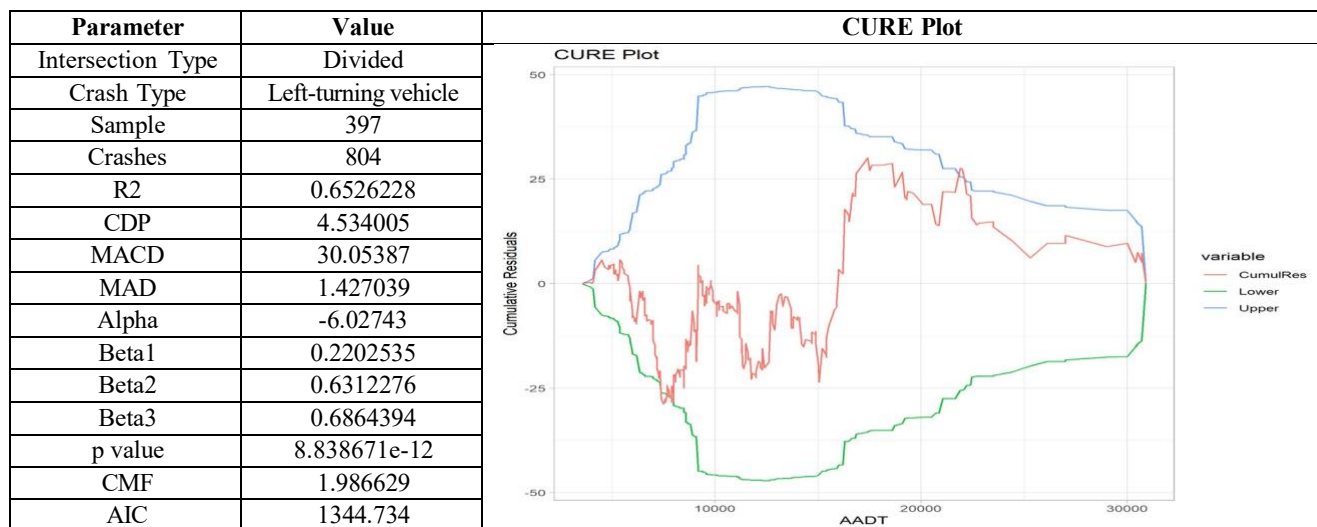
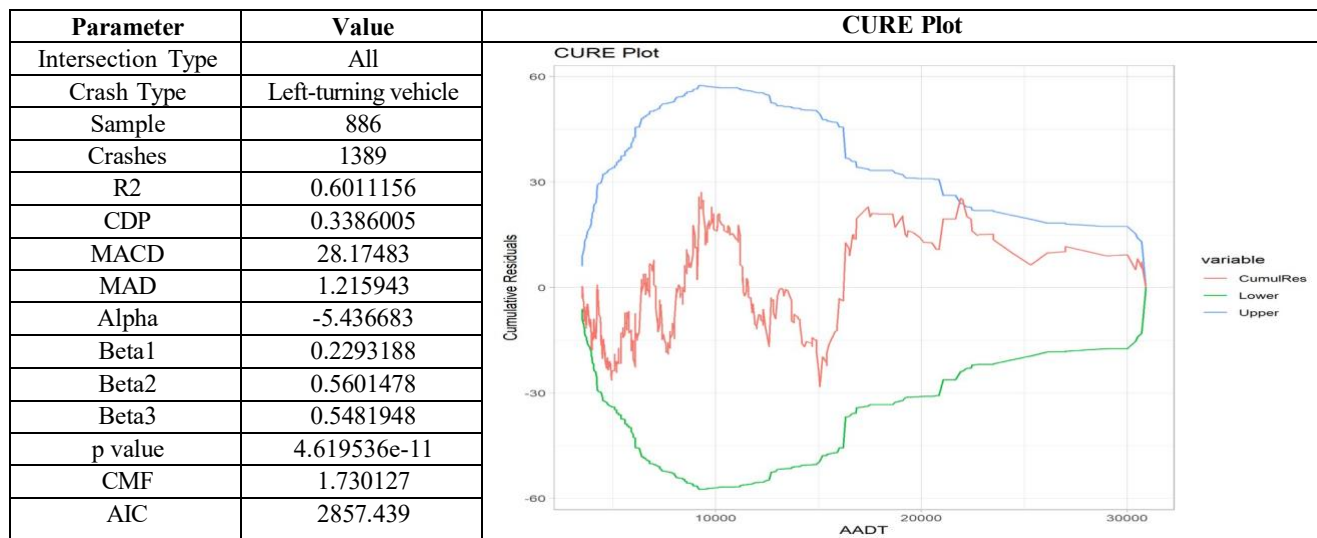


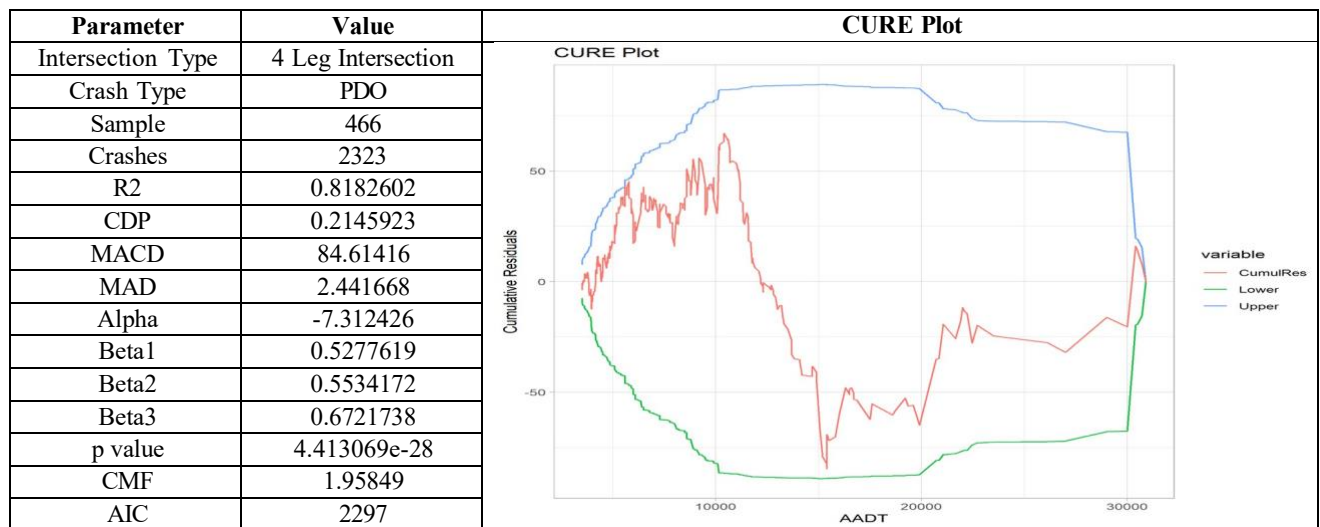
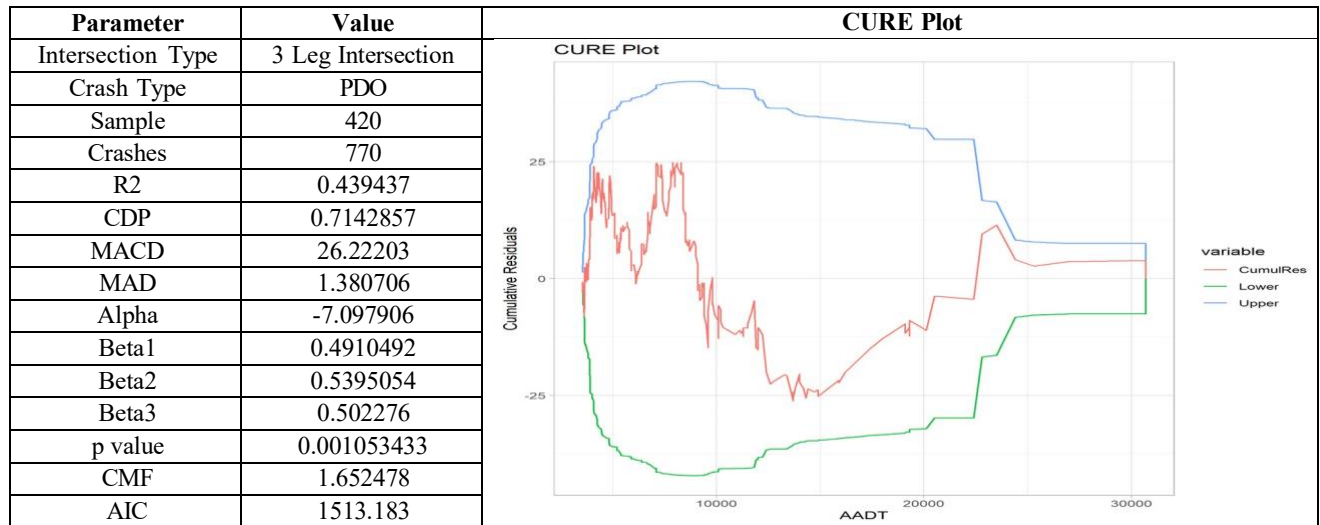
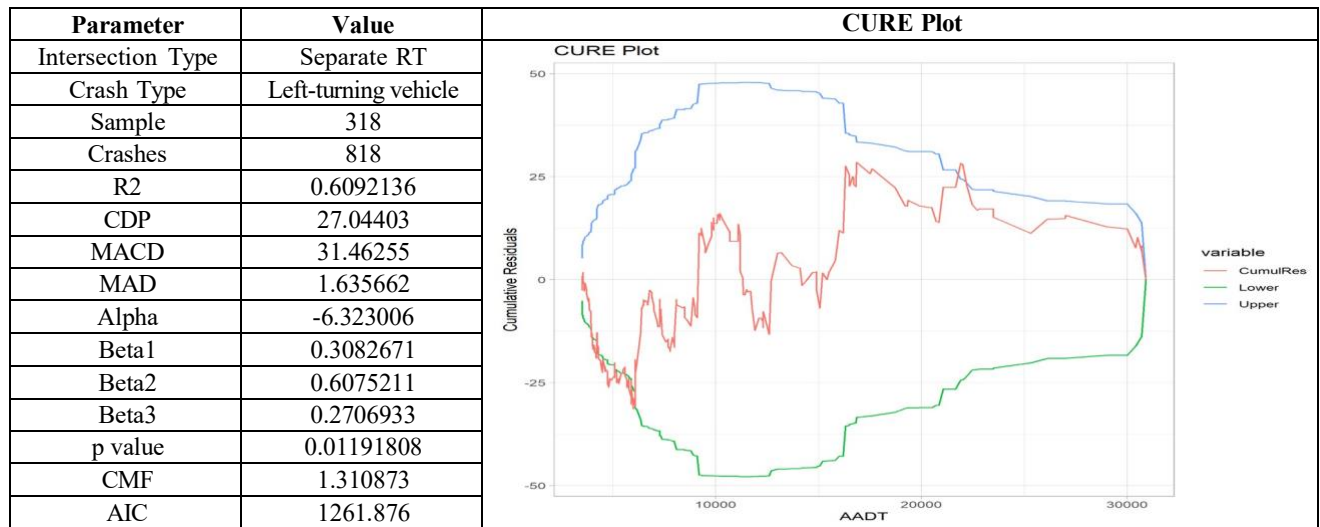




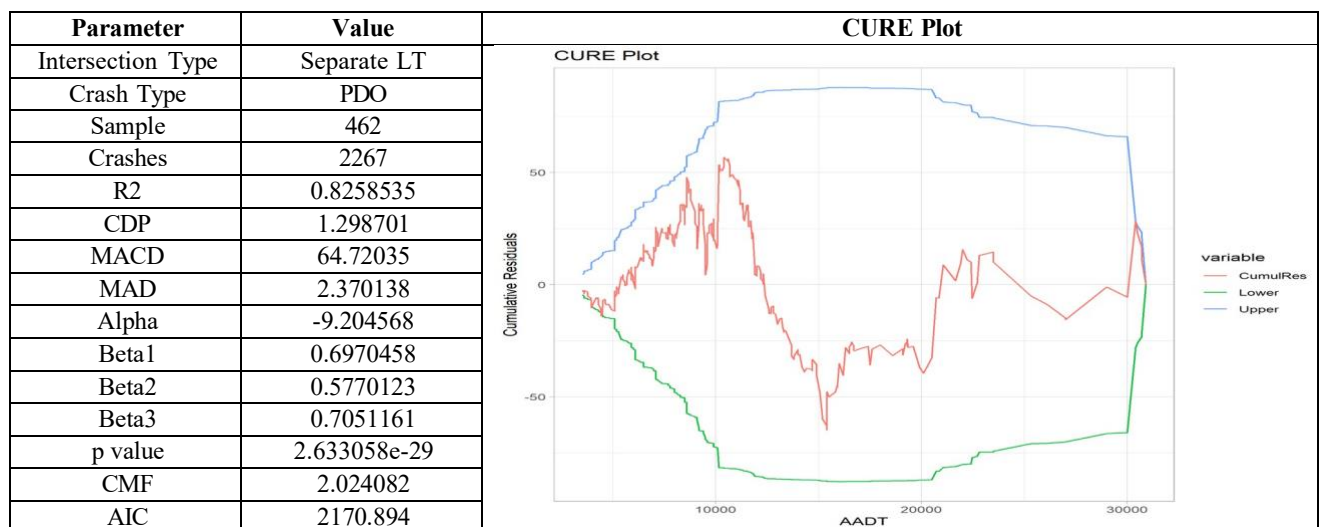
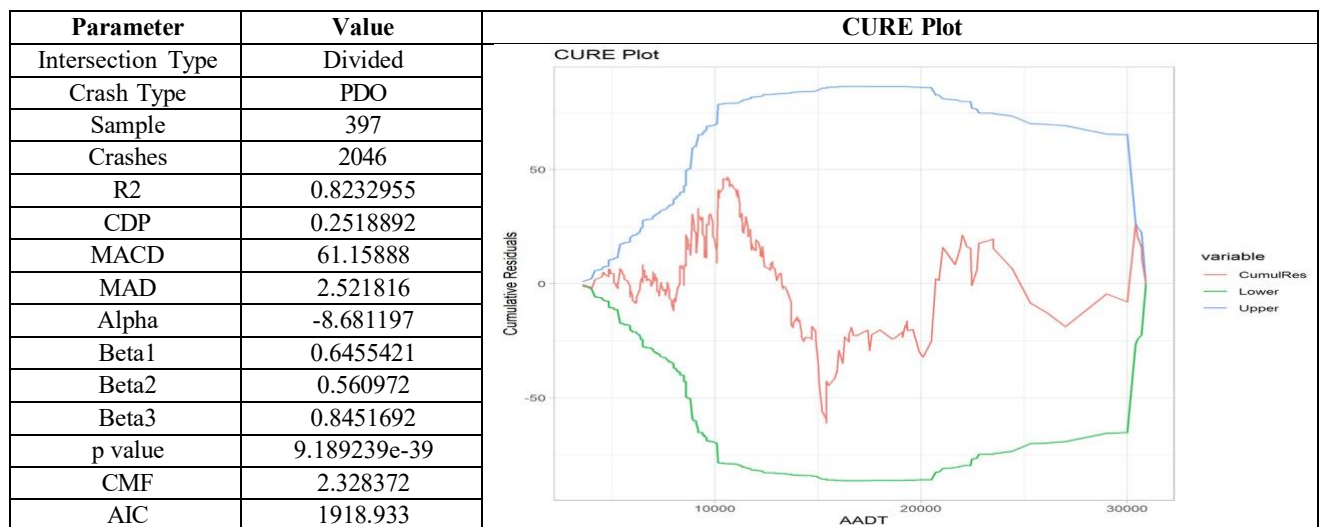
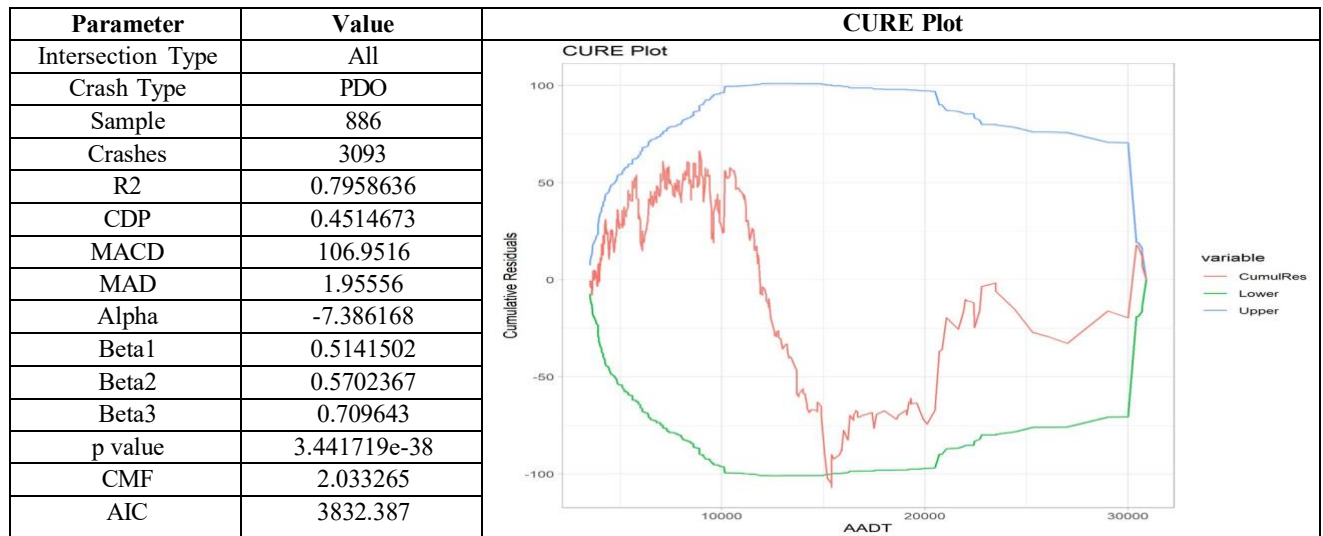


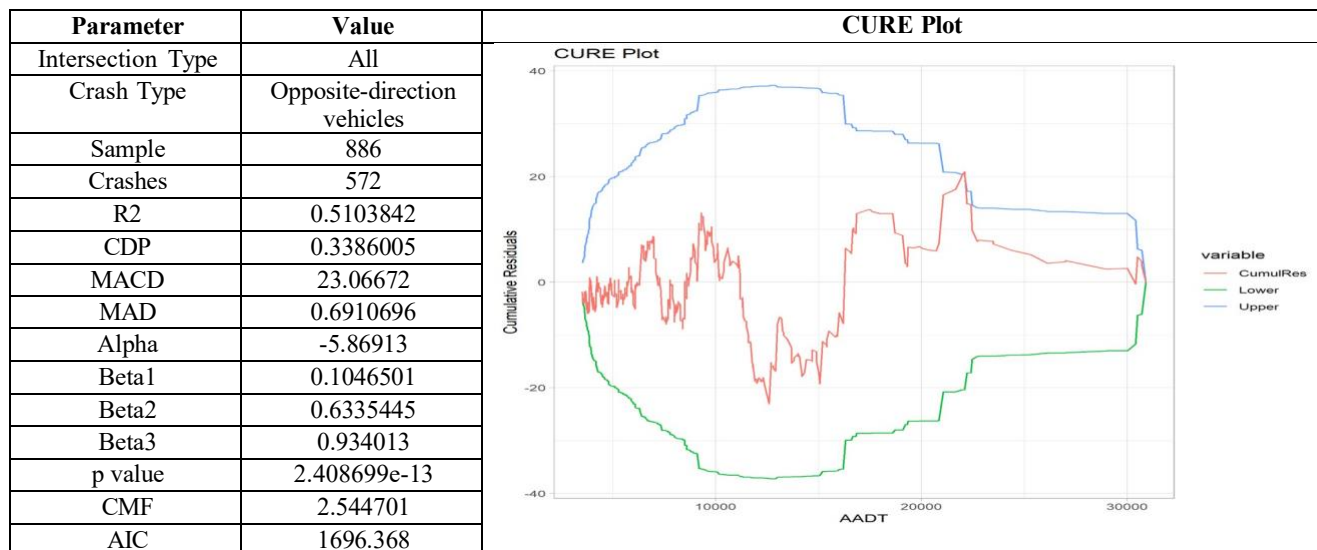
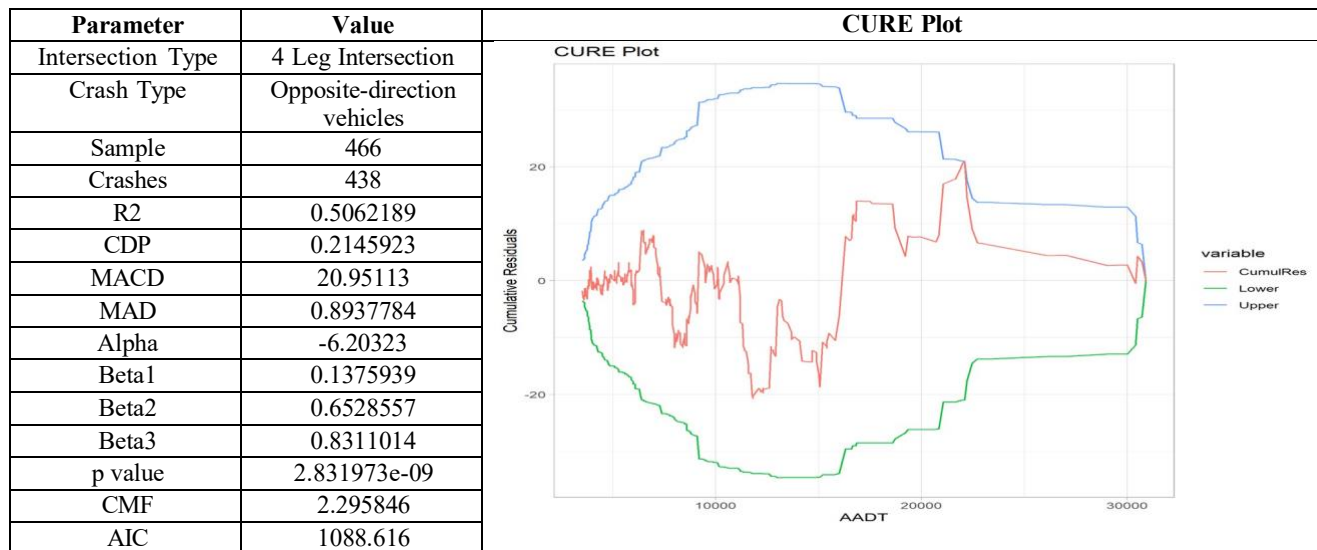
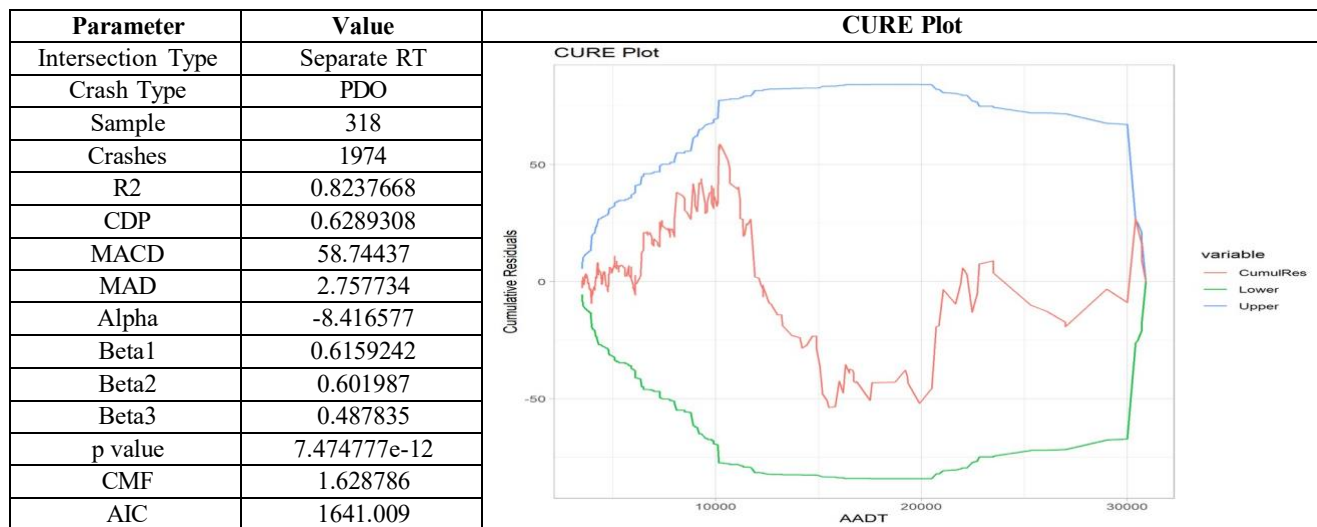




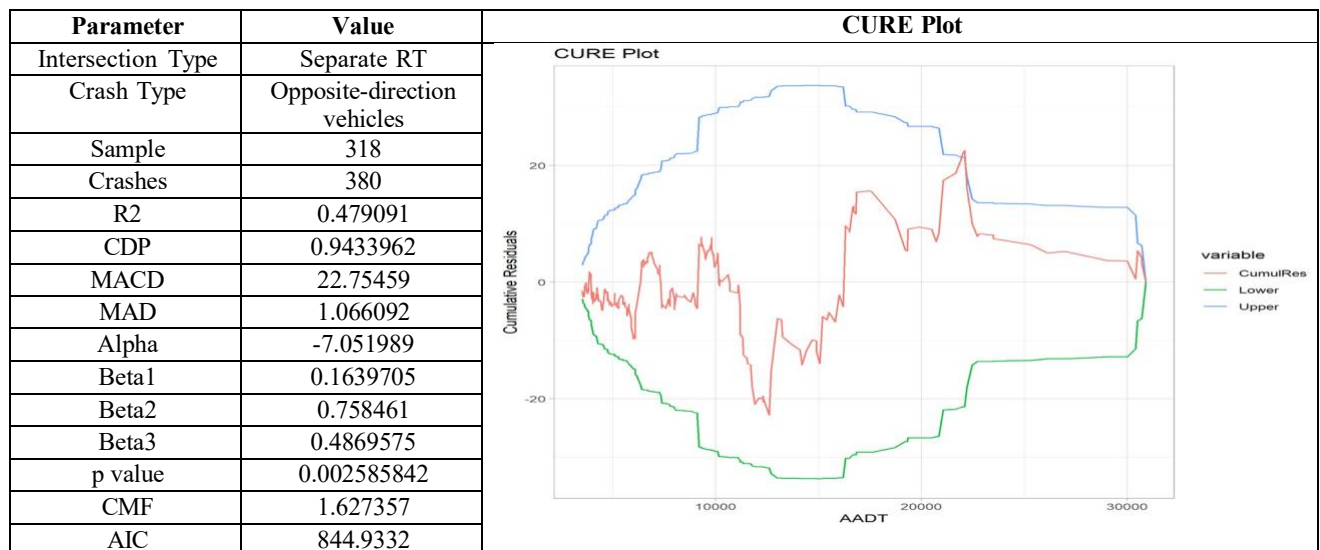
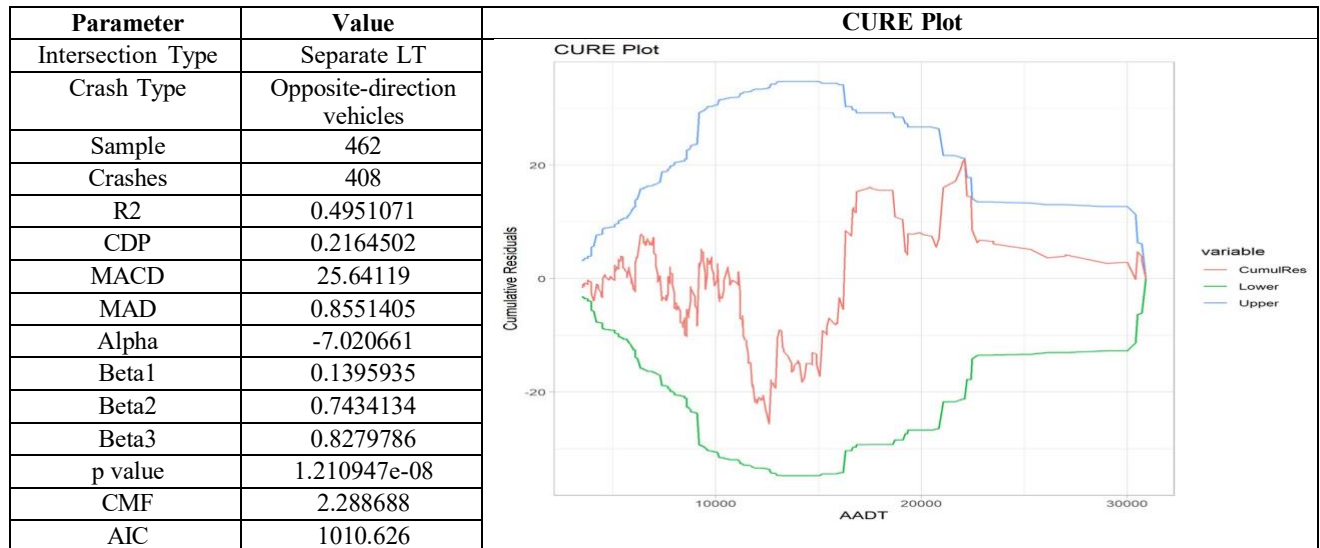
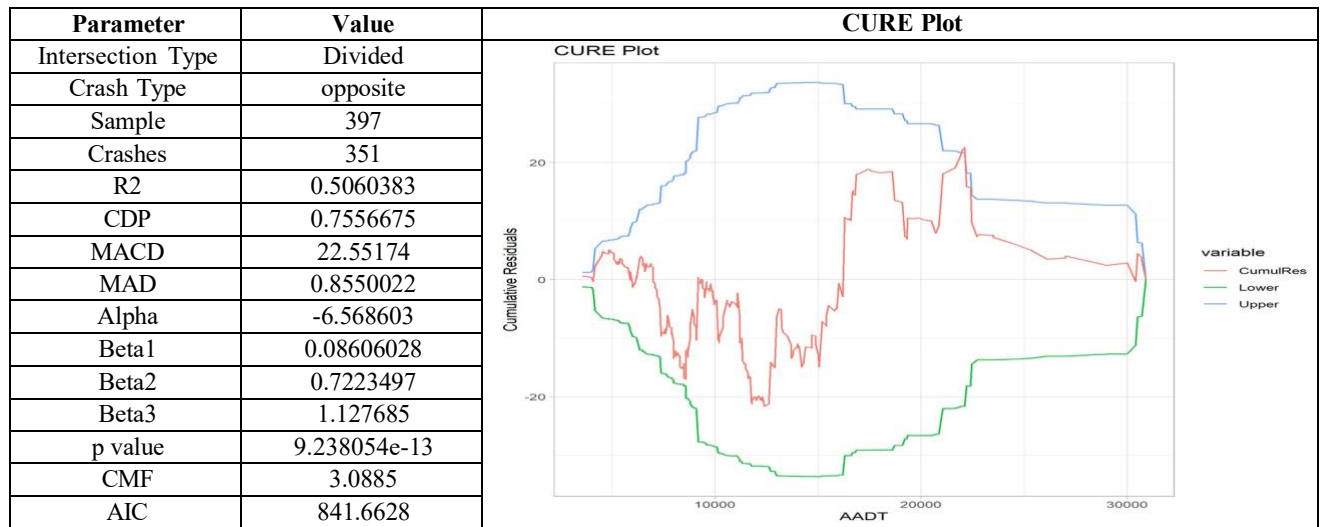


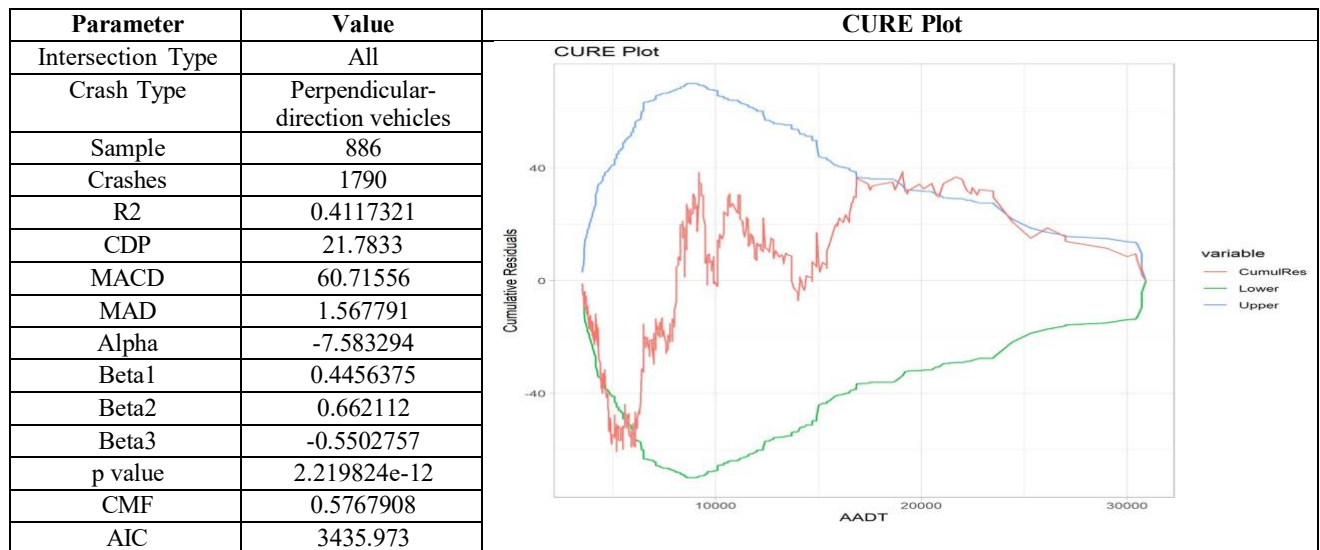
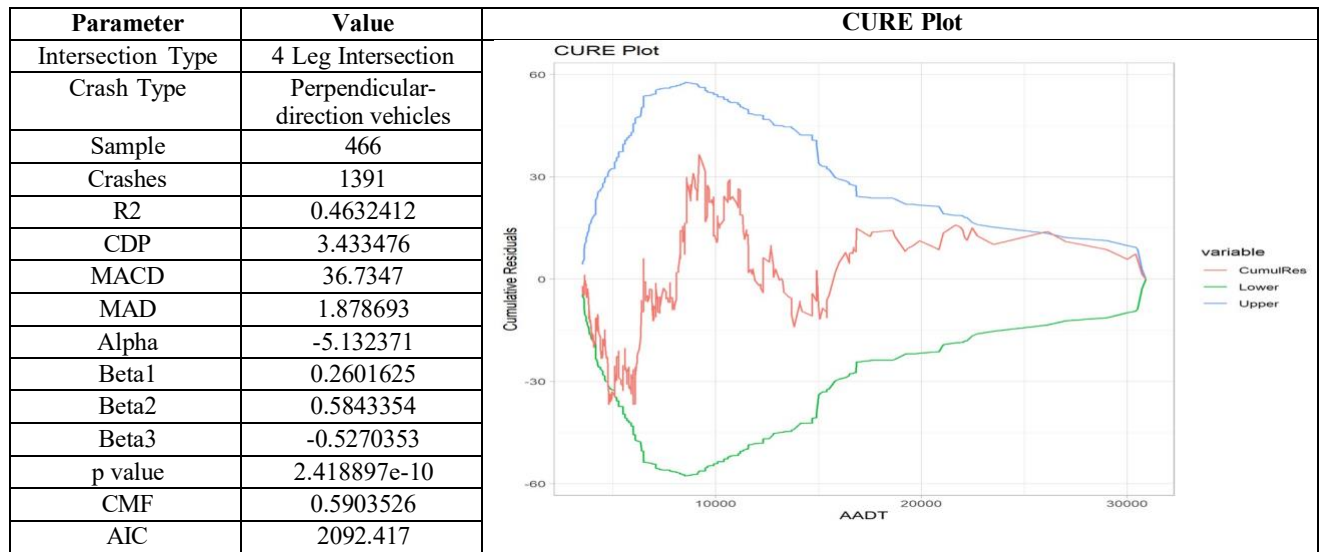
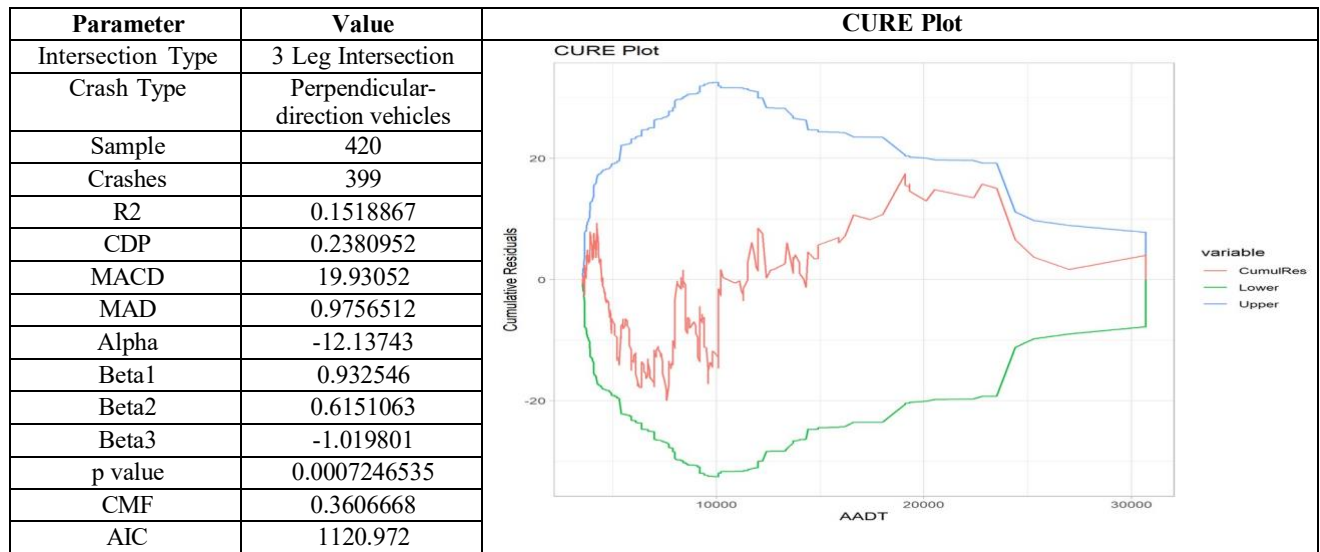


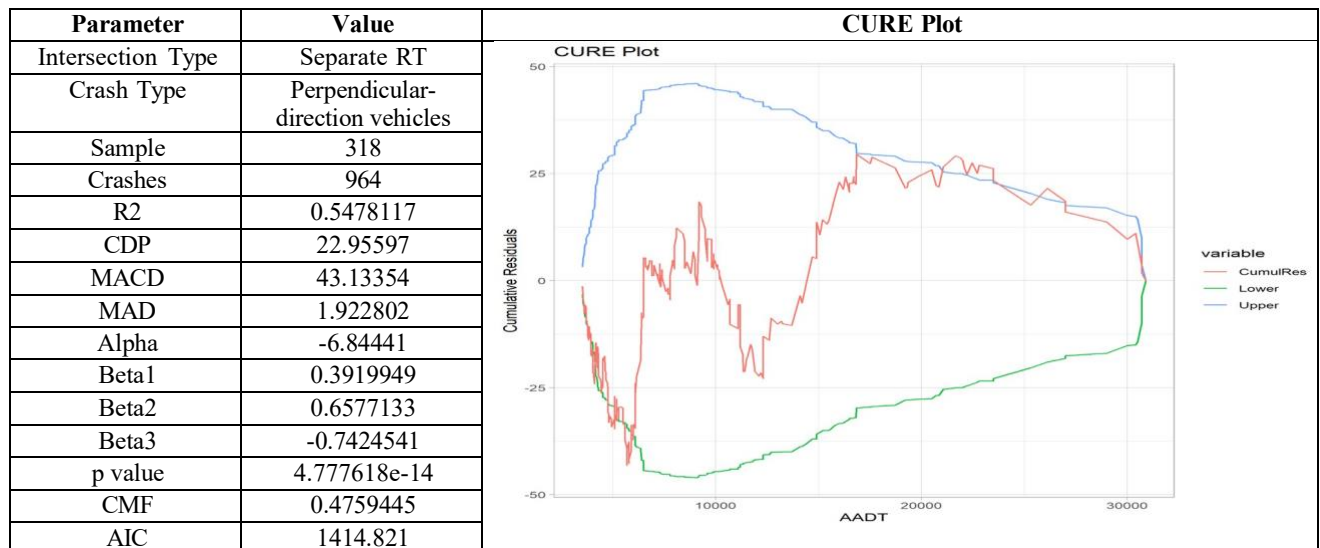
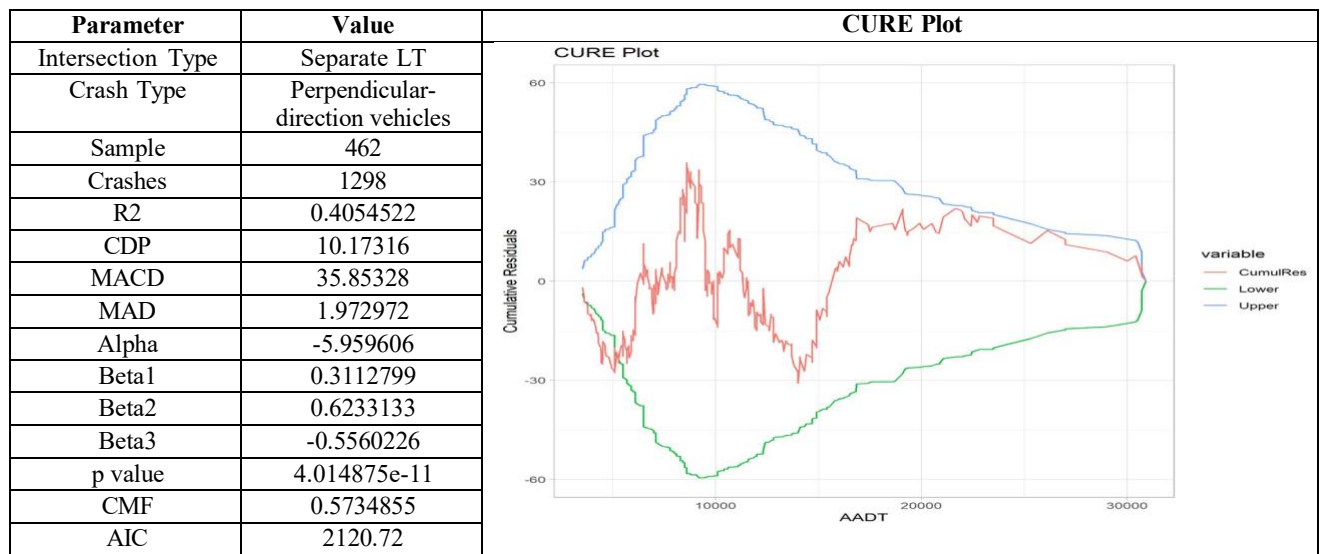
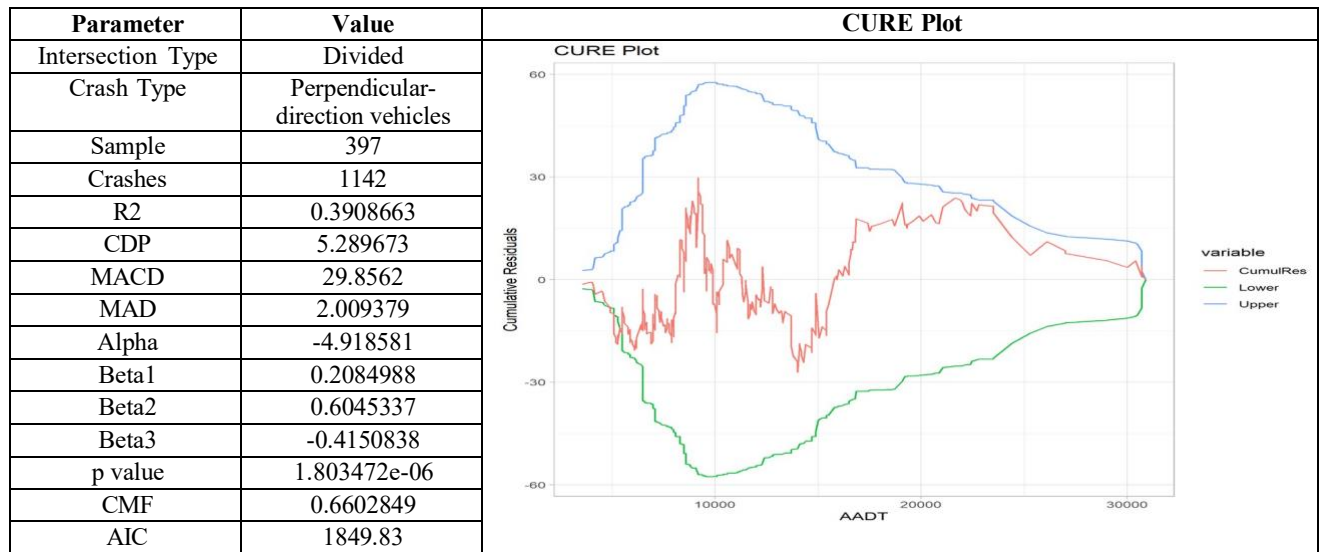


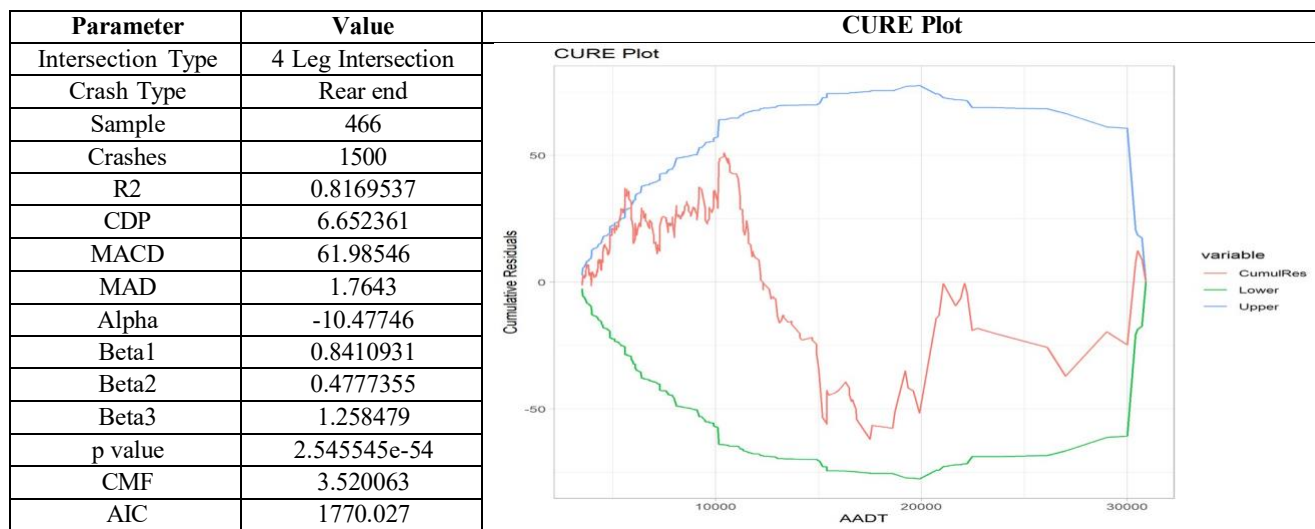
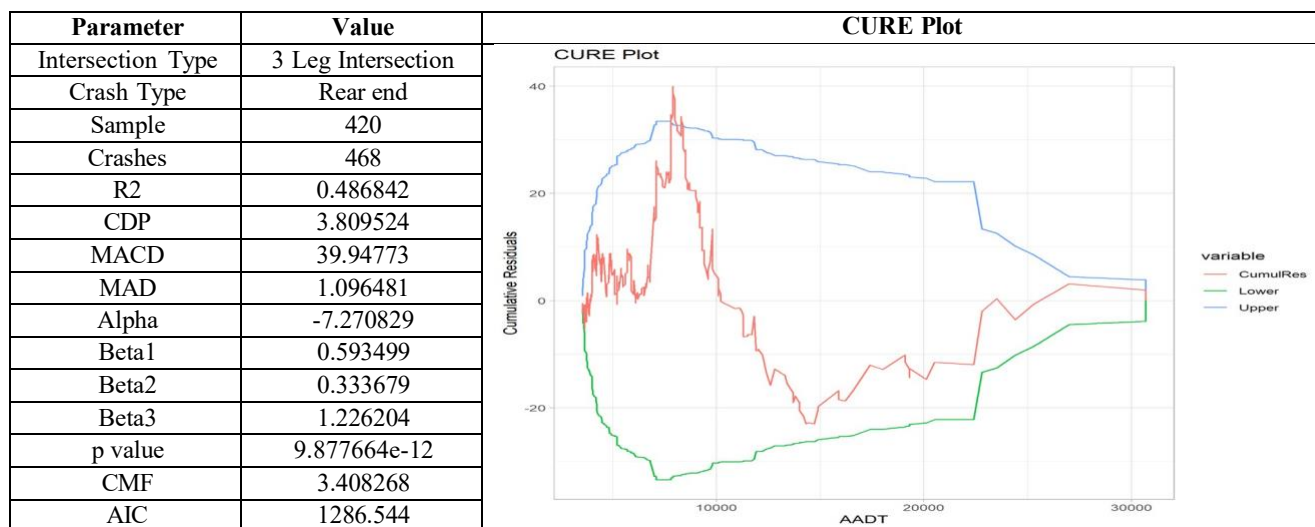
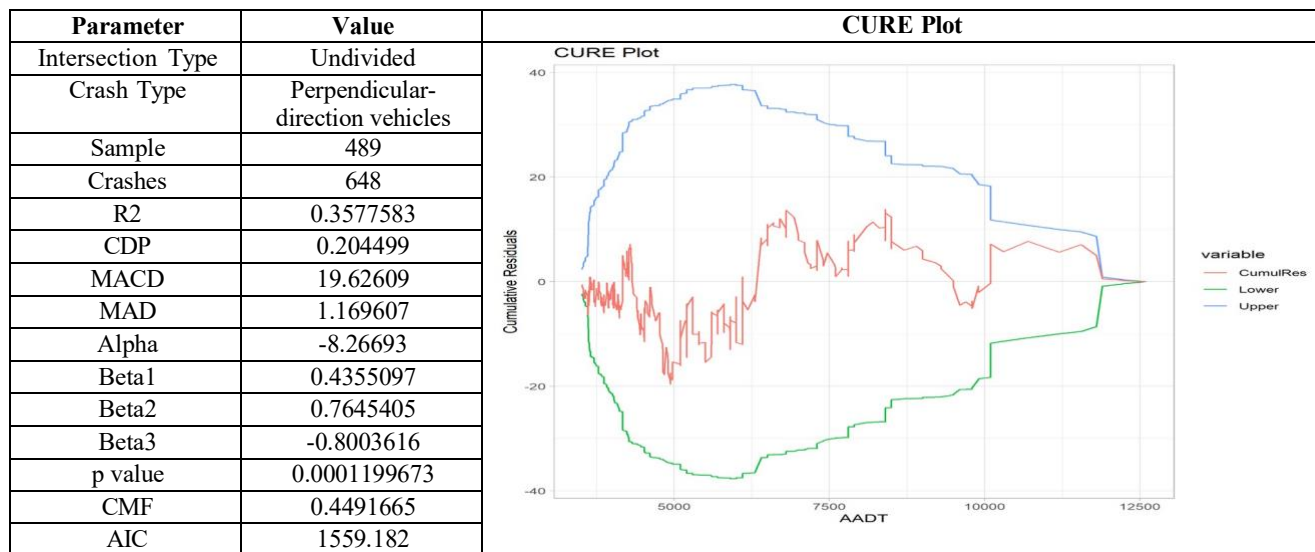


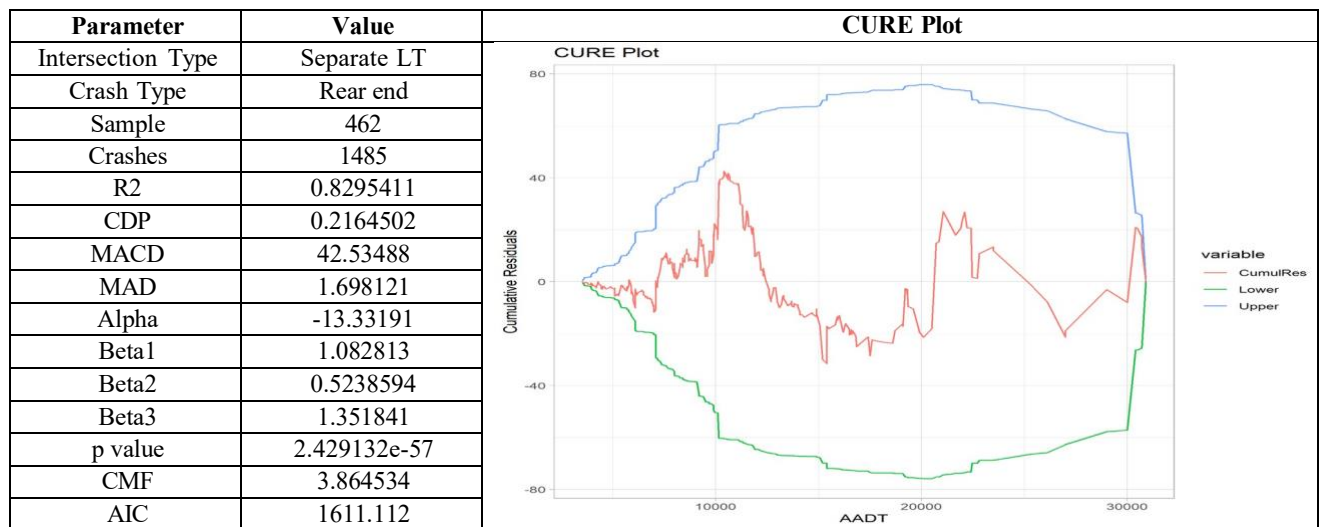
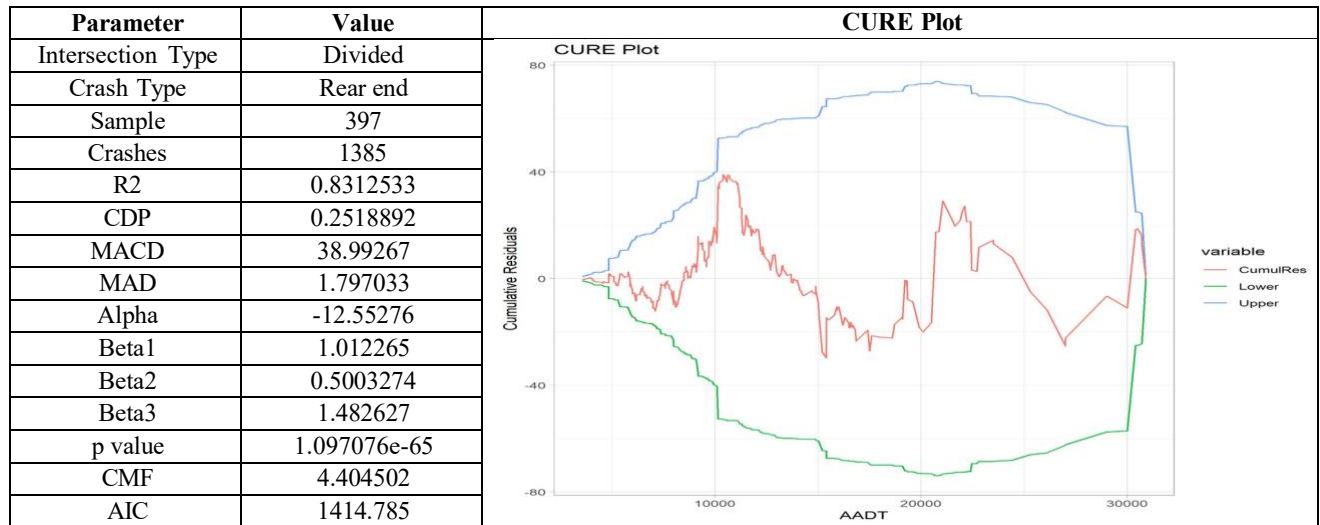
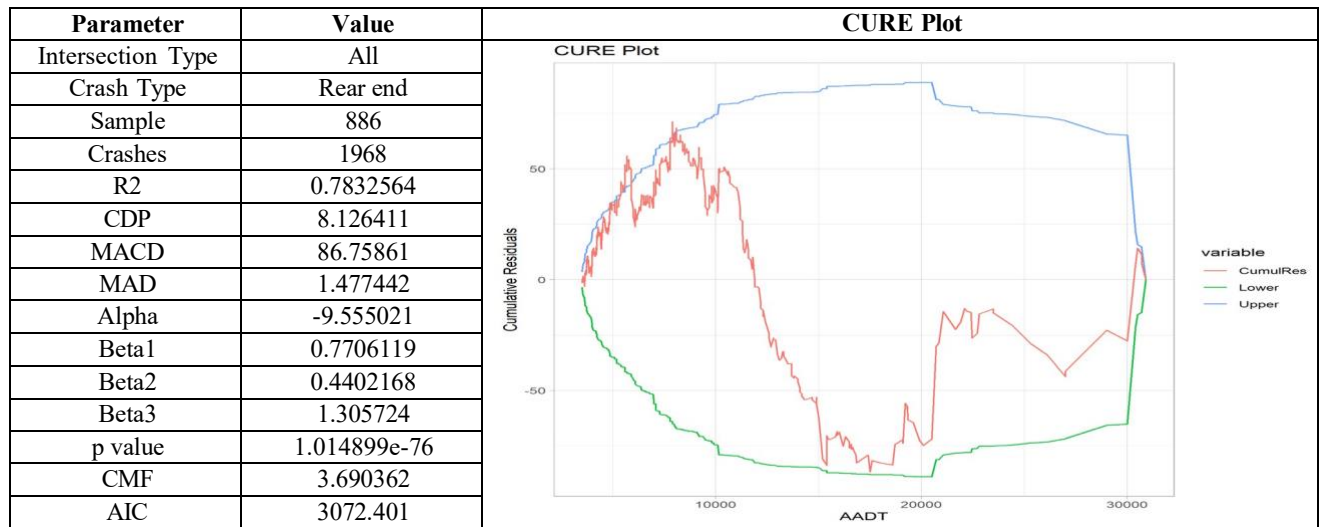


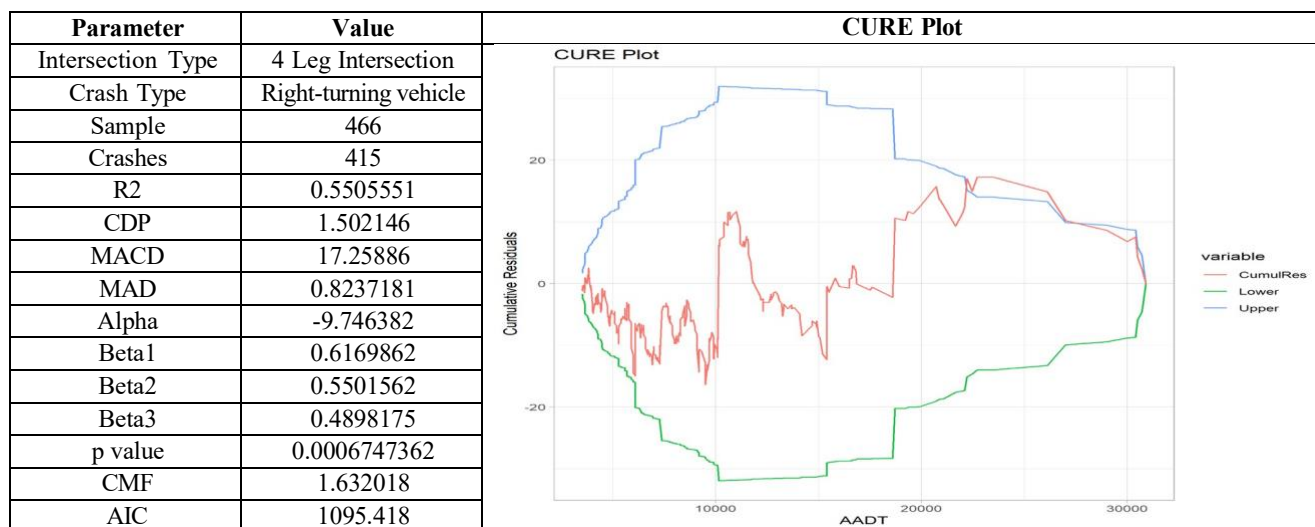
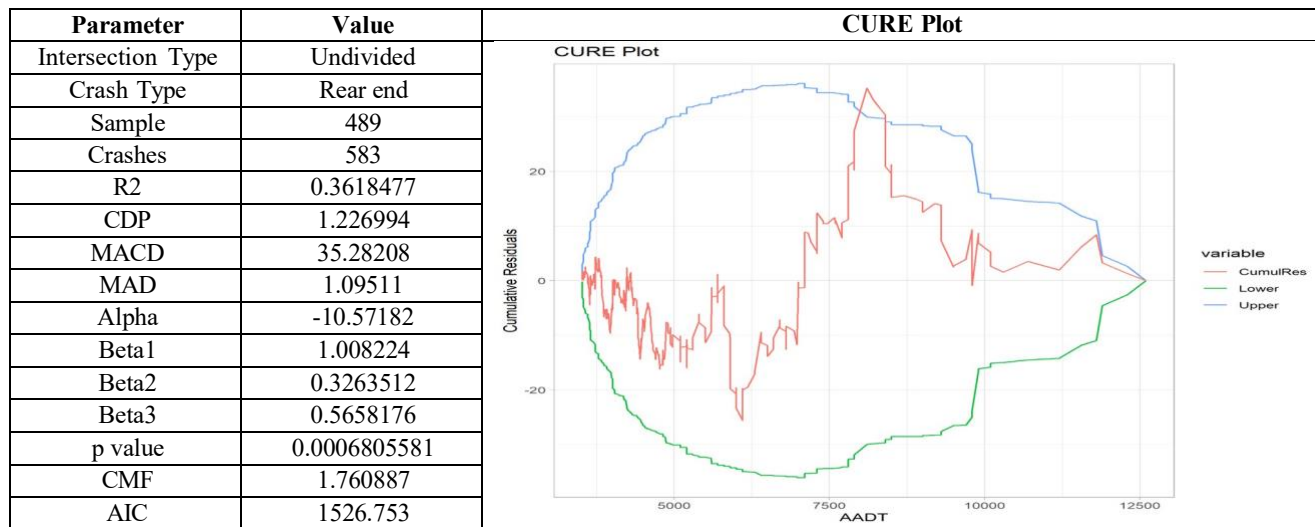
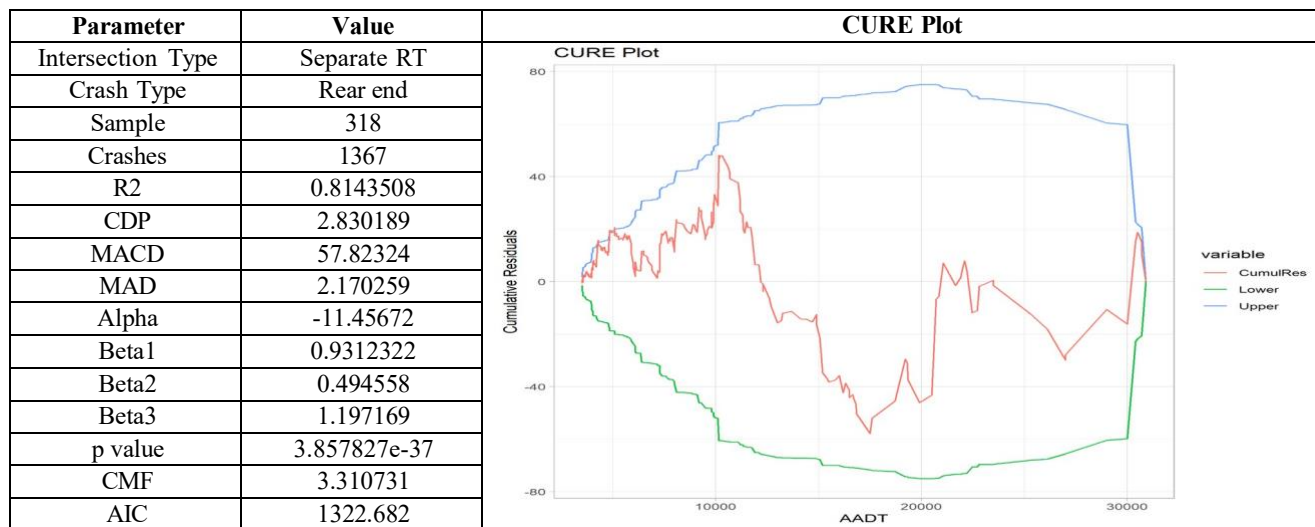




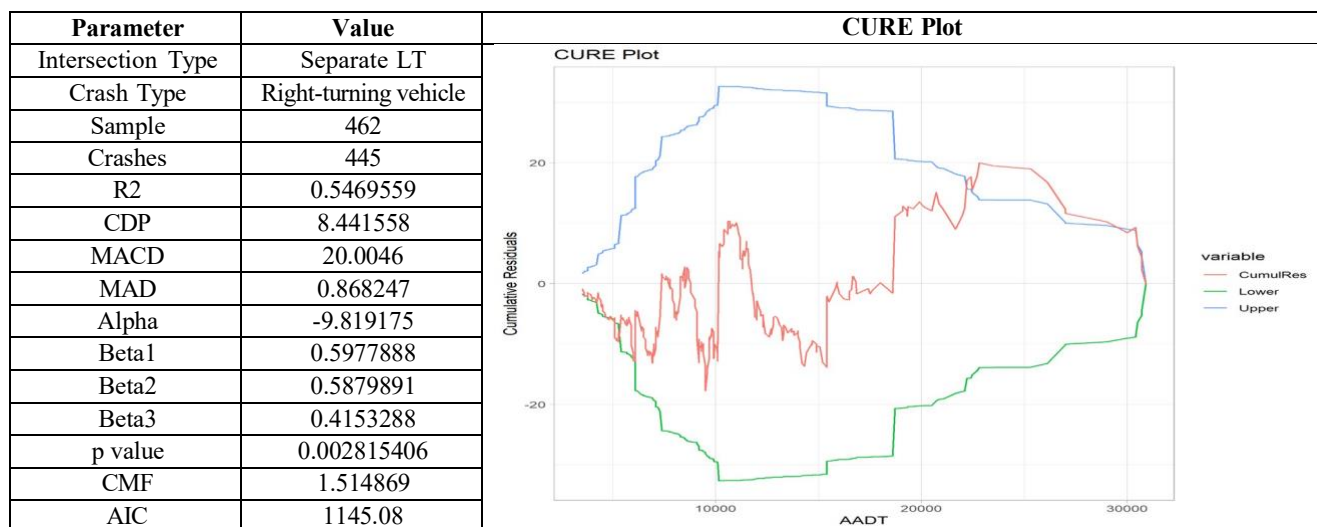
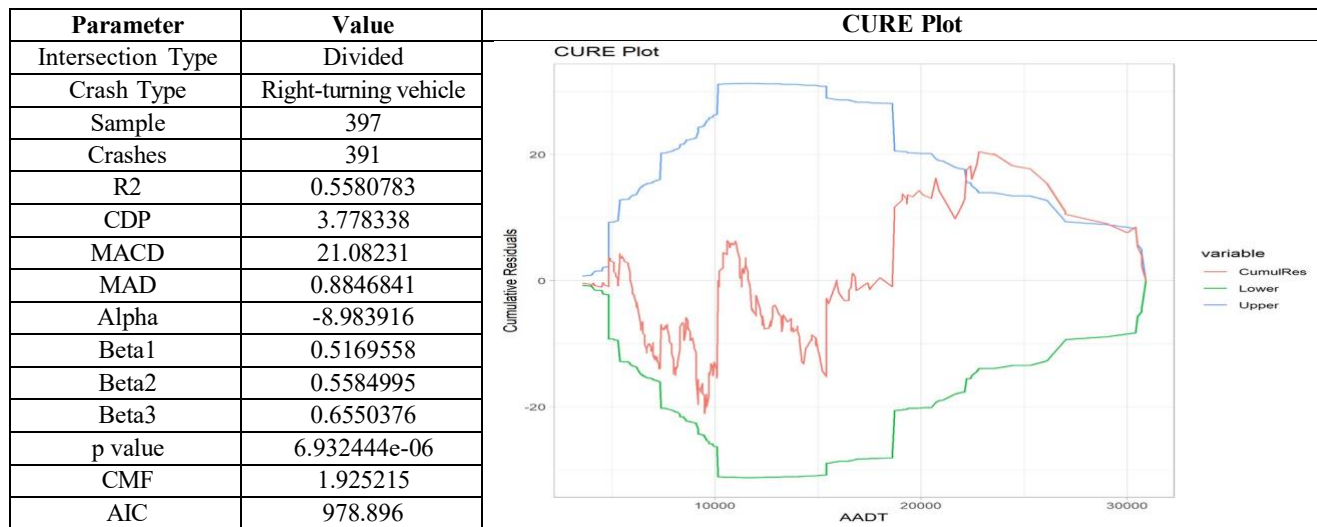
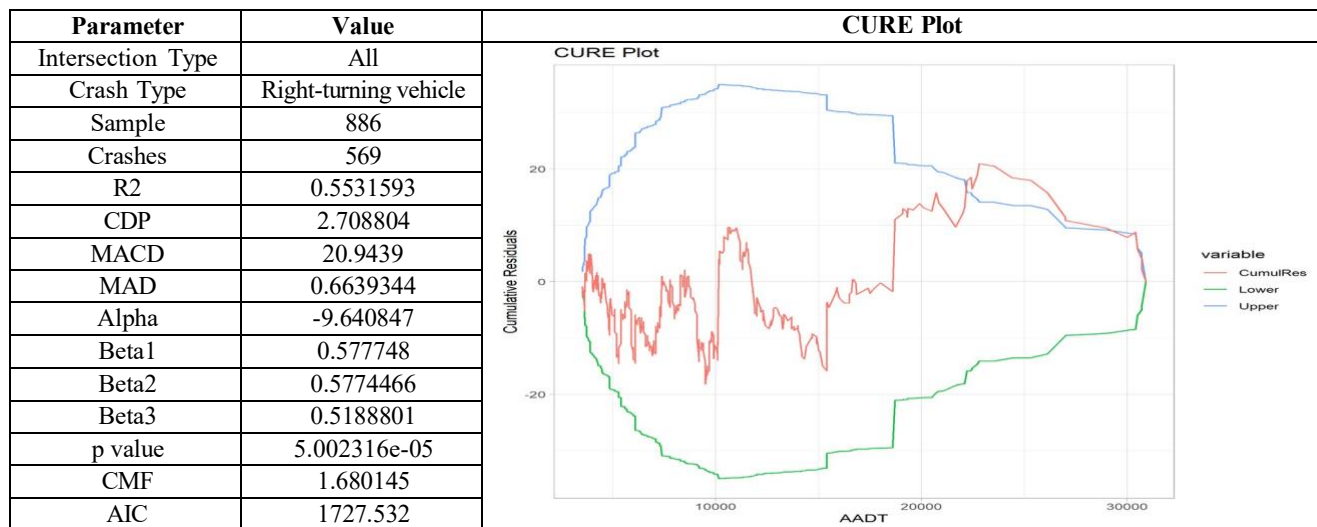


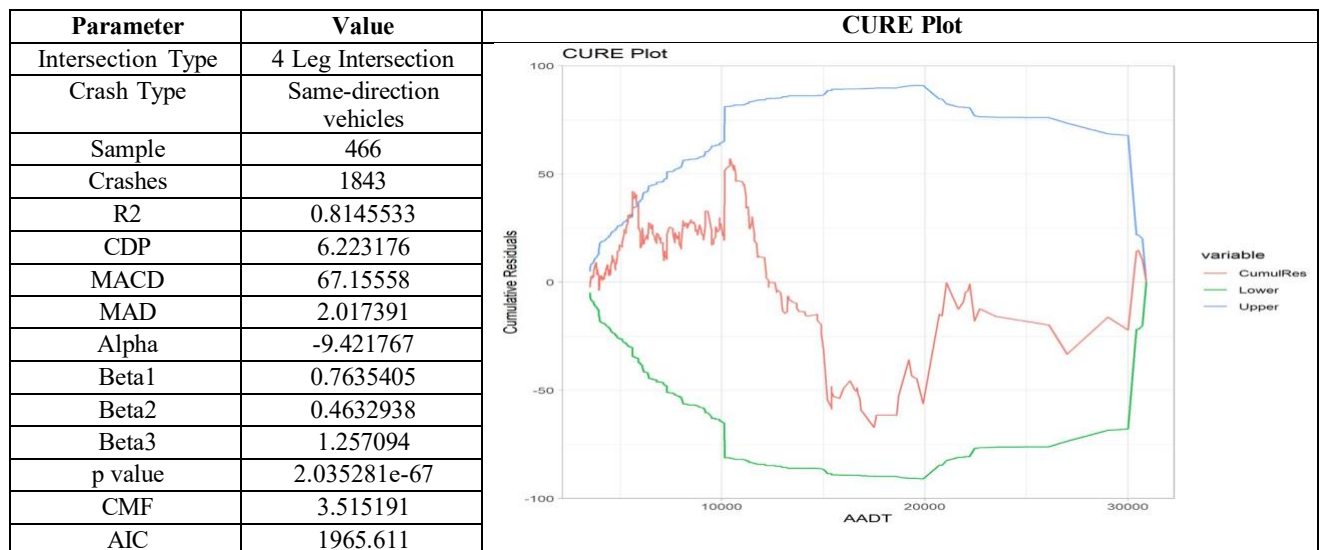
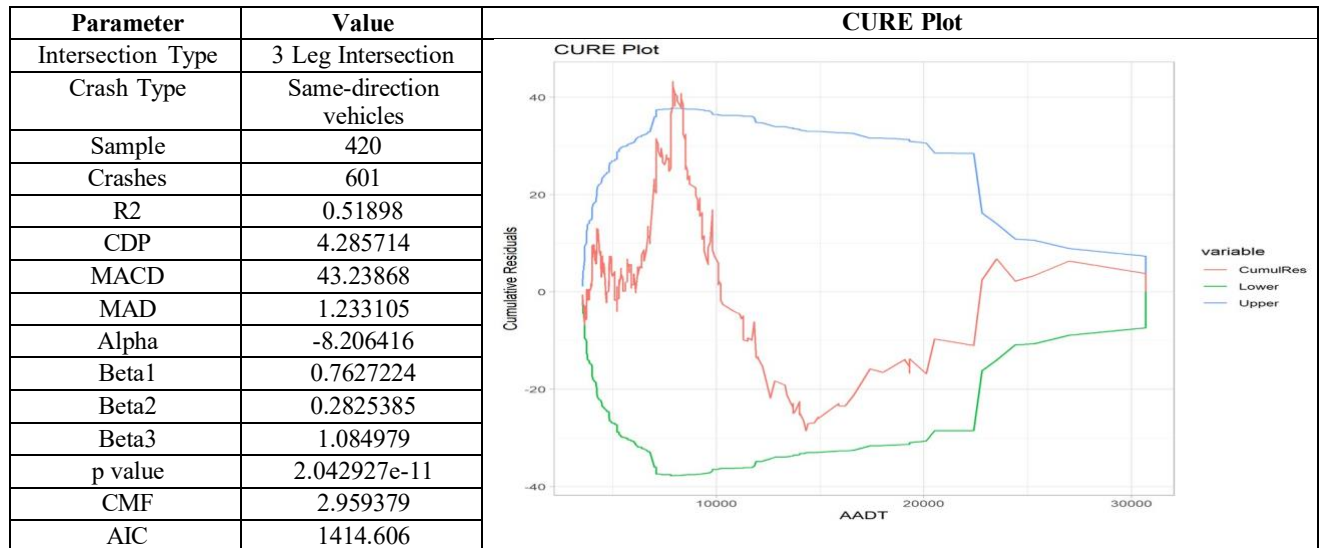
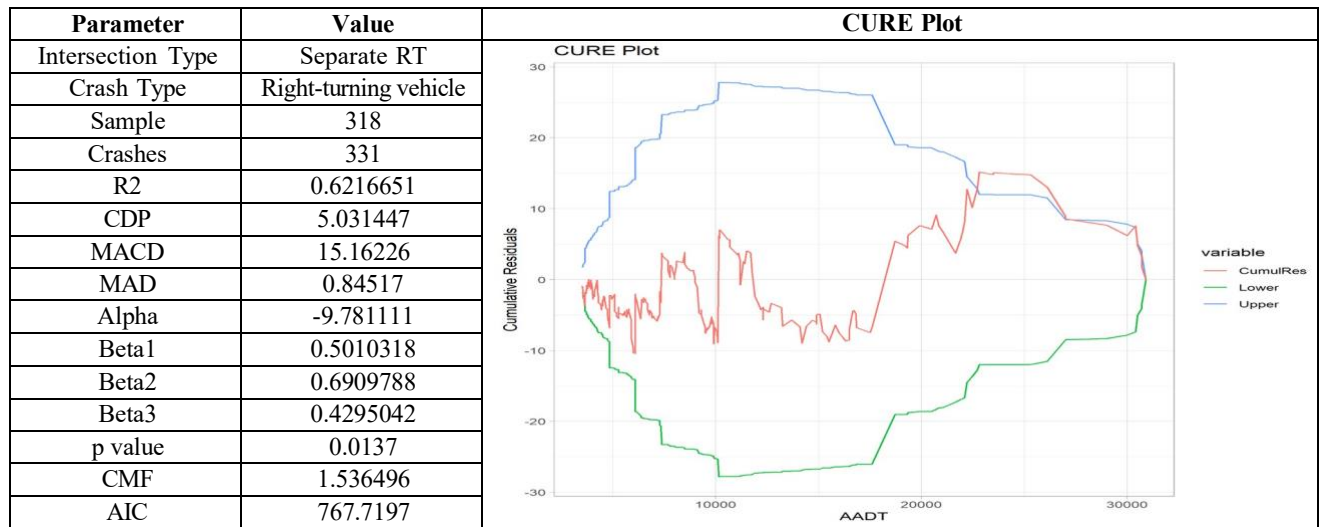




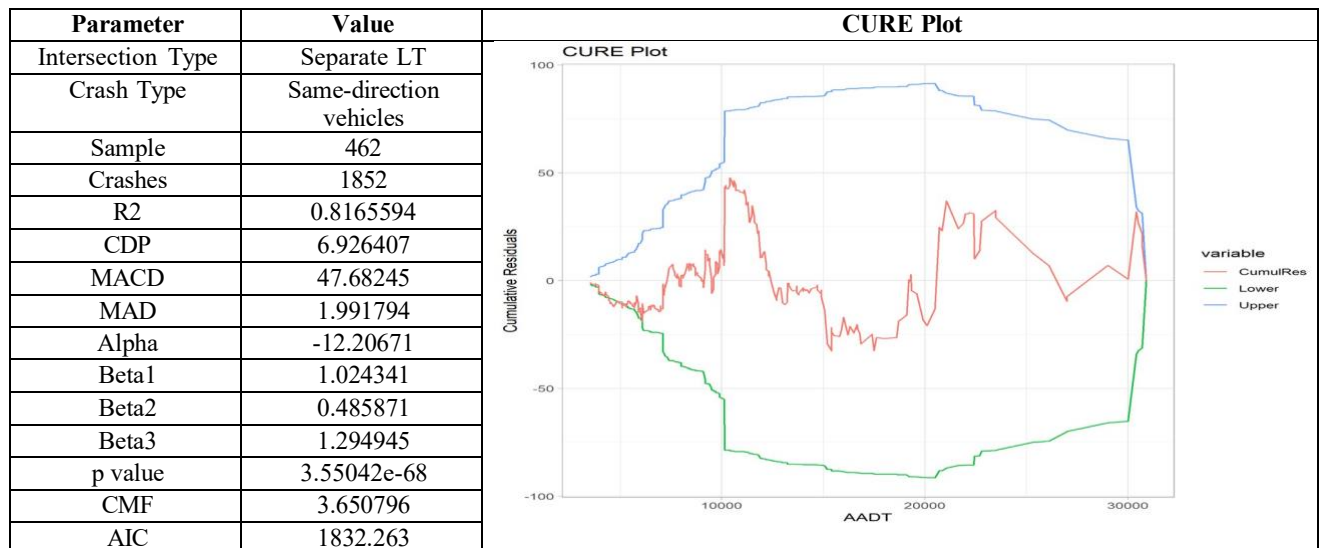
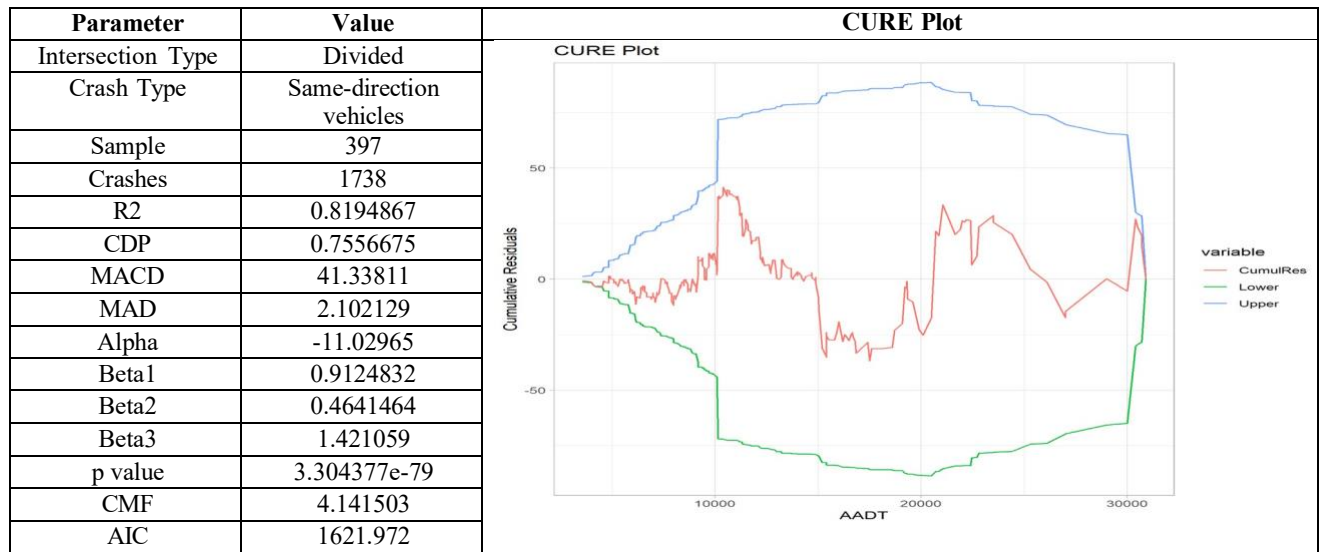
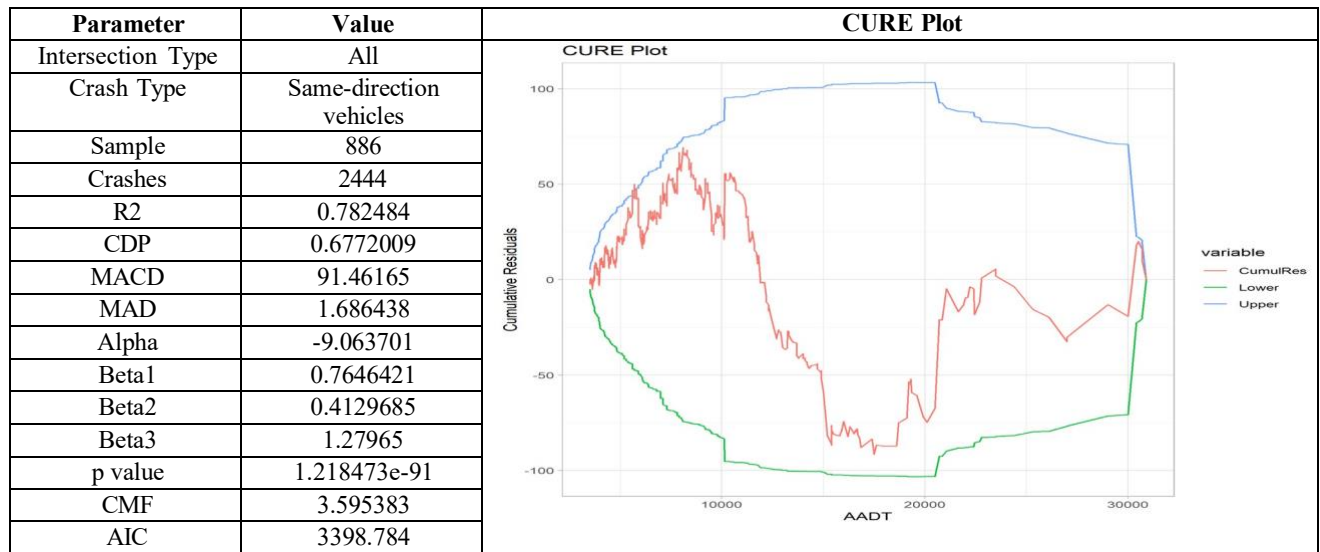


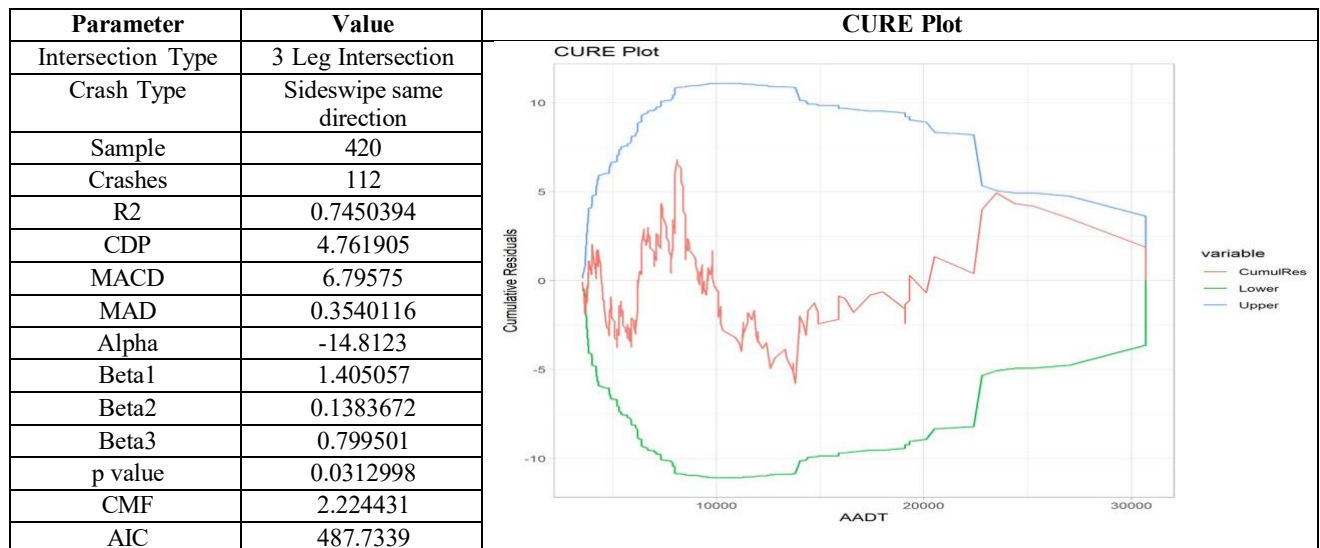
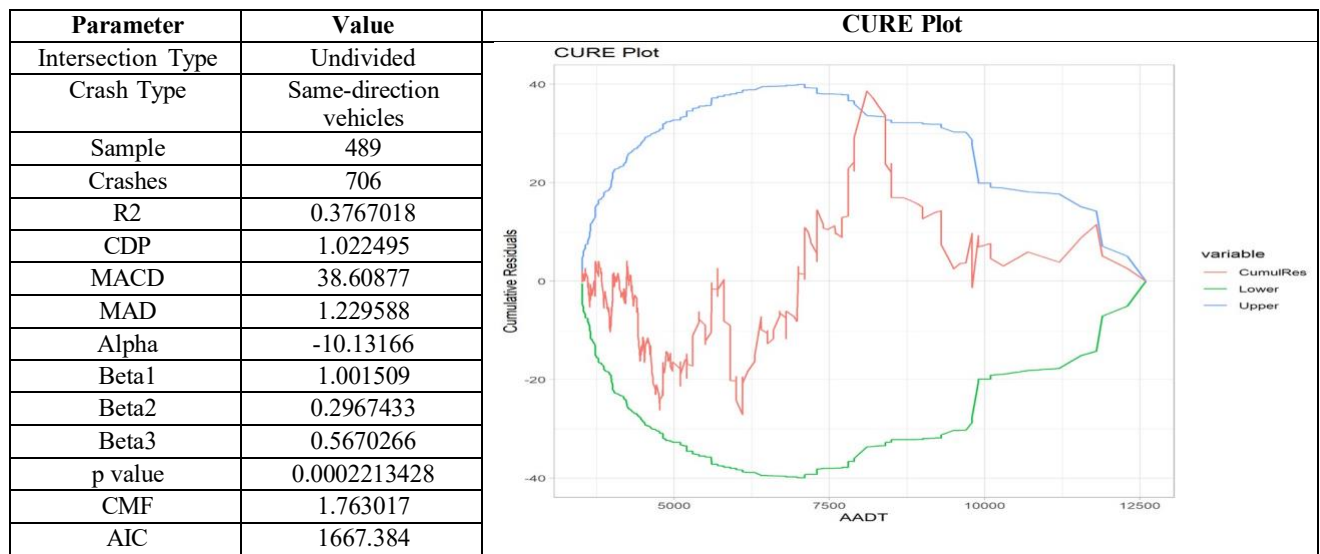
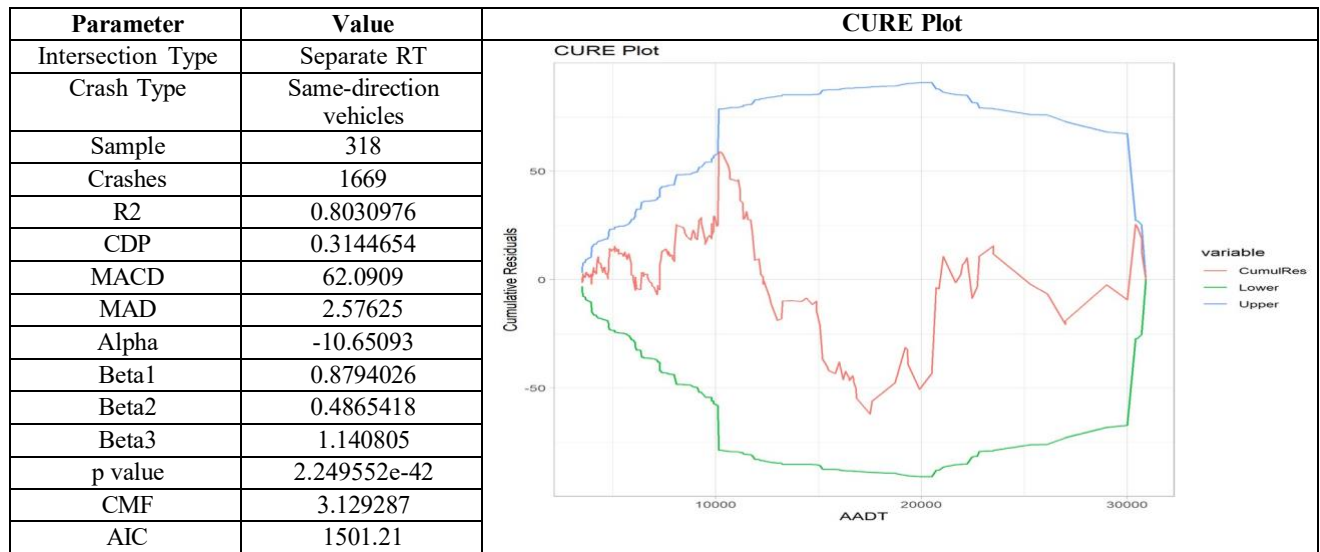


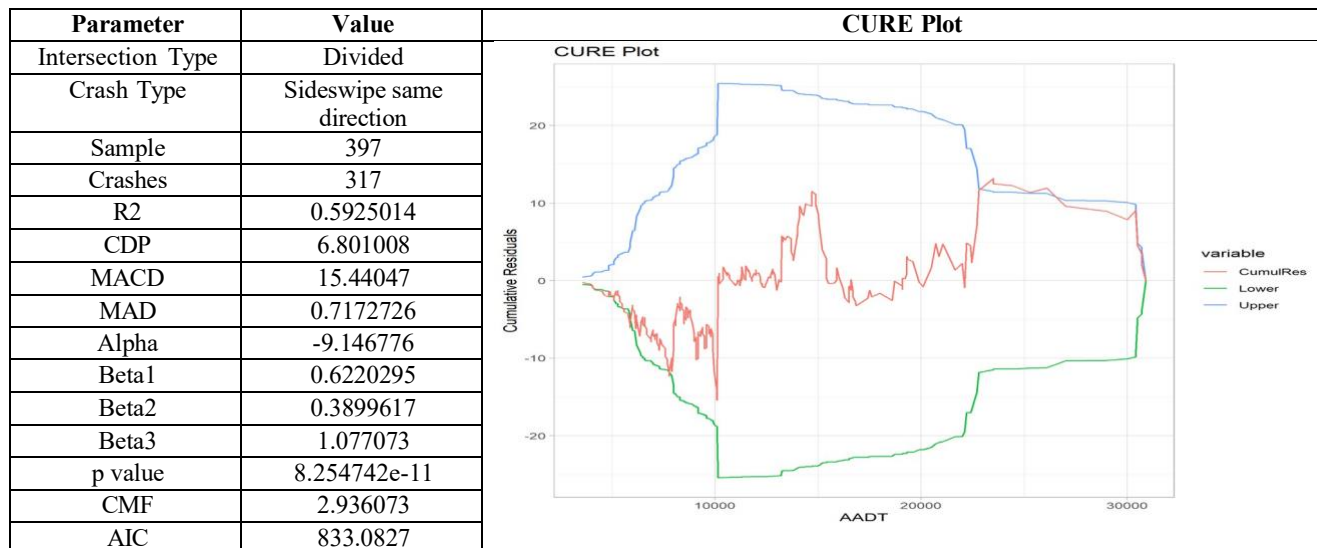
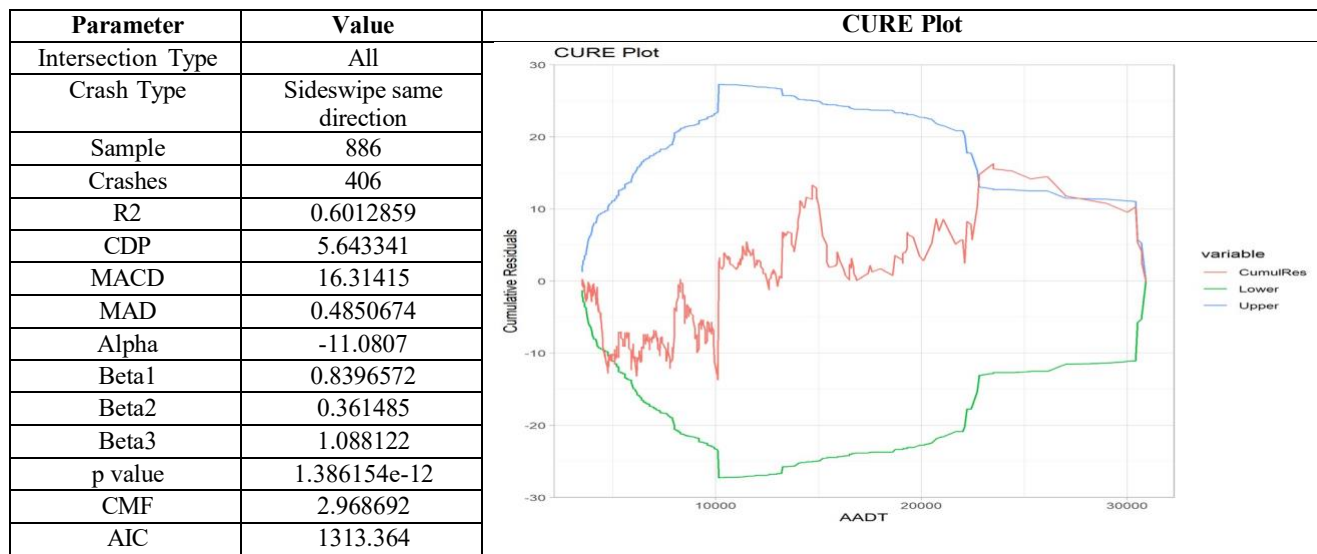
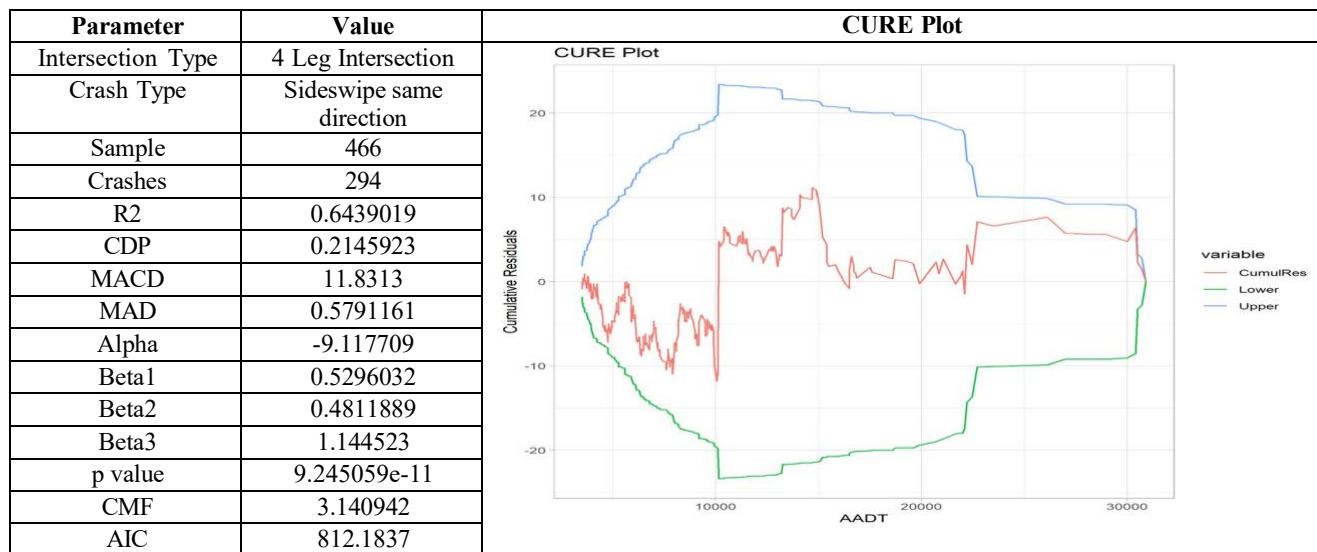


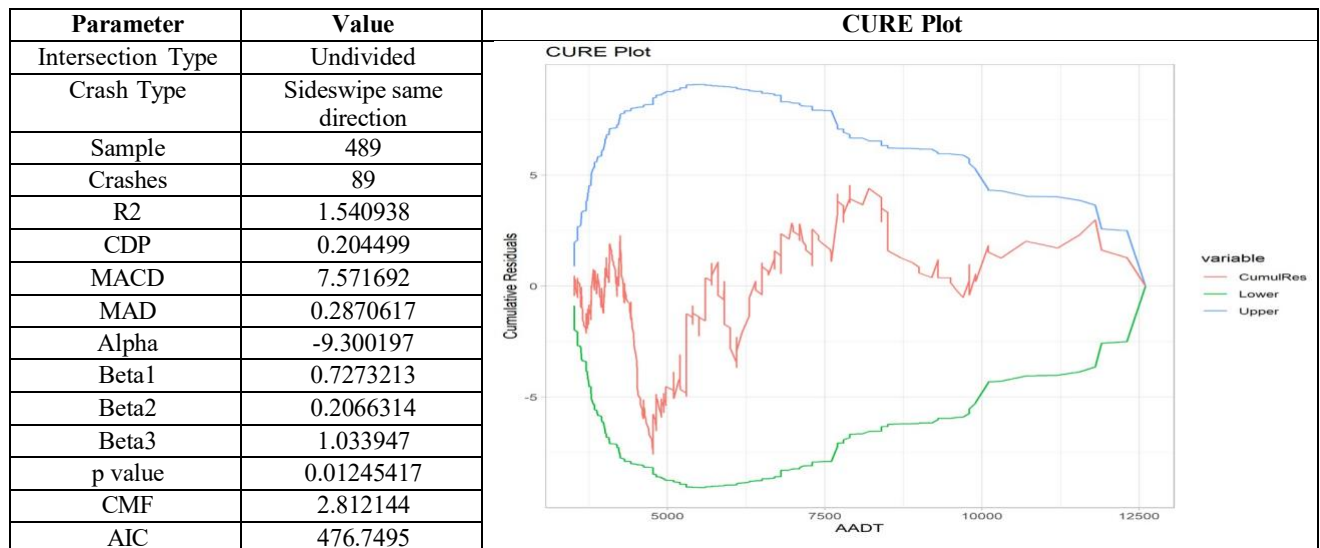
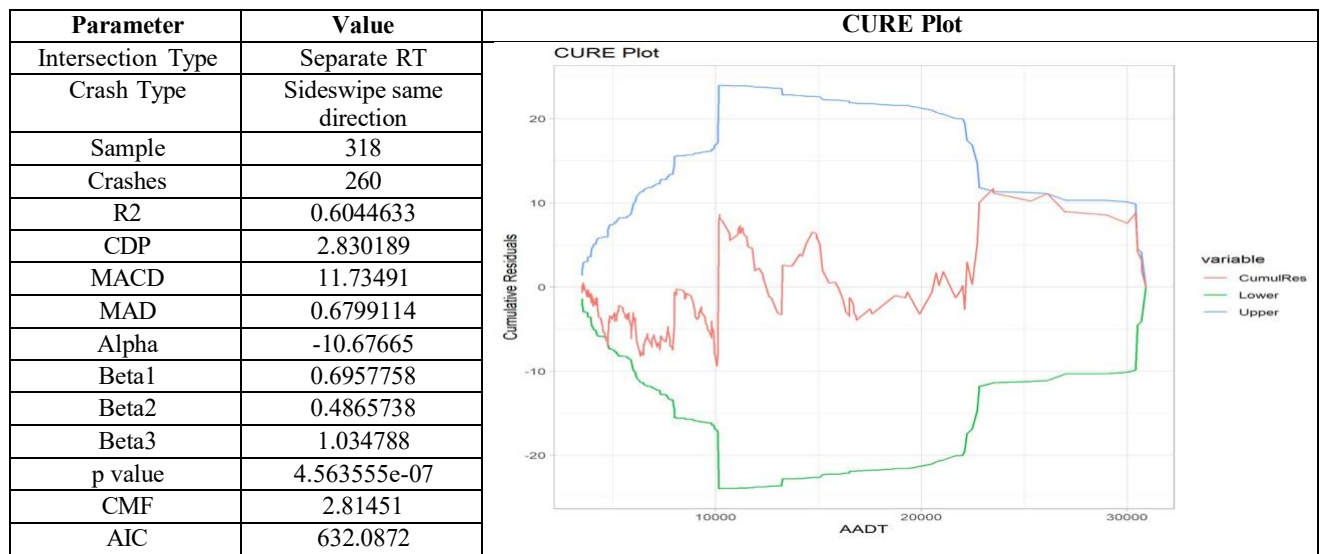
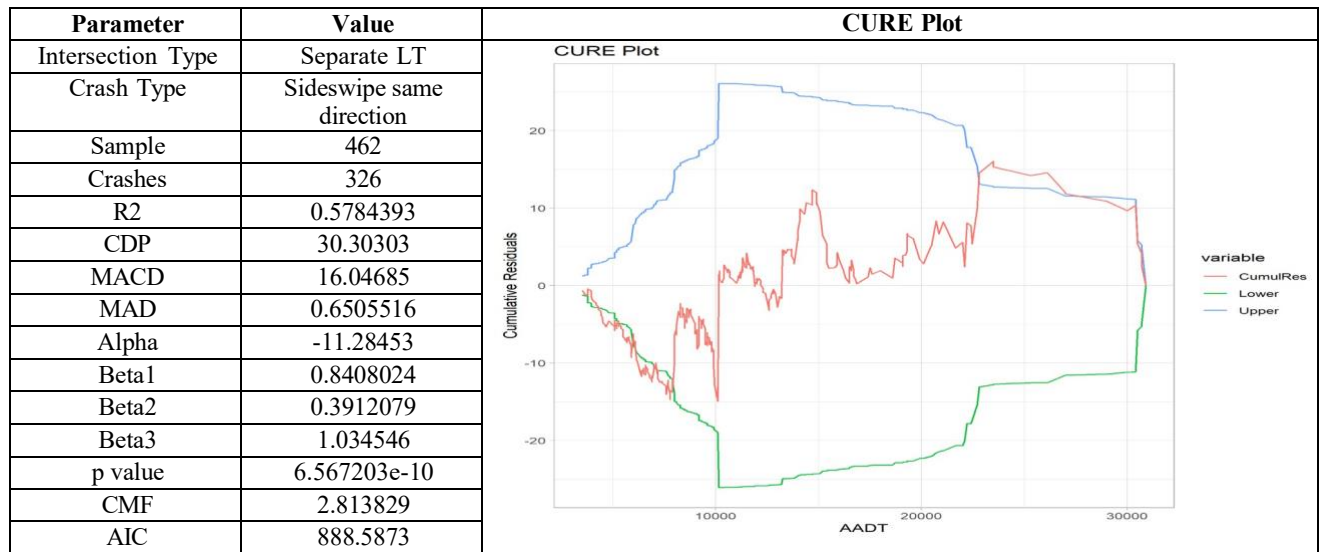


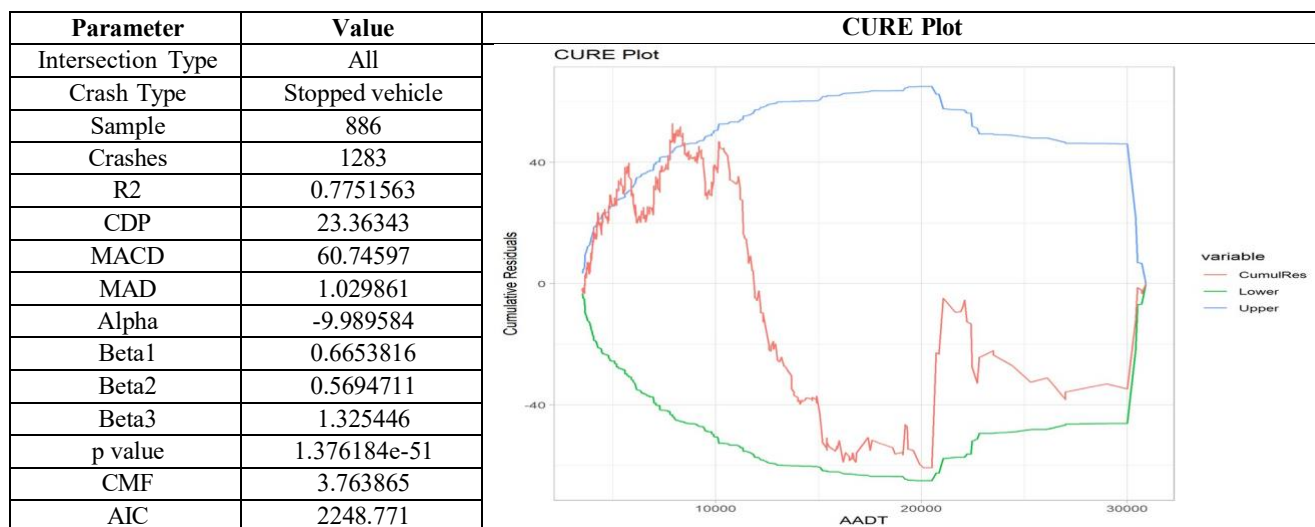
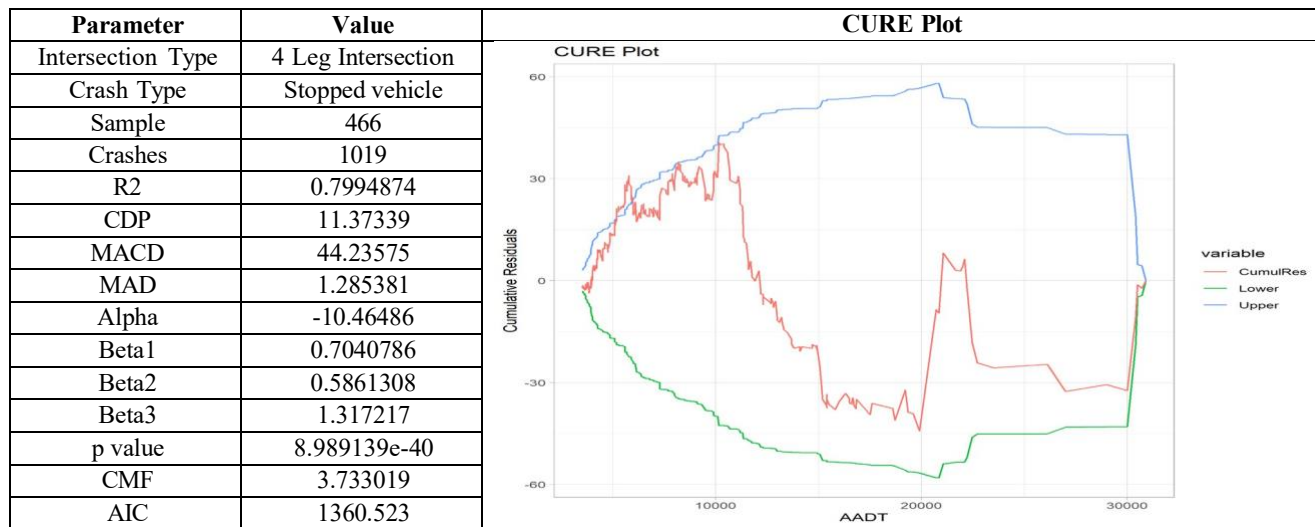
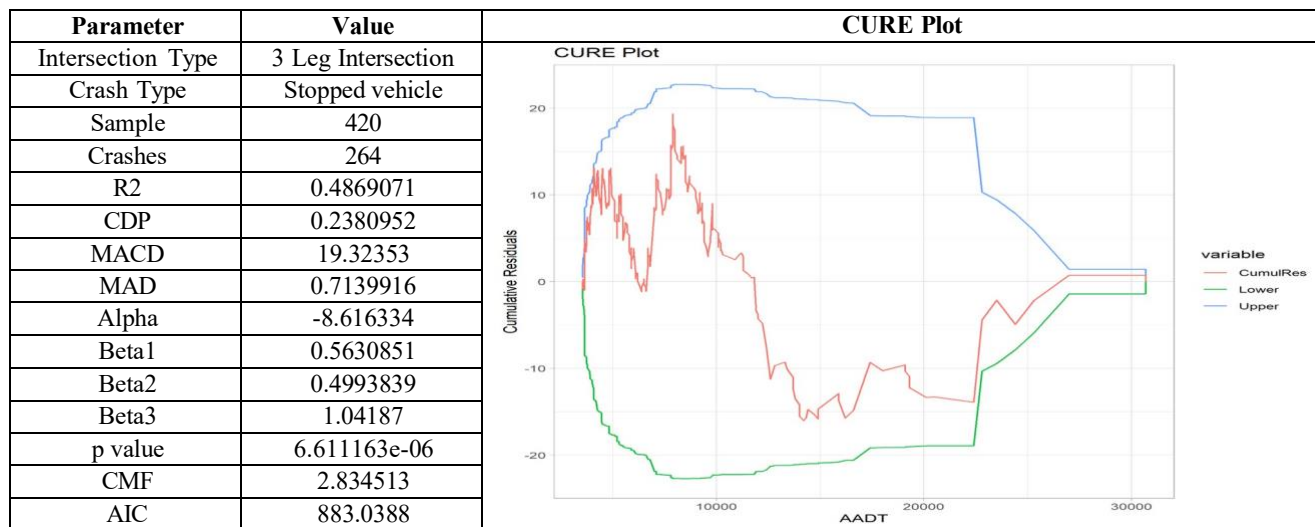


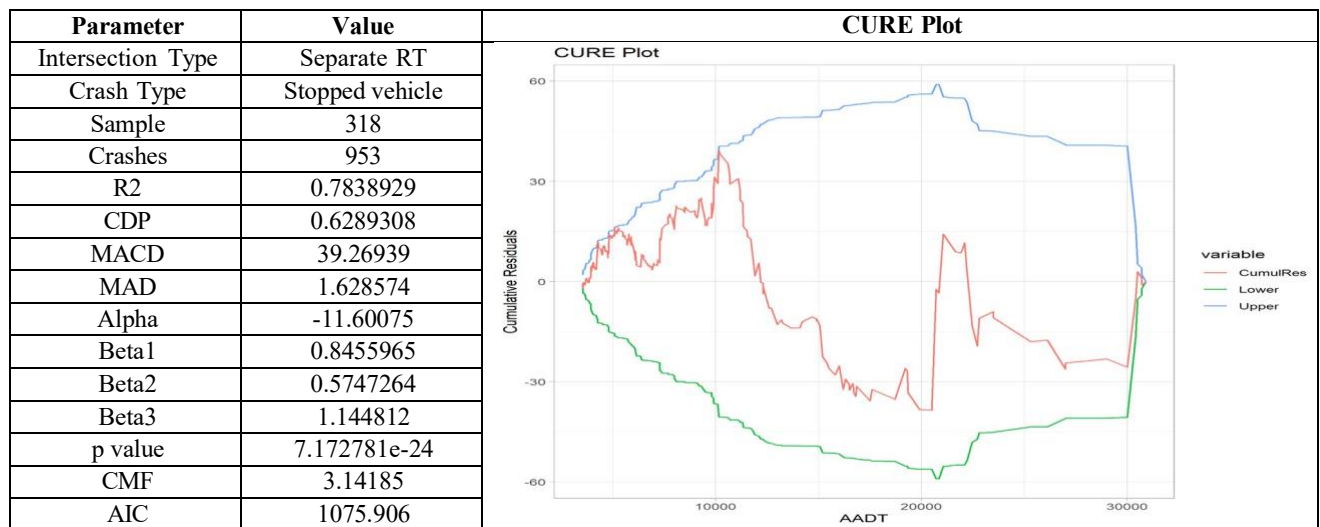
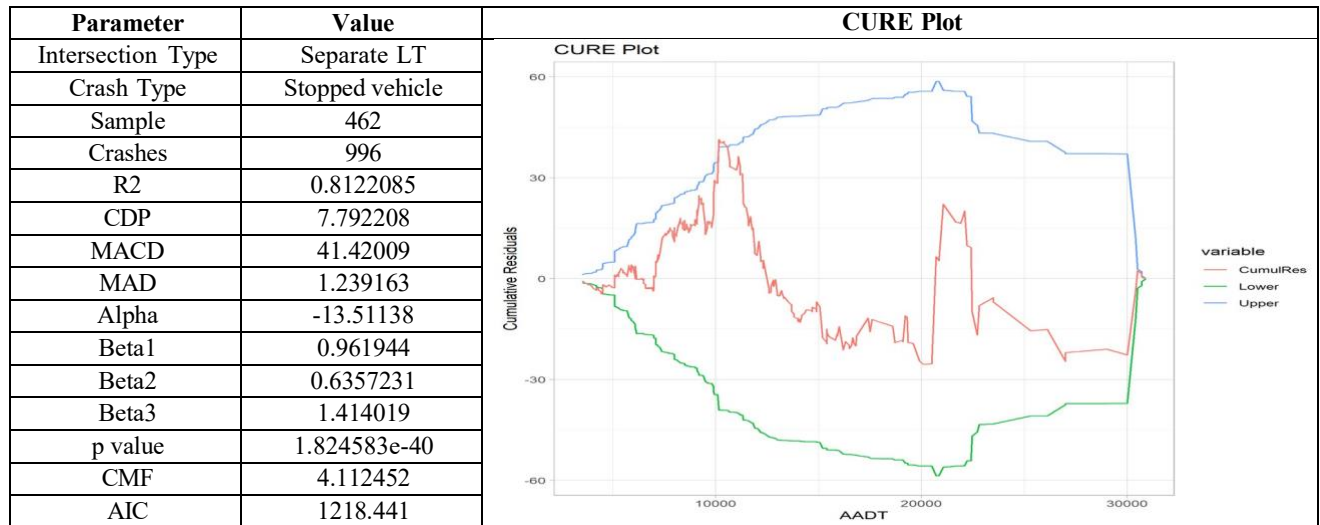
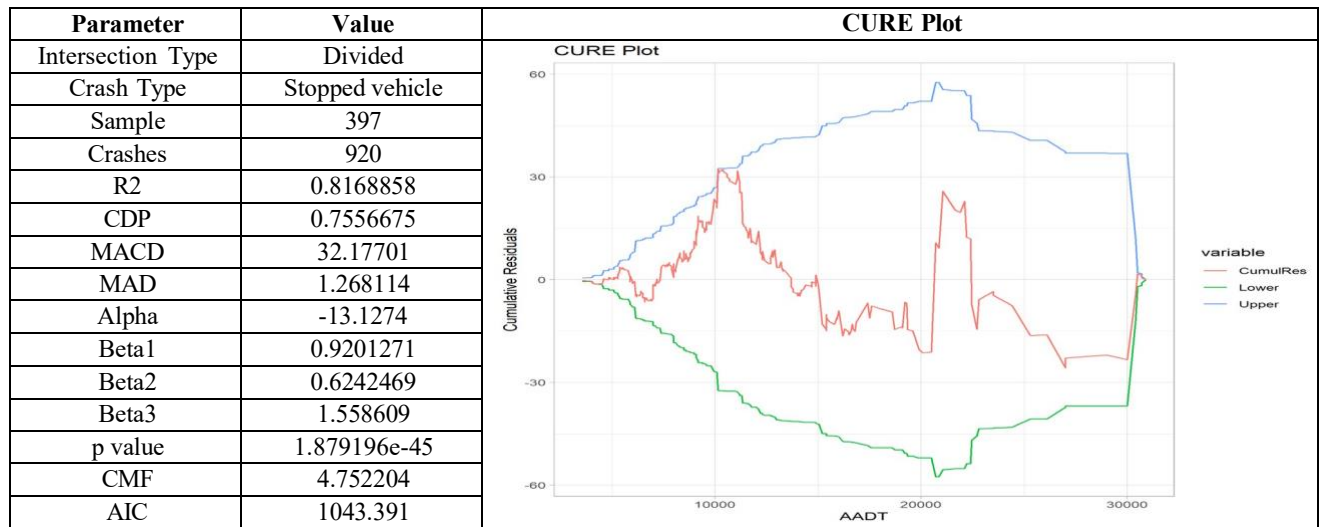


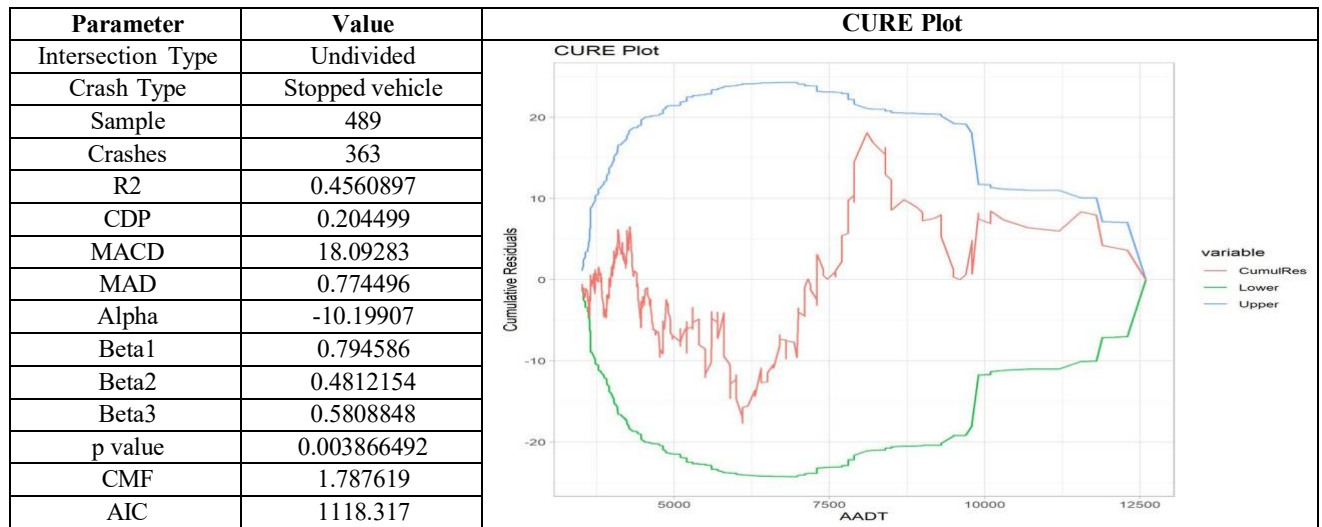


















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